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Review article

Children’s multi-dimensional accessibility to urban green infrastructure: A systematic review of assessment methods and outlook

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ABSTRACT

Previous literature extensively documents the multifaceted benefits of Urban Green Infrastructure (UGI) for children’s physical, mental, and social well-being, while also recognizing the limited UGI access for children in urban areas due to safety concerns, parental constraints, and the uneven UGI spatial distribution. Although prior studies have highlighted the challenges associated with evaluating UGI accessibility and its incorporation into urban planning, and some reviews have explored its implications for children’s health, a comprehensive review of methodological approaches specifically designed to assess children’s accessibility to UGI remains lacking. This systematic review analyzes 638 studies on UGI accessibility (including 80 focused on children) to first outline the most prevalent UGI accessibility dimensions, encompassing physical accessibility (e.g., proximity), perceived accessibility (e.g., perceived barriers), and sensory accessibility (e.g., views). Second, the review classifies methodologies used to assess these accessibility dimensions into two groups: Environmental Data Analyses (EDA) (e.g., physical distance analyses) and Participant Data Analyses (PDA) (e.g., questionnaires), and discusses each in detail. Findings from both general and children-focused studies reveal several limitations in current methodologies of assessing children’s accessibility to UGI. There is a lack of consideration of physical barriers (e.g., stairs), sensory factors (e.g., views), and the absence of validated questionnaires to assess perceived accessibility. This review introduces a conceptual framework that combines EDA and PDA to advance assessments of children’s accessibility to UGI. It addresses key methodological gaps by linking specific methods to each physical, perceived, and sensory dimension, indicating their usage frequency, and striving for more equitable, child-friendly urban environments.

1. Introduction

Urban green infrastructure (UGI) comprises various natural and semi-natural areas within urban settings, such as parks, street trees, suburban forests, grasslands, private gardens, and urban wetlands European Commission (2023); (European Environment Agency, 2018). UGI provides essential ecosystem services, including water purification, air quality improvement, urban cooling, stormwater runoff control,

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habitat provision or recreational opportunities (European Commission, 2023). Therefore, UGI plays a significant role in conserving biodiversity, enhancing public health, and adapting to climate change in cities (European Commission, 2023).

Prior literature has repeatedly stated that UGI has been associated with improved children's physical, mental, and social health (Bao et al., 2022; Dzhambov et al., 2018; Zare Sakhvidi et al., 2022). Exposure to UGI enhances children's cognitive, social-emotional, and motor skills (World Health Organization, 2023). Furthermore, Early interactions with nature have been shown to leave a lasting impact on adulthood, influencing behaviors such as maintaining a healthy lifestyle and reducing the risk of psychiatric disorders (Bozkurt, 2021; Engemann et al., 2019). Issues such as increased screen time, academic pressures, parental restrictions, and lack of greenery around schools or homes have been identified as barriers to providing opportunities for children's contact with urban nature (Bikomeye et al., 2021; Christian et al., 2015; Larson et al., 2018). Children in socio-demographically disadvantaged neighborhoods, including those from low-income families or racial and ethnic minority backgrounds, can face significant barriers to accessing UGI compared to their peers in more affluent areas (Strife and Downey, 2009). To aim for more livable and child-friendly cities, developing UGI planning strategies to bring more nature contact opportunities tailored to children should be a priority (UNICEF, 2022).

In studies assessing residents' contact with UGI, the term "exposure to green spaces" is commonly used (Battiston and Schifanella, 2024; Zare Sakhvidi et al., 2022). This concept encompasses the actual experience of being in or near green areas, including time spent in nature, activities engaged in, and the potential benefits provided by such spaces. (Biernacka and Kronenberg, 2018; Zare Sakhvidi et al., 2022). There is no consensus on the relationship between accessibility and exposure assessments in previous literature. Some studies, such as Zare Sakhvidi et al. (2022), integrate accessibility assessments as a component of exposure evaluations, suggesting that UGI exposure can be categorized into three primary groups: (i) availability, referring to the presence and quantity of green spaces, (ii) quality and usage, capturing public perceptions of the UGI characteristics and (iii) accessibility to UGI considering the proximity to UGI. Conversely, some research distinguishes between exposure and accessibility, defining exposure as the overall presence of green features in the surrounding environment, regardless of their accessibility or intended use. This form of exposure is often assessed through remote sensing techniques, such as the Normalized Difference Vegetation Index (NDVI), which quantifies the surrounding greenness.(Battiston and Schifanella, 2024; Jarvis et al., 2020).

UGI accessibility specifically refers to the extent to which individuals can conveniently and equitably access natural or recreational areas in urban contexts (Wang et al., 2015a). According to this definition, accessibility and exposure are conceptually distinct but significantly overlap, particularly when accessibility is understood beyond mere physical distance (Park, 2017). In this broader sense, accessibility encompasses not only the physical distance to UGI but also individuals' perceptions and sensory experiences when engaging with UGI (Park, 2017; Weerasuriya et al., 2019). The perceived (e.g., subjective distance to UGI) and sensory (e.g., visual or auditory engagement with greenery) dimensions of accessibility align closely with exposure, focusing on the presence and availability of green features in the surrounding environment (Tang et al., 2023). By including these experiential aspects, accessibility bridges the gap with exposure, emphasizing that the benefits of UGI are not limited to physical entry but also extend to the broader perceived and sensory interactions individuals have with UGI (He et al., 2022). Fig. 1 represents the distinction and overlap between concepts of accessibility and exposure to UGI:

This systematic review classifies UGI accessibility into three main dimensions: i) physical, ii) perceived, and iii) sensory:

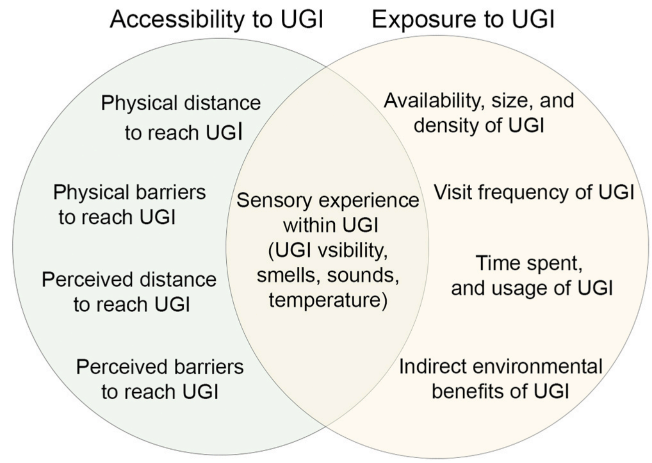

Fig. 1. Conceptual distinction and overlap between accessibility and exposure to UGI.

i) Physical accessibility to UGI describes the possibility of entering UGI and the ability to move in the environment (Lis et al., 2019; Sezavar et al., 2023). Within physical accessibility assessments, there are two main types: i) physical distance accessibility, which determines the proximity and distance to the UGI, and ii) physical barrier-free accessibility, on the other hand, which aims at assessing the physical obstacles that impede the full access of individuals to UGI spaces (Barber et al., 2021).
ii) Perceived accessibility refers to the subjective assessment individuals make regarding the ease or difficulty of reaching the UGI based on their perception (Park, 2017). Perceived accessibility includes two types: i) perceived distance accessibility to UGI, which refers to individuals' subjective assessment of the actual distance or the time needed to cover the distance to UGI (Zhang and Tan, 2019) and ii) perceived barrier-free accessibility, which refers to the subjective evaluation of barriers and enablers in accessing UGI, including perceived obstacles and enablers, including economic, institutional, and social aspects (Biernacka and Kronenberg, 2018; Dai et al., 2023; Robinson et al., 2022).
iii) Sensory accessibility refers to how individuals engage with and experience UGI through various sensory channels, encompassing the extent of their interactions with the immediate sensory stimuli present in UGI (He et al., 2022; Stigsdotter et al., 2017). This dimension includes several types, such as visual accessibility (which refers to the degree to which a person can observe UGI without obstructions) (Sezavar et al., 2023), olfactory accessibility (which refers to the extent to which individuals can detect and engage with the natural scents present in UGI, such as plant aromas or earthy smells) (He et al., 2022), auditory accessibility (which involves the extent to which natural sounds in UGI, such as rustling leaves or birdsong, are audible and unobstructed by urban noise) (Jaszczak et al., 2021; Martínez-Soto et al., 2021), and thermal comfort accessibility (which refers to the extent to which individuals feel comfortable in UGI in terms of temperature, affected by shading, airflow, and sun exposure) (Chen et al., 2022; May and Oliphant, 2023). Unlike physical or perceived accessibilities, sensory accessibility is less commonly addressed in the general literature, though it has been gaining attention in recent studies.

Prior literature has proposed various methodologies to develop UGI accessibility assessments, including the use of physical distance analyses to quantify UGI proximity (Lis et al., 2019), or perceived surveys (Zhang and Tan, 2019) used to ensure that green infrastructure is both economically viable and equitably accessible to diverse urban communities (Mell, 2020; Wang et al., 2015a) amongst others.

Some previous literature reviews focused on the general population have analyzed the methodological approaches utilized in studies assessing UGI accessibility. For example, the review of Li et al. (2023) classified the measurement methods into objective methods (e.g., travel time and distance analyses), and perceived methods (e.g., satisfaction surveys), stressing the equal importance of both methodological approaches and the necessity of integrating them to assess access to UGI comprehensively. Park (2017) reviewed the methods used to assess perceived accessibility to urban parks, highlighting the role of individual perceptions and advocating for a combined approach of physical distance analyses and methods related to perceived accessibility such as questionnaires, interviews, and observations. Weerasuriya et al. (2019) on the other hand conducted a systematic review of papers addressing considerations such as viewing, observing, listening, exploring, and sitting in urban green spaces in healthcare settings by considering methods including behavioral observations, questionnaires, and interviews.

Previous literature reviews focused on children have predominantly examined the relationship between UGI exposure and children's health outcomes (by considering physical distance as a component of UGI exposure), and they have had limited consideration of methods applied in UGI accessibility assessments (Barnett-Itzhaki et al., 2024; Browning and Rigolon, 2019; Jia et al., 2021; McCormick, 2017; Vanaken and Danckaerts, 2018). In addition to exploring the association between UGI exposure and health aspects, some children-focused reviews have assessed the measurements to evaluate UGI exposure (Davis et al., 2021; Liu and Green, 2023; Zare Sakhvidi et al., 2022). The review of Davis et al. (2021) identified nature exposure measurements (including NDVI, buffer analysis, self-developed surveys, GPS tracking, and parent reports) used in the literature and evaluated their association with childhood mental health and development. Additionally, the review of Liu and Green (2023) examined observational and experimental studies in residential settings, considering remote-sensing satellite data, on-site tools, and perceived assessments to investigate the psychological benefits of nature exposure for children aged 6–12.

Notably, among the children-focused literature reviews, Teeuwen et al. (2024), examined the factors influencing children's access to urban green spaces for those aged 6–11 years. They developed a conceptual model with five clusters addressing key questions about accessibility: *With whom* does the child access? From *where? How?* To *where?* and *Why?* The review indicated that children's access involves a trade-off between reachability (determined by the route to the greenspace) and attractiveness (how well the

Despite increasing attention to UGI accessibility, there is a lack of systematic synthesis of assessment methods tailored to children, a population whose unique developmental characteristics, such as limited mobility, reduced abstract reasoning, shorter attention spans, and greater dependence on adults, fundamentally shape how they navigate, perceive, and interact with green environments. These age-based characteristics not only influence children's engagement with UGI but also challenge the suitability of conventional research methods (Bell, 2007; Parker, 1984). To the best of the authors' knowledge, no existing literature reviews have comprehensively assessed the diverse methodological approaches used to study the physical, perceived, and sensory accessibility to UGI for children.

Hence, this systematic review aims, first, to identify and classify the prevalent methods for assessing UGI accessibility; and to evaluate their application and adaptability to child-specific contexts. Grounded in UNICEF's Child-Friendly Cities Initiative—launched in 1996 and reaffirmed in its 2022 framework, which advocates for equitable, safe, and inclusive urban environments for children (UNICEF, 2022)—this review provides a structured overview of existing assessments and proposes a conceptual framework to inform child-friendly urban planning practices.

2. Review method

The 2020 version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol was followed for this review to ensure methodological rigor, transparency, and reproducibility (Moher et al., 2015; Page et al., 2021). The adopted approach involved conducting a targeted resource search, applying eligibility criteria for article inclusion, and performing a detailed analysis of the content and results of the selected articles.

2.1. Search strategy and eligibility criteria

The primary objective of the search strategy was to identify general studies evaluating UGI accessibility and classify the methods employed. Following this, the review focused on studies specifically addressing children's accessibility to UGI within the selected literature, to identify methodological gaps and areas requiring further research. Accordingly, the search strategy was designed to target articles assessing UGI accessibility in general using three databases, namely Web of Science, Scopus, and PubMed. Additionally, the Google Scholar database was accessed to conduct a manual search.

To compile literature focusing on UGI accessibility assessment, the following search criteria were defined using four thematic keywords. The first thematic area focused on keywords related to green infrastructure. The second emphasized the geographic area of interest, specifically urban areas, and related scales. The third centered around access and related terminology of accessibility, while the fourth delved into keywords linked to the assessment dimensions of UGI accessibility. The keyword search string within titles and abstracts was undertaken using the following code: ("Green Environment" OR "Green Infrastructure" OR "Green Space" OR "Green Area" OR Greenery OR Greening) AND (Urban* OR Cit* OR Neighborhood OR Neighbourhood) AND Access* AND (Proximity OR Distance OR Perceived OR Physical OR "Walking Time" OR Barrier* OR Physiol* OR Psychol* OR Cognit* OR Attention* OR Behavior* OR Behaviour* OR Expos* OR Olfactory OR Odor OR Odour OR Audit* OR Sound* OR Touch* OR Tactile OR Visual* OR Vision* OR Thermal OR Heat* OR Comfort* OR Measur* OR Assess* OR Evaluat* OR Quanti* OR Tool* OR Test* OR Method* OR Metric* OR Regress*).

The inclusion and exclusion criteria were established a priori to reduce selection bias and ensure replicability. Studies were included if they met all the following conditions:

1. Published in peer-reviewed journals or conference proceedings, in English, between January 2012 and December 2024;
2. Focused explicitly on UGI, or closely related urban green environments;
3. Employed explicit methodological approaches for assessing accessibility to UGI, whether through quantitative techniques (e.g., GIS, network-based models, statistical analysis) or qualitative and perception-based methods (e.g., surveys, interviews);
4. Had accessible full texts at the time of review.

Studies were excluded if they:

E1: Focused solely on non-urban contexts;

E2: Did not center on UGI or comparable green elements (e.g., only grey infrastructure or general ecosystem services);

E3: Lacked a methodological assessment of accessibility (e.g., studies merely discussing green space benefits without spatial or experiential assessment);

E4: Were not retrievable in full-text through institutional or open-access sources.

These criteria were developed iteratively during protocol piloting to maintain consistency while encompassing the methodological diversity within the field.

2.2. Screening and Selection Process

The systematic search process retrieved a total of 8479 articles from three databases—Web of Science (4941), Scopus (3097), and PubMed (551)—through a comprehensive title, abstract, and keyword search. The records were first refined by restricting results to English-language, peer-reviewed publications from January 2012 to December 2024, which yielded a refined pool of 7319 articles (4283 from Web of Science, 2612 from Scopus, and 424 from PubMed). Duplicate records were identified and removed using EndNote 20, resulting in the exclusion of 2278 items and leaving 5041 unique records for title and abstract screening.

To ensure transparency and reproducibility in line with the PRISMA 2020 guidelines (Page et al., 2021), the screening process was conducted using a standardized, multi-phase protocol. Two independent reviewers, trained in systematic review procedures, screened all records at the title and abstract level. Prior to full screening, a pilot test on 100 randomly selected articles was conducted to calibrate inclusion judgments and ensure inter-reviewer consistency. Any discrepancies at either the abstract or full-text stages were resolved through consensus or adjudication by a third senior reviewer.

In the full-text screening phase, a total of 677 articles were assessed for eligibility. 42 articles were excluded due to failure to meet the inclusion criteria, and an additional 29 were excluded due to unavailability of the full text. Reasons for all full-text exclusions were logged and categorized. This phase concluded with 606 articles remaining for inclusion.

To improve the comprehensiveness of the review and minimize publication or indexing bias, backward and forward snowballing strategies were employed following the recommendations of Wohlin (2014).

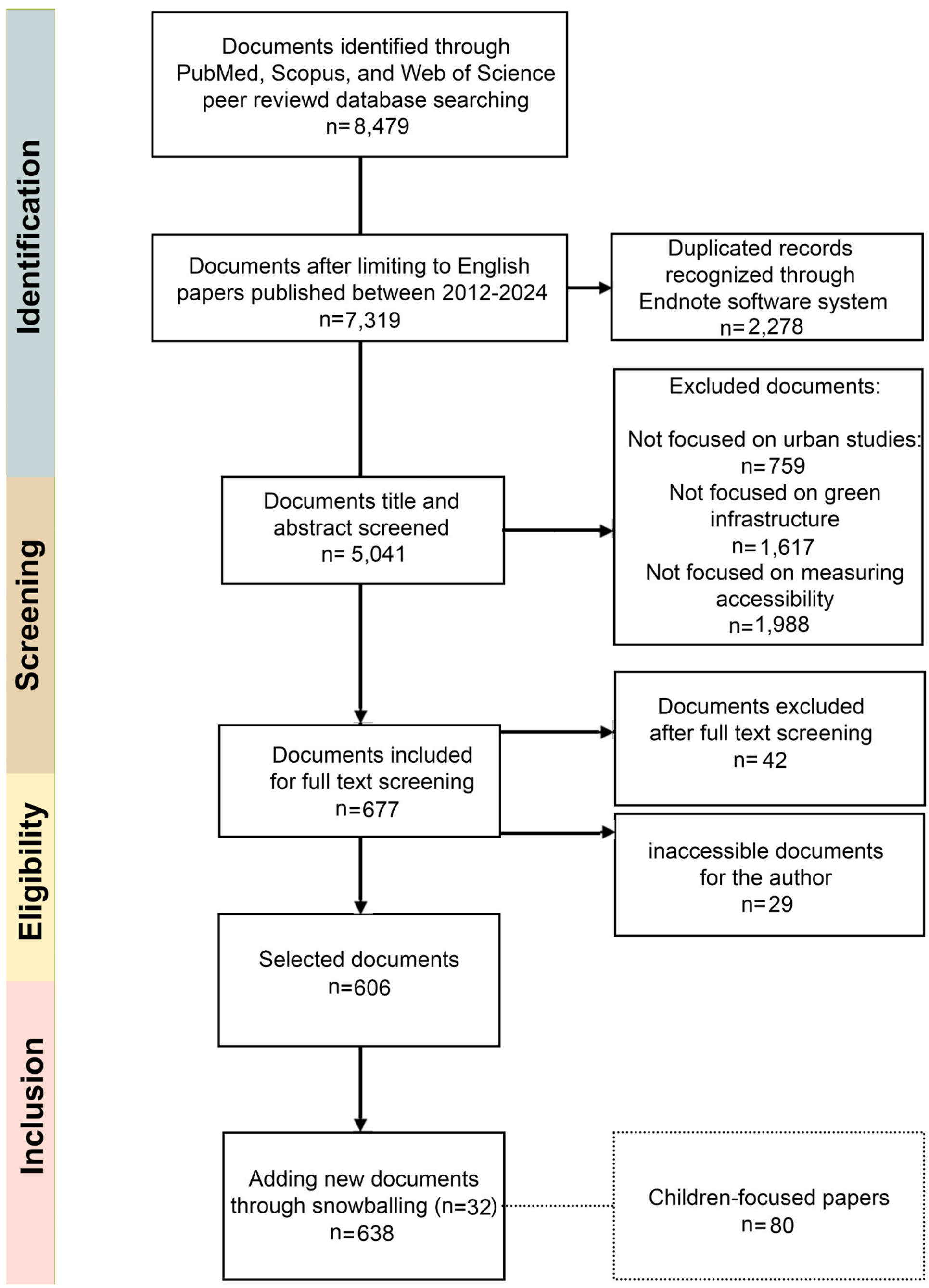

Fig. 2. Review process.

Backward snowballing involved manually screening the reference lists of all 606 included studies to identify additional relevant literature. Concurrently, forward snowballing was conducted using the "Cited by" feature in Google Scholar, tracing subsequent studies that cited the included articles. Only peer-reviewed studies that met all predefined eligibility criteria were retained during this phase. This process resulted in the identification and inclusion of 32 additional articles.

As shown in Fig. 2, this process resulted in 638 articles for inclusion in this review study. This study defines children as individuals between the ages of 0 and 18, in alignment with the United Nations Convention on the Rights of the Child (UNCRC) (UN, 1989). Among the 638 selected literature, 80 papers (~ 12.5 %) (see Supplementary Table S1) focused on children's accessibility to UGI.

2.3. Data extraction process

In line with PRISMA (2020) guidelines (Page et al., 2021), the authors developed a standardized data extraction table to systematically record key characteristics and methodological attributes of each included study. The extraction framework captured critical variables such as author(s), year of publication, study design, target population, geographical coverage, and types of UGI examined. Furthermore, it included detailed information on the dimensions of UGI accessibility addressed, as well as the methods and tools used for accessibility assessment. Where applicable, the outcomes measured and any policy or practice implications were also documented. This structured approach facilitated a consistent and transparent synthesis of the evidence base and enhanced the reproducibility of the review process. To provide additional insight into the strength of the children-focused literature, a contextual quality appraisal was conducted based on the following criteria: recency of publication, journal indexing and reputation, scope relevance, methodological novelty, multidimensional accessibility perspective, policy and planning relevance, and target population specificity. Studies were qualitatively rated as high, moderate, or low quality based on their alignment with these criteria.

3. Results

3.1. Methods used in UGI accessibility assessments

This review organizes the methods used to assess physical, perceived, and sensory accessibilities to UGI in two methodological groups.

Environmental Data Analyses (EDA) encompass a wide range of techniques using remote sensing or Geographic Information Systems (GIS) data and two-dimensional (2D), and three-dimensional (3D) environmental and geographical analyses —such as physical distance analyses, physical barrier index analysis, Green View Index (GVI), viewshed analysis, space syntax analysis, Land Surface Temperature (LST) analysis, Sound Pressure Level (SPL) analysis, and on-site quantifications (such as on-site physical barrier analysis). These approaches are typically referred to as quantitative, data-driven, or objective methods (Bopp et al., 2024; Jaszczak et al., 2021; Kawai et al., 2024; May and Oliphant, 2023; Teeuwen et al., 2023).

On the other hand, Participant Data Analyses (PDA) encompasses methods for collecting and analyzing data from individuals, including questionnaires, interviews, observational methods, photovoice, and Virtual Reality (VR) immersion. These methods generally prioritize understanding subjective experiences, perceptions, and behaviors. PDA often involves methods that gather subjective insights or behavioral data from individuals and provide an understanding of how people interact with and experience UGI (Kandasamy et al., 2024; Kawai et al., 2024; Park, 2017).

Generally, in the previous literature, physical accessibility has been assessed through EDA, perceived accessibility has been assessed through PDA and the utilization of both EDA and PDA has been documented for sensory accessibility assessments.

Table 1 illustrates the classification of the selected children-focused literature according to the considered UGI accessibility dimensions, types, and deployed methodologies. As shown, most of the children-focused literature used EDA methods to assess physical distance accessibility to UGI.

3.1.1. Environmental Data Analyses (EDA)

Table 2 shows the classification of EDA methods used in the general literature based on the assessed UGI accessibility dimensions and types.

3.1.1.1. Straight-line analysis. Also known as Euclidean distance analysis, the straight-line analysis is a method of measuring the shortest geometric distance between two points in a spatial context, usually without considering the existing network or pathways, providing a direct and simple measure (Nicholls, 2001; Oh and Jeong, 2007).

Among the children-focused literature that utilized straight-line analysis (see Table 3), for example, Walker et al. (2021) employed a 3000 m straight-line analysis to determine the proximity to the nearest entrances of public parks and gardens from primary schools across England. They found most schools offer children direct access to UGI.

3.1.1.2. Buffer analysis. Buffer analysis is a geospatial technique that creates a zone within a specified radial distance around a geographic feature to evaluate spatial relationships, physical accessibility, or impact within that defined zone (Van Herzele and Wiedemann, 2003). The center of the buffer could be the UGI component, residential areas, commuting routes, and other urban facilities such as schools (Schipperijn et al., 2017).The use of buffer analysis to assess UGI accessibility for children has been widespread in previous studies (see Fig. 3). For example, Dzhambov et al. (2018) employed buffer analysis (100 m, 500 m, 1000 m) to assess auditory accessibility to UGI by integrating data from the strategic noise map of Plovdiv, Bulgaria. The study found that living in less green neighborhoods may worsen the negative impact of traffic noise on students' mental health.

While most published articles about UGI accessibility for children have primarily focused on residential areas in their methodologies, in recent years, school and other educational settings have started to be studied as reference areas for UGI assessments, given the significant time children spend in these spaces (Almeida et al., 2022; Teeuwen et al., 2023). For example, in the study conducted by Meng et al. (2022), a buffer size of 60 m was selected to assess UGI accessibility from primary schools, revealing disparities in access to green environments for students in developing regions of China.

3.1.1.3. Network analysis. Network analysis evaluates accessibility to UGI by measuring actual travel distances or time along street, pedestrian, or transport networks, rather than relying on straight-line distances as in traditional buffer analysis(Comber et al., 2008). It encompasses various techniques in GIS, including shortest path analysis (e.g., identifying the most efficient route to UGI), origin-destination matrices (e.g., calculating travel distance or time between multiple origins and UGI), service area analysis (e.g., delineating zones reachable within a given distance or time to a UGI), and location-allocation modeling (e.g., optimizing the placement of new UGI to serve underserved areas) (Comber et al., 2008; Semenzato et al., 2023). Within this framework, street-network buffer analysis is frequently employed to define proximity zones to UGI based on distances measured along the actual street or pedestrian network. While methodologically part of network analysis, it is often viewed in the literature as a specialized or evolved form of traditional buffer analysis, since it builds upon the buffer concept but replaces circular, straight-line radii with buffers constrained by the real-world network layout distance (Teeuwen et al., 2023).

Among the studies that utilized network analysis for assessing children's accessibility to UGI (see Table 3), the study of Laszkiewicz and

Table 1
UGI accessibility dimensions, types, and methodologies utilized for children in the selected.

Physical	Perceived		Sensory	
Physical Distance	Perceived Distance	Perceived Barrier-Free	Visual	Auditory
▲ [1-47], [49-52], [69-78]	○ [9], [60-61], [63], [66], [67-68]	○ [62], [64-65], [80]	▲ [28], [43], [78]	▲ [48]
■ [53-58], [79-80]	■ [59], [80]	■ [58]		

Notes: articles utilized environmental data analyses (EDA): ▲, articles utilized participants data analyses (PDA): ○, review papers: ■

1-3 paper(s) 4-10 paper >40 papers

(see Supplementary Table S1 for the numbered references).

Table 2
EDA methods used in the general population based on assessed UGI accessibility.

Accessibility Dimensions	Accessibility Types	EDA Methods
Physical Accessibility	Physical Distance Accessibility	Straight-Line Analysis Buffer Analysis Network Analysis Travel Time Analysis Gravity-based Models
	Physical Barrier-Free Accessibility	On-Site Barrier Analysis Barrier Index Analysis
Sensory Accessibility	Visual Accessibility	GVI Viewshed Analysis Visibility Space Syntax Buffer Analysis
	Thermal Comfort Accessibility	LST Analysis Network Analysis Buffer Analysis Gravity-based Models
	Auditory Accessibility	SPL Analysis Buffer Analysis

Sikorska (2020) used Network Analysis in ArcGIS to assess the green walking distance from each child's home to their primary school, assuming children take the shortest route due to daily repetition and time efficiency, and considered a maximum walkable distance of 1.5 km, as shorter distances increase the likelihood of active commuting. They found that children from lower welfare-status groups have less greenery along their home-school routes compared to others. In another children-focused paper that utilized network analysis, Teeuwen et al. (2023) assessed children's accessibility to green spaces by considering access from residential areas, schools, and commuting routes, utilizing a street-network buffer analysis. They found that smaller green spaces are more accessible from children's schools than from their homes and are situated in areas with lower children's population density.

3.1.1.4. Gravity-based models. Gravity-based models evaluate green space accessibility by considering the inverse relationship between distance and accessibility, with closer green spaces being more accessible (Laan and Piersma, 2021; Xu and Wang, 2023). Among them, the Two-Step Floating Catchment Area (2SFCA) method evaluates green space accessibility by considering both supply (UGI quantity, size) and demand (population) factors, along with the distance to park entrances as a friction factor. (Luo and Wang, 2003). This was followed by enhancements by Luo and Qi (2009), leading to the development of the Enhanced Two-Step Floating Catchment Area method (E2SFCA). The E2SFCA method incorporates a distance decay function, which reflects the diminishing influence of UGI components as distance increases (Luo and Qi, 2009). Further enhancements to the 2SFCA model include the Weighted 2SFCA, which introduces weighted factors to account for the varying importance of different facilities (Audi et al., 2022), and the Gaussian and Multi-Modal 2SFCA, designed to capture the non-linear relationships between accessibility and distance (Wu et al., 2020). Additionally, the Huff 2SFCA model combines proximity with a parameter for green space attractiveness, such as size or available amenities (Zhang et al., 2021). Furthermore, the 3SFCA method mitigates the overestimation of population demand by subdividing service areas into multiple sub-zones and applying Gaussian weights (Ye et al., 2024). Moreover, the nSFCA (n-step Floating Catchment Area) method introduces additional steps to capture accessibility dynamics considering spatial interactions, service competition, and travel impedance. Unlike the standard two-step approaches, nSFCA iteratively redistributes demand and adjusts weightings across multiple steps (Liang et al., 2024).

Among the children-focused articles utilizing gravity-based models (see Table 3), Martori et al. (2020) utilized the E2SFCA method to evaluate park and playground accessibility by considering socioeconomic factors. They involved computing the actual distances to the nearest playground and population group accessibility within defined catchment areas (250 m, 500 m, 750 m, and 1000 m). They found no significant spatial disparities in access to children's playgrounds in Barcelona, Spain.

In another children-focused study, Liao and Furuya (2024) employed a Huff-based 2SFCA model integrated with a Gaussian decay function to assess park accessibility for children. This approach refined the analysis by incorporating a probability-based accessibility measure. Specifically, the model accounted for variations in park size and quality, recognizing that larger parks with diverse recreational facilities are more attractive to children. The Gaussian decay function replaced the traditional distance decay in the Huff model to better reflect spatial friction, while 750 m was set as the effective walking distance based on real-world mobility patterns. The study found significant disparities in children's park accessibility across Changsha City.

3.1.1.5. Travel Time Analysis. Travel time analysis involves evaluating the time required for individuals to reach urban green spaces from their respective locations (Grahn and Stigsdotter, 2003; Oh and Jeong, 2007). Travel time analysis is conducted by computing the travel time between specific locations and considering different traffic modes (Chen et al.,

Table 3
EDA methods utilized in the selected children-focused articles and focused areas.

Buffer Analysis
▲ [4], [6-8], [11-12], [16-17], [19-21], [25], [27], [29-30], [34-37], [39], [40-42], [44-50], [52], [75] ■ [2], [6], [10], [14], [18], [22], [31], [38], [71], [77-78] ▲■ [15], [32-33], [51]

Street-network buffer analysis	Network Analysis	Straight-Line Analysis
▲■◆ [1]	▲ [3], [5], [69], [74] ■ [9], [71] ◆ [24], [28], [43]	▲ [23], [72] ■ [9]

E2SFCA	Gaussian 2SFCA	Huff 2SFCA
▲ [13]	▲ [70]	▲ [73]

Walking Travel Time Analysis	Isochrone Travel Time Analysis	Viewshed Analysis	GVI
■ [76]	▲ [26]	◆ [28], [43]	■ [78]

Notes: residential area: ▲, (pre) school environment: ■, commuting routes: ◆

1-3 paper(s) 4-10 papers >40 papers

2020). Additionally, isochrone travel time analysis delineates areas reachable within specified time intervals from a given point, accounting for available transportation modes. It also aligns with network analysis due to its definition of service areas based on network-based travel time (Bao et al., 2022).

Among the children-focused studies utilizing travel time analysis, the study by Bao et al. (2022) used isochrone travel time to define a 10-minute coverage area and found a negative relationship between children's accessibility to UGI and social anxiety. Additionally, the study of Krawczyk et al. (2024) employed walking distance travel time analysis to evaluate children's accessibility to outdoor green spaces from kindergartens in Poland, using a 5-minute walking threshold as a measure of walkability. The results indicated that there is a disparity in access to urban green spaces for kindergartens in Polish cities.

3.1.1.6. Physical barrier index analysis. The physical barrier index method systematically evaluates the physical barriers impacting accessibility to UGI by aggregating data from defining and weighting indicator classes across distinct spatial dimensions. In the general literature, only Barber et al. (2021) applied this approach to analyze physical barriers to UGI in Halle, Germany. The barrier index for each greenspace was calculated by aggregating ratings from specific indicator classes across three spatial dimensions—inside (obstacles within the space), boundary (obstructions at the edges), and outside (barriers in the surrounding area)—with the resulting values combined and classified into quintiles to reflect the cumulative effect of physical barriers, where higher values indicate greater.

No children-focused literature utilized the physical barrier index analysis method to assess physical barrier-free accessibility to UGI.

3.1.1.7. On-site physical barrier analysis. On-site barrier analysis is a research method that directly surveys and measures physical obstacles in a specific location. Among the selected general literature, only Lepoglavec et al. (2023), assessed the physical barrier-free accessibility to a park for individuals using wheelchairs through an on-site barrier analysis using GAIA GPS and GNSS GS mobile applications to survey slopes and identify other accessibility barriers.

No children-focused literature utilized on-site physical barrier analyses to assess physical barrier-free accessibility to UGI.

3.1.1.8. Green View Index. The Green View Index (GVI) quantifies the presence of green vegetation within a specific area or viewshed by analyzing images to assess the extent of the vegetation coverage (Wu et al., 2022). This method is primarily used to evaluate visual exposure and also visual accessibility to UGI by measuring the percentage of tree canopy and vegetation visible from a specific vantage point or location,

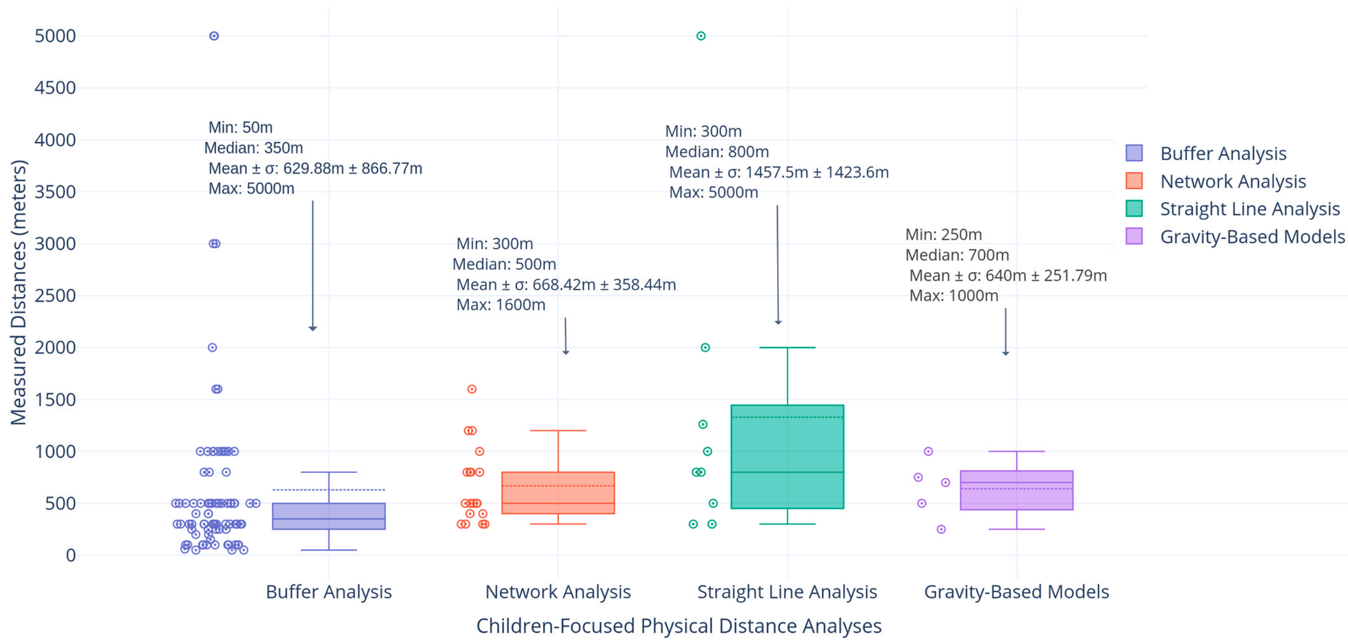

Fig. 3. Statistical data on the EDA measures used in physical distance analyses in children-focused literature.

often based on street-level images or panoramic views. The GVI is calculated by dividing the area of visible greenery by the total visible area from an observation point, with higher GVI values indicating greater greenery (Cui et al., 2022; Yang et al., 2009).

Among the general literature, various studies used the GVI method or its enhancements to assess visual accessibility to UGI (Tang et al., 2023; Yan et al., 2023). For example, Xiao et al. (2021) applied a 2D GVI using street view images to assess neighborhood greenness and Tang et al. (2023) used point cloud data to evaluate 3D GVI.

Among the studies focused on children, only the research by Lun et al. (2024)employed 2D GVI to assess visual accessibility to UGI in the school environments of China, using static street view images. The study found that GVI has a positive impact on children's mental health.

3.1.1.9. Viewshed analysis. The viewshed analysis is a geospatial methodology that is applied using 2D geospatial maps, 2.5D maps with elevated surface features using digital surface models, and 3D using detailed building and city geometries to assess the visibility of greenery from various viewpoints (Khanian et al., 2024).

Within the children-focused literature utilizing viewshed analysis (see Table 3), the study by Khanian et al. (2024) utilized 2.5D viewshed analysis to evaluate children's visual accessibility to UGI along home-school routes. The observer's height was set at 1.4 m to reflect the average height of primary school-aged children, ensuring the analysis aligned with their visual perspective. A 10-meter visibility area was used to capture the distance at which children can recognize basic plant species and experience direct contact with greenery. They found children from disadvantaged socio-economic groups have less greenery along home–school routes, highlighting environmental injustice. Additionally, Laszkiewicz and Sikorska (2020) utilized 2D viewshed analysis to evaluate greenery visibility along home-school routes. They calculated visibility areas at 10 m intervals with buffers of 5 m, 10 m, 30 m, and 50 m, analyzing different greenery types and key metrics, including median visibility, route segments with visibility below 10 %, and the number of children with low visibility. They found most home-school routes have low greenery visibility, particularly within a 5 m distance, with nearly 40 % of children having less than 10 % greenery.

3.1.1.10. Visibility space syntax analysis. The visibility space syntax analysis considers the spatial configuration of the area and the presence of obstacles that may impede sightlines, reflecting the likelihood that pedestrians will encounter UGI along the spatial network. Among the general literature, Fan et al. (2022), utilized space syntax to assess adults' visual accessibility to UGI from pedestrian routes.

No literature focusing on children that used space syntax analysis to assess UGI visual accessibility was found in the selected studies.

3.1.1.11. Land Surface Temperature analysis. Land Surface Temperature (LST) analysis is typically performed using satellite imagery and remote sensing techniques to assess how the surface temperature of the Earth changes due to factors such as land use, vegetation cover, urbanization, and climate change (Chen et al., 2022).

Among the general literature, for assessing the thermal comfort accessibility to UGI, physical distance analyses and LST analyses have been combined (Chen et al., 2022; Xiao et al., 2023). For example, the study of Xiao et al. (2023) analyzed the cooling effect of urban parks, focusing on the LST-distance relationship for each park. They utilized a 300 m buffer divided into 10 zones of 30 m each to illustrate the correlation between distance from the park and the corresponding LST.

However, no UGI accessibility studies focused on children's communities used LST analysis.

3.1.1.12. Sound Pressure Level analysis. Sound Pressure Level (SPL) analysis refers to the measurement of sound pressure levels to quantify noise intensity in decibels (dB) at specific points in space (Jaszczak et al., 2021). From the selected general literature utilizing SPL analysis, Jaszczak et al. (2021) evaluate the auditory accessibility of adults to UGI by assessing the soundscape of parks, in two periods (leafless and leafy).

Within the selected children-focused literature, no papers utilizing SPL analysis were found.

Table 3 shows the EDA methods deployed in the selected children-focused articles and the chosen study areas for their assessments, including residential areas, (pre)school environments, and children's commuting routes.

Fig. 3 presents the statistical data on the measures used in physical distance analyses in children-focused literature.

Additionally, Fig. 4 provides a graphical representation of the EDA methods employed in evaluating UGI accessibility in the children-focused literature.

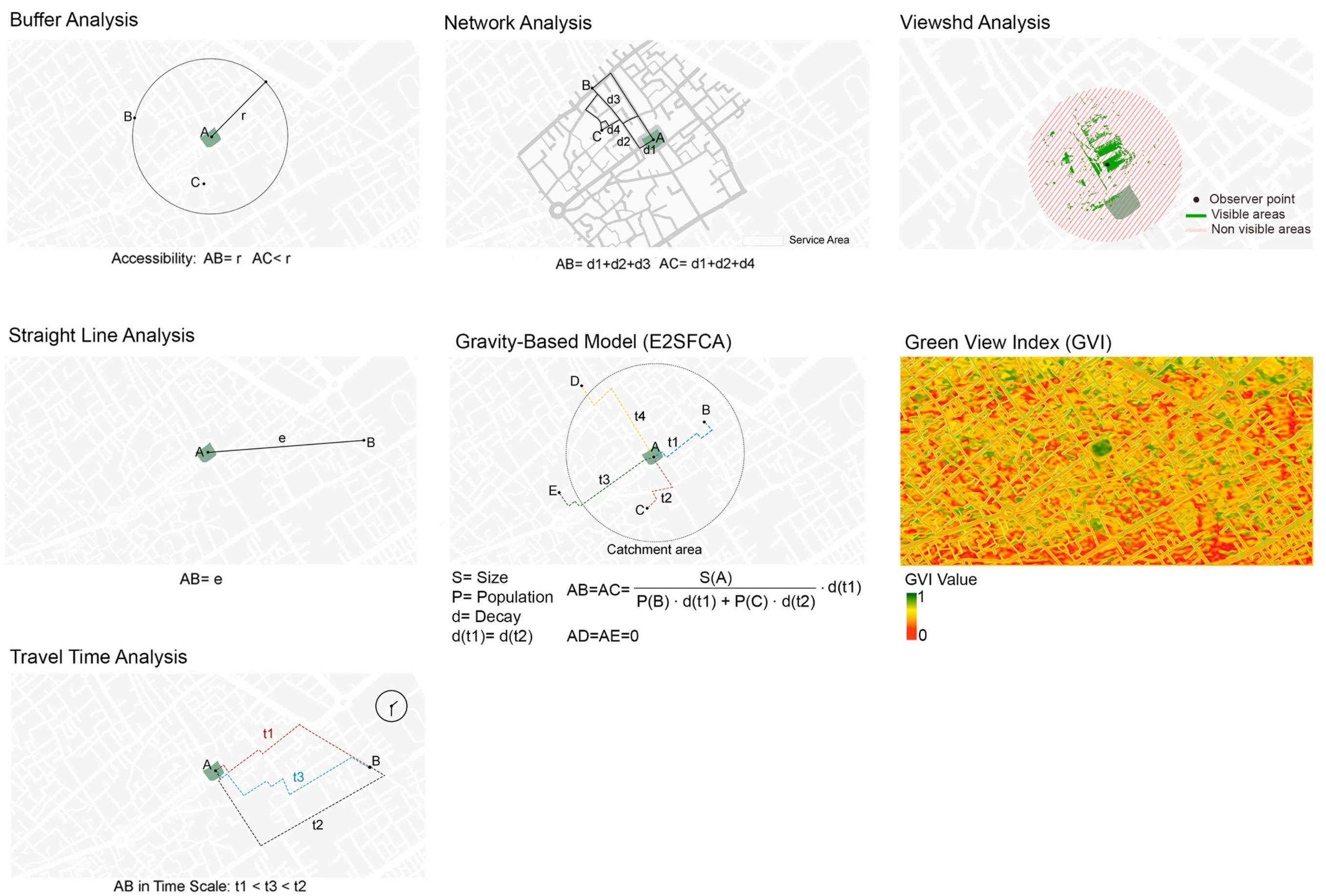

Fig. 4. Visual representations of EDA methods employed in evaluating UGI accessibility in children-focused literature.

3.1.2. *Participant Data Analyses (PDA)*

Table 4 shows the classification of PDA methods used in general literature based on the assessed UGI accessibility dimensions and types.

3.1.2.1. *Validated questionnaires.*

A validated questionnaire is a research instrument that has undergone a rigorous process to ensure it accurately and reliably measures the intended construct. This process includes defining the questionnaire's purpose, structuring questions to capture the targeted concept, and conducting psychometric validation (Juniper.; Rosellini and Brown, 2021). Reliability, assessed through consistency measures, ensures stable results over repeated applications, while validity confirms that the questionnaire accurately reflects the construct it aims to measure. Statistical methods, including correlation analyses, help detect biases and verify measurement accuracy, and expert evaluations further ensure content and construct validity (Juniper.; Rosellini and Brown, 2021).

The utilized validated questionnaires identified in the general literature about UGI accessibility are listed in Table 5.

None of the children-focused literature deployed validated questionnaires to assess UGI accessibility.

Table 4
PDA methods used in general population based on assessed UGI accessibility dimensions and methods.

Accessibility Dimensions	Accessibility Types	PDA Methods
Perceived Accessibility	Perceived Distance Accessibility	Validated Questionnaire Survey Database Self-Developed Questionnaire Self-Developed Interview Observational Method
	Perceived Barrier-Free Accessibility	Validated Questionnaire Self-Developed Questionnaire Self-Developed Interview Survey Database Photovoice
Sensory Accessibility	Auditory Accessibility	Validated Questionnaire Self-Developed Questionnaire Virtual Reality (VR) Immersion
	Thermal Comfort Accessibility	Self-Developed Questionnaire
	Visual Accessibility	Self-Developed Questionnaire
	Olfactory Accessibility	Self-Developed Questionnaire

3.1.2.2. *Survey databases.*

A survey database is a repository of data collected from various sources, including administrative records established by governments and organizations, social media platforms, and other contributors such as independent surveys or third-party tools. (Rehling et al., 2021; Rout and Nesbitt, 2024).

Among the selected children-focused literature, only Rehling et al. (2021) utilized survey databases to examine the association between individual socioeconomic position and walking distances to public green spaces among the youth in German urban settings. The results indicated that children in urban Germany experience unequal access to the health benefits of green space.

3.1.2.3. *Self-developed questionnaires.*

A self-developed questionnaire is designed by an individual or group of researchers for specific research or information-gathering purposes (Anpar Research Ltd, 2020). Unlike validated questionnaires, these are developed without pre-existing

Table 5
The list of validated questionnaires utilized in the selected general literature.

Validated Questionnaire	Description/ Full Name	Number of Articles
RPRS	Revised Perceived Restorativeness Scale (Martínez-Soto et al., 2021)	2
ROS	Restoration Outcome Scale (Kanelli et al., 2024)	1
NoiSeQ-R	Noise sensitivity assessment tool (Kawai et al., 2024)	1
POMS	Profile of Mood States (Martínez-Soto et al., 2021)	1
SAACH	Stress and Arousal Adjectives Checklist (Martínez-Soto et al., 2021)	1
TPB-Based Questionnaire	-Theory of Planned Behavior (Sia et al., 2023) -Framework explaining behavior based on individual beliefs, attitudes, social influences, and perceived control.	2
AUQ	Audiometry Questionnaire (Pearson et al., 2021)	1
PSS	-Perceived Stress Scale (Reid et al., 2022)	2
NR−6	-Nature-relatedness (Pearson et al., 2021)	2
NEWS	Neighborhood Environment Walkability Scale (Schipperijn et al., 2017)	1
MMPI−2	Minnesota Multiphasic Personality Inventory−2 Anxiety Scale (Reid et al., 2022)	1
CES-D−10	The Center for Epidemiological Studies Depression (Reid et al., 2022) Scale	1
SRRS	Self-Rating Restoration Scale (Wang et al., 2022)	2
STAI	State-Trait Anxiety Inventory (Wang et al., 2022)	1
SHS	Scottish Household Survey (Olsen et al., 2022)	1

templates or established guidelines, allowing them to be tailored to the specific needs and objectives of the researchers (Díaz-Oreiro et al., 2019).

Among the children-focused literature, the use of self-developed questionnaires to assess perceived accessibility to UGI is well-documented (Akpinar, 2017, 2020; Bozkurt, 2021; Gustafsson et al., 2021; Ma et al., 2022; Rupprecht and Cui, 2020; Walker et al., 2021) (see Table 6). For example, Gustafsson et al. (2021) investigated parents' perceived barriers to visiting nature with their children and the relationship between their mental well-being and the frequency of these visits by employing a self-developed questionnaire based on an online survey. The study found that barriers such as time and interest reduced the frequency of nature visits.

3.1.2.4. Self-developed interviews. A self-developed interview is another social research method in which the interviewer designs the conversation framework without adhering to a standardized format. This approach allows for open-ended questions and flexible dialogue, enabling the interviewer to explore specific topics in depth based on the participant's responses about personal experiences, opinions, and perspectives (Kallio et al., 2016).

The utilization of self-developed interviews to assess UGI accessibility has been documented in children-focused literature (Freeman et al., 2022; Manandhar et al., 2019; Walker et al., 2021) (see Table 6). For example, Walker et al. (2021) used semi-structured interviews with school staff to identify perceived barriers, such as academic and economic factors, to accessing outdoor nature in school settings.

Although children-focused literature has not employed self-developed questionnaires and interviews to assess sensory accessibility to UGI, the use of these methods has been documented in studies involving adults. Sezavar et al. (2023) utilized a self-developed questionnaire to evaluate how visual accessibility to UGI affects safety perception. Using a visual discrete choice experiment, respondents were presented with two alternatives with different UGI visual accessibility levels by considering differences in forms of paths and asked to select the option that offered them higher perceived safety. Auditory accessibility to UGI has been evaluated by using environmental experience surveys including user interviews and questionnaires (Jaszczak et al., 2021; Martínez-Soto et al., 2021). Olfactory accessibility to UGI has been assessed through the creation of odor maps using a field survey combined with smellwalk (He et al., 2022).

3.1.2.5. Observational methods. Observational methods are used to analyze how individuals interact with UGI in their natural settings, including behavioral mapping, which tracks specific behaviors in a designated area; shadowing, which follows individuals to understand their experiences; and photographic analysis, which documents visual aspects of UGI use. By employing these approaches, researchers gain insights into user behaviors, preferences, and the effectiveness of UGI in promoting accessibility (McCormick, 2017; Park, 2017).

Among the children-focused papers, only Ma et al. (2022) utilized observational methods through GPS tracking and accelerometers to understand children's visitation and utilization patterns of UGI in Suzhou, China, during the COVID-19 pandemic, and highlighted the critical role of green spaces in promoting children's physical activity.

Table 6
Selected children-focused articles utilized PDA and focused areas.

Survey Database	Self-Developed Surveys: Self-Developed Questionnaire	Self-Developed Surveys: Self-Developed Interview	Observational Method
▲ [68]	▲ [62-63], [66-67]	▲ [60-61]	▲ [67]
	■ [9]	■ [9]	
	□ [64-65]		

Notes: residential area: ▲, (pre) school environment: ■, other urban areas: □.

1-3 paper(s) 4-10 papers

3.1.2.6. Photovoice. Photovoice is a participatory research method used in public health and community studies, where participants use photography to document and reflect on their environment. It highlights factors influencing well-being, including environmental barriers within urban infrastructure (Wang and Burris, 1997). Among the general literature, Kandasamy et al. (2024) used photovoice to examine barrier-free accessibility to green spaces in a newcomer-dense neighborhood. Through focus groups, photowalks, and interviews, participants identified both the benefits of green spaces and barriers such as poor maintenance, unsafe traffic conditions, and limited infrastructure.

Among the children-focused literature, no papers utilized the photovoice method to assess UGI accessibility.

3.1.2.7. Virtual reality immersion. Virtual Reality (VR) immersion is a research method that utilizes VR technology to simulate realistic environments, enabling participants to interact with and experience these spaces through various sensory channels. This approach allows for the assessment of the accessibility and restorative benefits of UGI in controlled, interactive settings without the need for physical presence in UGI (Kawai et al., 2024). Among the general literature, only the study of Kawai et al. (2024) utilized VR immersion to assess auditory accessibility to UGI by examining the impact of road traffic noise levels on stress and recovery using immersive 360° VR. The results highlighted the ability of UGI to mitigate noise-induced stress and enhance restoration.

Within the children-focused literature, no papers utilized VR immersion.

Table 6 represents the children-focused articles in this review study that utilized PDA in their methodology, considering the focused study areas for their assessments, including the residential area, school environments, and other land uses.

3.2. Research fields and methodological trends

Selected children-focused literature investigated the association between UGI accessibility assessments and various research fields such as environmental epidemiology including physical health (e.g., weight status, physical activity), mental health (e.g., behavioral patterns, cognitive development), social health (e.g., prosocial behaviors), and UGI inequality studies, (see Supplementary Table S2 for the detailed subhealth domains).

Table 7 presents the classification of research domains in children-focused papers based on the methods used.

A Sankey diagram compiling the data from all selected literature (n = 638) has been presented in Fig. 5. The columns of the Sankey describe the year of publication, the type of UGI, the urban areas examined, the dimensions and the types of accessibility evaluated, the applied methodological group, and the utilized methods. This diagram

Table 7
Research domains of children-focused literature based on the applied methods.

Methodologies and Methods		Environmental Epidemiology			Inequality/ Inequity
		Physical Health	Mental Health	Social Health	
EDA	Buffer Analysis	[6], [7], [11], [17], [19], [21], [23], [25], [27], [29], [31], [34-36], [39], [42], [44], [45], [46-47], [49], [50-51], [54]	[4], [6] [8], [13], [14-16], [18], [20], [22], [24], [32-33], [37], [40-41], [44], [48], [52], [75]	[29], [52]	[1], [2], [8], [10]. [12], [21], [77-78]
	Network Analysis		[5]		[1], [3], [9], [24], [28], [43], [69], [71], [74]
	Straight-Line Analysis				[9], [23], [72]
	Travel-Time Analysis		[26]		[76]
	Gravity-Based Models		[70]		[13], [73]
	Viewshed Analysis				[28], [43]
	GVI		[78]		[78]
PDA	Self-Developed Questionnaire	[62-64], [66]			[9], [65], [67]
	Self-Developed Interview	[61]			[9], [60]
	Survey Database				[68]
	Observational Method	[67]			
Review Paper		[53], [79]	[54-59]	[57]	[80]

Notes:

1-3 paper(s) 4-10 papers 11-20 papers 21-30 papers

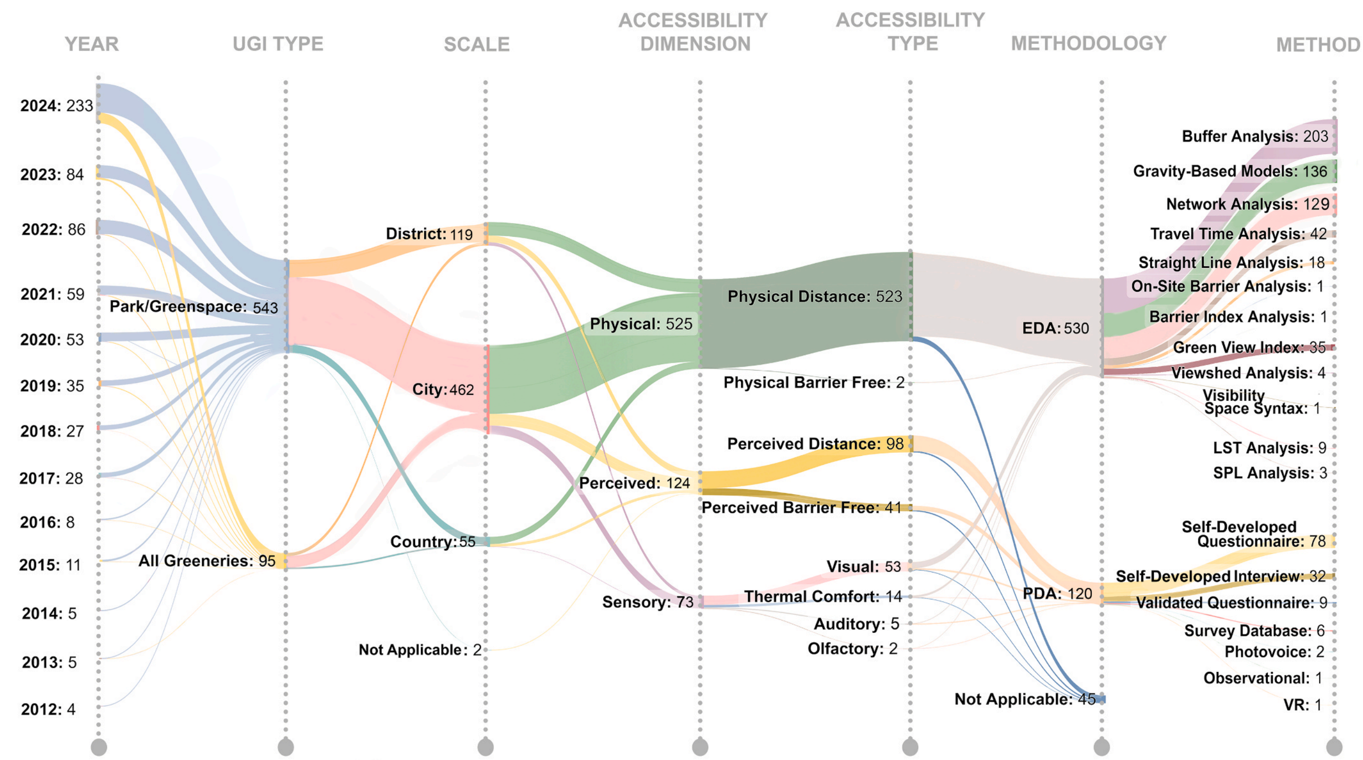

Fig. 5. Sankey diagram of selected articles.

shows the increasing number of publications, with ~ 81 % (515 out of 638) of selected articles published in the last five years. 72 % of the selected literature focused on the city scale for their UGI accessibility assessments, and 19 % focused on the district scale. Only ~ 9 % of the selected articles have targeted national scales.

The data shows that among the 638 reviewed articles, 525 (82 %) are focused on physical accessibility (523 articles on physical distance and 2 articles on phyical barrier-free), 124 articles on perceived accessibility (98 articles on perceived distance and 41 articles on perceived barrier-free), and 73 articles assessed the sensory aspects of accessibility to UGI (53 articles on visual accessibility, 14 articles on thermal comfort accessibility, five articles on auditory perception and two articles on olfactory perception).

Amongst the selected articles, 530 articles assessed the UGI accessibility through EDA, and 120 articles included PDA for their methodologies. Moreover, 45 of the selected articles were review papers. The methods included buffer analysis (203 articles), Gravity-based models (136 articles), network analysis (129 articles), travel time analysis (42

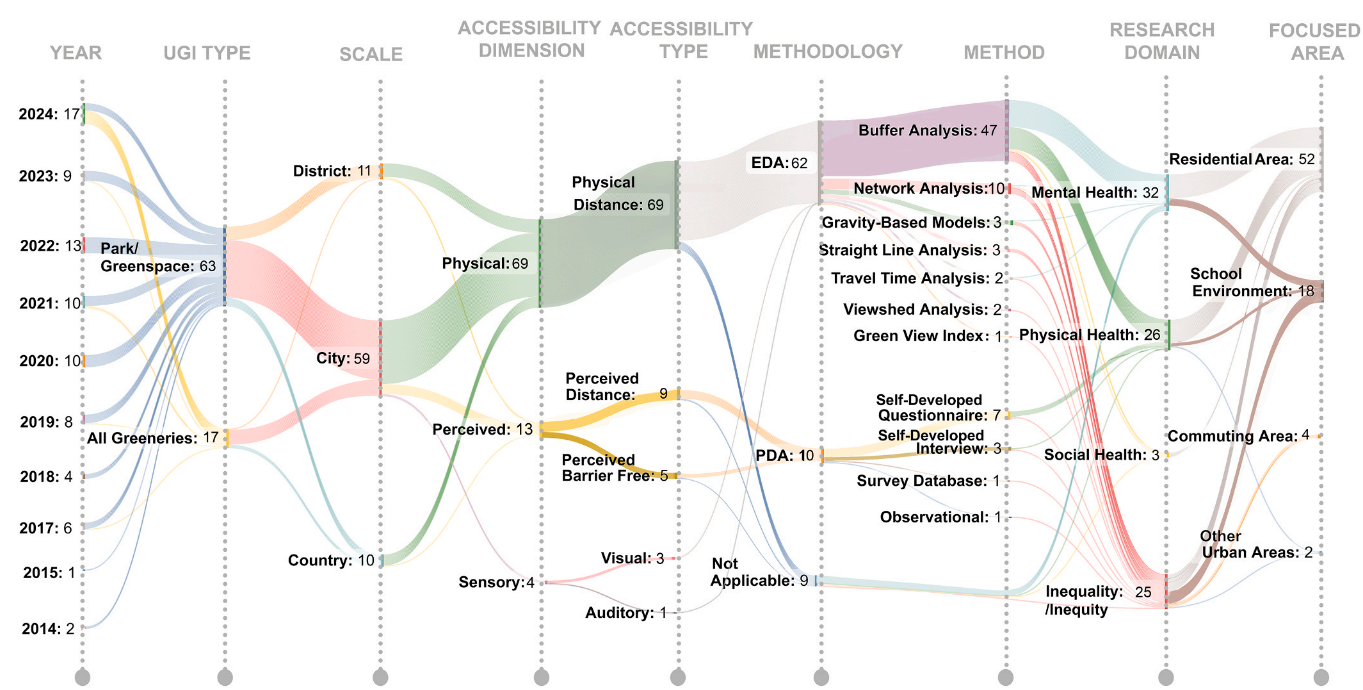

Fig. 6. Sankey diagram of children-focused literature.

articles), GVI (35 articles), straight-line analysis (Euclidean distance analysis) (18 articles), LST analysis (nine articles), viewshed analysis (four articles), SPL analysis (three articles). physical barrier index analysis (one article), on-site physical barrier analysis (one article), and visibility space syntax (one article).

Additionally, 78 articles used self-developed questionnaires, 32 articles utilized self-developed interviews, nine articles applied validated questionnaires, and six articles utilized survey databases. Moreover, two papers utilized photovoice, one paper used VR immersion, and one article assessed the UGI accessibility using the observational method.

Fig. 6 represents a Sankey diagram including data from the selected literature of 80 articles focusing on children's accessibility to UGI.

Among them, ~74 % focused on UGI accessibility assessments on the city scale and ~14 % on the district scale. ~13 % of the chosen articles conducted research at the national level. The data reveals that out of the 80 selected articles, 69 articles (~86 %) concentrated on physical accessibility, specifically on physical distance. Furthermore, 13 articles addressed perceived accessibility, nine focusing on perceived distance and five on perceived barrier-free accessibility to UGI. Only four articles considered the sensory accessibility of children to UGI, including visual accessibility (three articles) and auditory accessibility (one article).

In terms of the deployed methodologies, 62 articles (~78 %) employed EDA, and 10 articles (~13 %) utilized PDA to assess UGI accessibility for children. Moreover, among the children-focused literature, nine articles were review papers.

The literature utilized EDA, including buffer analysis (47 articles), network analysis (10 articles), Euclidean distance analysis (three articles), gravity-based models (three articles), travel time analysis (two articles), viewshed analysis (two articles), and GVI (one article).

Among the selected articles that conducted PDA for UGI accessibility assessments for children, seven studies used self-developed questionnaires (three directed at children (Akpinar, 2017; Bozkurt, 2021; Ma et al., 2022), three directed at parents (Akpinar, 2020; Gustafsson et al., 2021; Rupprecht and Cui, 2020), and one directed at school staff (Walker et al., 2021)), three studies performed self-developed interview (one with children (Freeman et al., 2022), one with mothers and caregivers (Manandhar et al., 2019), and one with school staff. (Walker et al., 2021)), one study used an observational method, and one study used database surveys. None of them employed validated questionnaires.

In children-focused studies, 55 papers focused on environmental epidemiology (32 papers addressed mental health, 26 papers focused on physical health, and 3 papers evaluated social health), and 25 papers examined urban inequalities/inequities.

Additionally, 52 articles considered residential areas in their methods, 18 papers conducted their methods by considering schools or preschools, four papers focused on commuting routes, and two papers focused on other urban areas in their methods.

4. Discussion

This section discusses the identified methodologies to assess children's accessibility to UGI, presents recommendations for future research, and addresses limitations inherent in this study.

4.1. Methodologies to assess children's accessibility to UGI

The assessment of UGI accessibility for children has progressed from a primary focus on physical accessibility, often analyzed through buffer methods, to increasingly incorporating dimensions such as perceived and sensory accessibility, reflecting a more holistic approach to understanding equitable accessibility to UGI.

Previous children-focused literature has primarily focused on assessing physical distance to evaluate the relationship between health outcomes and accessibility to UGI. However, the limitations associated with predefined mobility parameters in these analyses can be restrictive when applied to children. Previous children-focused studies have often overlooked age-specific differences by applying uniform distance thresholds based on adult mobility patterns. Children's mobility and autonomy vary significantly by age: young children under six years old typically have limited walking capacity, require adult supervision, and have more constrained activity ranges, whereas older children and adolescents enjoy greater independence and can navigate more complex urban environments (Gill, 2015). Applying standard distance thresholds without accounting for these age-based mobility patterns risks overestimating accessibility for younger age groups (Luo et al., 2024).

Buffer analysis remains the most utilized method (~59 % of the papers) to assess UGI physical accessibility for children. Previous studies focused on children have suggested buffer distances ranging from 50 m to 5000 m. To define the service area in network analysis, previous studies focused on children, employed varying distance thresholds, ranging from 300 m to 1600 m. This highlights a lack of consensus on defining a specific distance range for analyzing children's accessibility to UGI, and hence, guidelines on age and context-based accessibility distance criteria are yet to be agreed upon. In this context, guidelines such as those proposed by UNICEF (2018) which advocates for UGI accessibility within 200–400 m (~ 5 min walking distance) for children aged 6–12—considering their inability to drive and heightened vulnerability in car-dominated environments—could serve as a foundation for establishing standardized guidelines on physical distance for children's accessibility to UGI.

Limitations associated with physical distance analysis should also be considered, particularly as Semenzato et al. (2023) highlight that both buffer and straight-line analyses tend to overestimate the population served. This overestimation is especially relevant for children's accessibility, as children's commuting patterns are highly dynamic and context-specific, often differing from the straightforward routes assumed by these methods. Similar limitations apply for network analysis deployed in 12.5 % of children-focused literature, given that prioritizing established routes in accessibility assessments may overlook unconventional paths, such as shortcuts through parks, alleys, or informal pathways, which are often preferred by children due to their directness and appeal. This omission can result in a misestimation of accessibility, particularly for individuals who rely on alternative routes in urban environments. Additionally, children move more slowly and have different travel behaviors compared to both adults and their peers, impacting the accuracy of travel time analysis methods.

Previous studies repeatedly mentioned that gravity-based models stand out as more comprehensive methods to assess physical distance accessibility compared to other physical distance analyses. In the selected literature, only one children-focused study used gravity-based models for UGI accessibility assessments. These models offer a more accurate representation of children's travel patterns by accounting for supply, population, and alternative paths, unlike buffer or network-based approaches. However, models based on predefined catchment areas may inaccurately represent accessibility, particularly for children, whose activity locations often vary and are less predictable. To enhance the gravity-based models for assessing children's accessibility to UGI, the decay function could be refined to reflect the limited mobility of children, utilizing steeper decay rates to represent their shorter travel ranges. Furthermore, incorporating child-friendly urban features, such as safe pedestrian pathways, school courtyards, seating areas, and playgrounds that enhance the attractiveness of UGI for children, into the weighting of accessibility scores would improve the method's applicability and precision

Additionally, incorporating penalty zones (areas designated with a higher cost or reduced accessibility due to physical barriers) would better capture the obstacles children face when accessing UGI (Marzi and Reimers, 2018). Finally, considering temporal variations, including different seasons and school hours in children's accessibility, would further improve the model's ability to accurately represent the unique constraints on children's access to green spaces (Wang et al., 2015b).

Children's ability to navigate physical and environmental barriers varies by age, with younger children facing greater challenges due to limited hazard recognition and mobility skills. Urban features such as traffic, major roads, uneven terrain, and infrastructure discontinuities can significantly hinder their independent accessibility to green spaces, particularly for those requiring supervision or using mobility devices. These limitations affect babies and toddlers who are often carried, young children who walk, and those using scooters, bicycles, or similar devices. As indicated in the selected general literature, studies examining the general population have emphasized the importance of assessing barrier-free accessibility to UGI (Barber et al., 2021; Lepoglavec et al., 2023). However, there is a lack of children-focused literature that employs age-based EDA to detect physical barriers by considering children's unique psychophysiological characteristics. In this context, the application of 3D geospatial analyses (e.g., 3D modeling and point cloud analysis approaches) could provide detailed geometric analyses of children's movement areas and the identification of potential physical barriers (Wang et al., 2024).

Research indicates that children spend considerable time in their daily commuting routes to school and on school grounds, highlighting the importance of integrating UGI into those environments (García-Serrano et al., 2017; Teeuwen et al., 2023). Beyond neighborhood disparities, the absence of UGI in school environments limits children's access to green spaces, which are vital for physical activity, social interaction, and overall well-being (Baró et al., 2021; Gallez et al., 2024). This shows the impact of considering school settings and commuting routes in UGI accessibility for children. However, among the children-focused literature, only 22.5 % considered school environments, and 5 % accounted for commuting routes, highlighting a need for further research on school environments.

Among the general literature that applied PDA, the utilization of validated questionnaires to assess perceived accessibility to UGI for adults is well documented. However, no validated questionnaires were used in the literature, specifically focusing on children to assess their UGI accessibility perceptions. The validated questionnaires listed in Table 5 were either developed for adults or adapted from general psychological constructs, not specific to UGI exposure and accessibility. This raises questions related to the variability in the data collection from children and analysis related to self-developed surveys, potentially affecting the reliability and consistency of the findings (Scribbr, 2023). Additionally, these questionnaires often fail to account for developmental differences in language, cognitive processing, and self-reflective abilities in children. In particular, adult-oriented questionnaires are frequently not linguistically appropriate for younger populations, whose vocabulary and comprehension abilities vary significantly by age. Moreover, children's limited introspective capacity can hinder their ability to respond accurately to conventional self-report formats (Bell, 2007; Parker, 1984). As such, there is a pressing need for the development and validation of child-specific tools, using age-appropriate formats such as visual prompts, simplified language, drawings, or comics for non-readers, possibly combined with proxy reports from caregivers or educators.

Although no validated questionnaire currently exists that directly measures children's perceived accessibility to UGI, several existing questionnaires can be adapted for use by parents or school staff (Rosenberg et al., 2009). For instance, the NEWS questionnaire evaluates perceptions of neighborhood walkability and accessibility, while the NR-6 questionnaire reflects attitudes toward and connections with green spaces. Additionally, child-adapted questionnaires, such as the State-Trait Anxiety Inventory for Children (STAI-C) (Nilsson et al., 2012) and the Perceived Stress Scale for Children (PSS-C) (White, 2014), can be used to directly assess their emotional perceptions before, during, and after greenspace visits.

From the children-focused literature, ~11 % (n = 9) used self-developed questionnaires and interviews. Among them, four papers were directed to children, four papers to parents, and one paper to school staff. Children-directed questionnaires and interviews provide direct feedback about children's experiences, making it easier for researchers to gather insights that are relevant to their needs. They can be tailored to be age-appropriate, ensuring that questions are understandable and engaging, which enhances participation. However, engaging children directly in questionnaires and interviews presents several challenges, given that, due to their developmental stages, they may face limitations in verbal expression, cognitive abilities, and articulating their preferences clearly. Additionally, variability in children's cognitive development can result in different levels of understanding when asking questions, while their potential lack of contextual awareness may lead to less informative responses (Bell, 2007; Parker, 1984). Furthermore, researchers must secure parental consent and ensure that children's participation is voluntary and free from coercion.

Parent or guardian-directed questionnaires and interviews provide valuable insights into children's experiences, as parents possess a unique understanding of their children's interactions with UGI. This approach captures the family's orientation toward outdoor activities and environmental engagement, thereby enhancing the comprehension of factors influencing children's experiences. Additionally, parental input is instrumental in identifying barriers and enablers to children's use of green spaces. However, the use of parent or caregiver-directed questionnaires can also introduce potential biases. Parents may project their own attitudes and preferences onto their children's experiences or may not fully understand or observe all aspects of their children's interactions with green spaces, especially when children engage with these areas independently or with peers. As Partington (2001) highlight that relying on others' perceptions may lead to inaccuracies, as these accounts may not reflect children's true experiences and preferences.

Teachers and school staff can offer valuable insights, especially concerning the school-related UGI environments and the patterns used by children, as they have firsthand experience observing how children interact with these spaces during structured activities or leisure time. They often play a central role in organizing outdoor activities for children within school curricula. Additionally, they have valuable insights into the economic and institutional barriers children face in accessing UGI in school environments during school hours. However, this approach may also introduce biases similar to those of parents or guardians. School staff typically observe children in structured settings, which may not represent the full range of children's interactions with green spaces, particularly during unstructured, independent play outside school hours.

On the other hand, the use of observational methods to assess children's accessibility to UGI remains a contested area due to both ethical and methodological concerns. Ethical considerations, including privacy, image rights, and informed consent, are particularly significant when observing or recording children in public spaces. Researchers must adhere to strict legal and ethical standards to protect children's privacy. Furthermore, observational techniques like behavioral mapping are susceptible to observer bias and have limited scalability, while requiring significant resources, including time, personnel, and technology, which may hinder their practical application.

Sensory accessibility varies significantly across childhood stages, as younger children rely more on sensory inputs (such as sound, texture, color, and smell) to interact with their environment. Exploring the assessment of UGI sensory accessibility could offer valuable insights into children's unique experiences with urban nature. However, research on sensory accessibility to UGI for children remains notably limited, despite the broader focus on visual, thermal comfort, auditory, and olfactory dimensions in studies examining the general population. Although three studies have explored visual accessibility and one has investigated auditory accessibility, there is a need for greater focus on these sensory dimensions, as they have not been adequately prioritized in the context of children's UGI accessibility.

Regardless of whether the focus of the papers was on the role of green accessibility in health dimensions, among other aspects, the majority of studies have predominantly relied on buffer analysis. This reveals that similar accessibility assessment methods are applied across distinct environmental epidemiology research fields. Within the selected literature, environmental epidemiology studies have received limited attention in incorporating observational methods or exploring sensory aspects—such as visual accessibility—in their evaluations of UGI accessibility. This is despite the growing recognition of the influence of sensory experiences, such as views or sounds, on mental health conditions (Dzhambov et al., 2018; Jaszczak et al., 2021) or the motivation to engage in physical activities (Ma et al., 2022; Molina-García et al., 2022). Conversely, studies focused on UGI inequalities have employed a more diverse range of methods. Therefore, further research is needed to advance the assessment of UGI accessibility and its relationship with health outcomes, moving beyond the relatively simplistic buffer analysis approach.

In conclusion, a holistic evaluation of UGI accessibility necessitates assessing physical, perceived accessibility, and sensory accessibility dimensions. The assessment of these dimensions of UGI accessibility requires the application of both PDA and EDA methodologies (Li et al., 2023; Park, 2017).This is particularly relevant for children-focused research, where the study of perceived accessibility, as well as sensory/ environmental accessibility, remains significantly lacking. Therefore, it is necessary to develop multidimensional assessments of UGI accessibility targeting children.

4.2. Recommendations for future research

The following recommendations are proposed for future research:

- Future studies may consider adopting refined methods of physical distance analyses, such as gravity-based models, which integrate decay functions to account for children's limited mobility and specific thresholds, incorporate penalty zones for physical barriers like major roads, the attractiveness of UGI for children, and integrate child-specific temporal variations to provide a more accurate assessment of accessibility to UGI.
- Given the potential of 3D geospatial analyses to provide detailed insights into the physical barriers from a child's eye-level perspective, the development of 3D EDA assessments should be considered to address the existing gap in evaluating physical barrier-free accessibility for children.
- Future research on UGI accessibility for children could benefit from considering established policy guidelines, such as the 3–30–300 rule (Konijnendijk, 2021) increasingly referenced in recent literature, which emphasizes the visibility of three trees from home, 30 % tree canopy cover in neighborhoods, and physical accessibility to green space within 300 m. While originally not designed specifically for children, these guidelines could be explored and adjusted to address their unique needs.
- Considering the significant amount of time children spend within school environments and commuting routes, future studies should prioritize context-specific assessments that encompass both school environments and daily commuting routes.
- Adapted versions of validated questionnaires should be explored to assess children's perceived and sensory accessibility to UGI, ensuring they are appropriate for age-based developmental considerations, offering a structured method for collecting reliable data and identifying barriers, enablers, and environmental features that may not be captured through EDA.
- Incorporating sensors and cameras that anonymously capture data on children's movement and physiological responses could be a valuable approach to understanding behavior in UGI. To ensure ethical implementation, researchers should carefully consider privacy concerns and adhere to stringent ethical standards while utilizing such technology.
- Future research could benefit from using Photovoice and VR simulations to assess barrier-free accessibility in UGI for children. These methods can help overcome comprehension challenges in written questionnaires by allowing children to provide more immediate and direct feedback. Photovoice can capture lived experiences, while VR simulations offer immersive, child-centered assessments to identify barriers and test design improvements.
- Further research is required to explore other types of sensory accessibility for children, such as auditory, thermal comfort, and olfactory, which are not documented in the previous children-focused literature, as well as further studies on visual accessibility.
- Further research is required to explore the integration of EDA and PDA methodologies in assessing children's accessibility to UGI.

Fig. 7 presents a conceptual framework for children-focused research that integrates the three types of UGI accessibility (physical, perceived, and sensory) discussed in general literature. It outlines the applicable methods for assessing UGI accessibility for children, emphasizing the use of both EDA and PDA. It is noteworthy that the selected methods for future children-focused research should be context-specific, taking into consideration the children's spatial environment, as well as the limitations, possibilities, and available resources.

4.3. Limitations of the study

This research has several limitations that need to be acknowledged. First, the literature review only included papers published up until the end of 2024. Additionally, the search strategy excluded the term "exposure" from access-related keywords to avoid irrelevant papers, which may have led to the unintentional omission of some pertinent studies. Furthermore, the study was restricted to articles published in English, potentially excluding pertinent research available in other languages. Although the search spanned multiple databases (Web of Science, Scopus, PubMed, and Google Scholar), reliance on these sources alone may have led to the exclusion of relevant studies indexed in other databases. A limitation of the existing literature is its dominant focus on specific regions, leaving significant areas of the world insufficiently explored. This may influence the scope and applicability of the findings. While this review introduces a tripartite framework (physical, perceived, and sensory accessibility), we acknowledge that these dimensions are conceptually interrelated. For instance, visual accessibility, though classified as sensory, is often assessed using spatial methods like GVI or viewshed analysis, typically linked to physical accessibility. Such overlaps may explain why sensory accessibility is seldom treated independently. Rather than a flaw, this reflects the multidimensional nature of accessibility and highlights the need for greater theoretical clarity and integrative methodological approaches in future research. Collectively, these limitations suggest that while the study offers a thorough review, it may not capture the full scope of existing research on UGI accessibility assessments for children.

5. Conclusion

This review proposes a multidimensional framework for assessing accessibility to urban green infrastructure, incorporating physical, perceived, and sensory dimensions, with a particular attention to its application for children. Enhancing the accuracy and equity of such assessments requires context-specific methods that consider land uses where children are commonly present (such as school environments and commuting areas), alongside age-specific measures reflecting the distinct needs and behaviors of infants, preschoolers, and primary and secondary school children. Key gaps include the lack of validated questionnaires for measuring children's perceived accessibility using age-appropriate formats, and insufficient attention to sensory experiences (e.g., visual, auditory, thermal, and olfactory). Additionally, the reliance on two-dimensional data limits the ability to identify physical

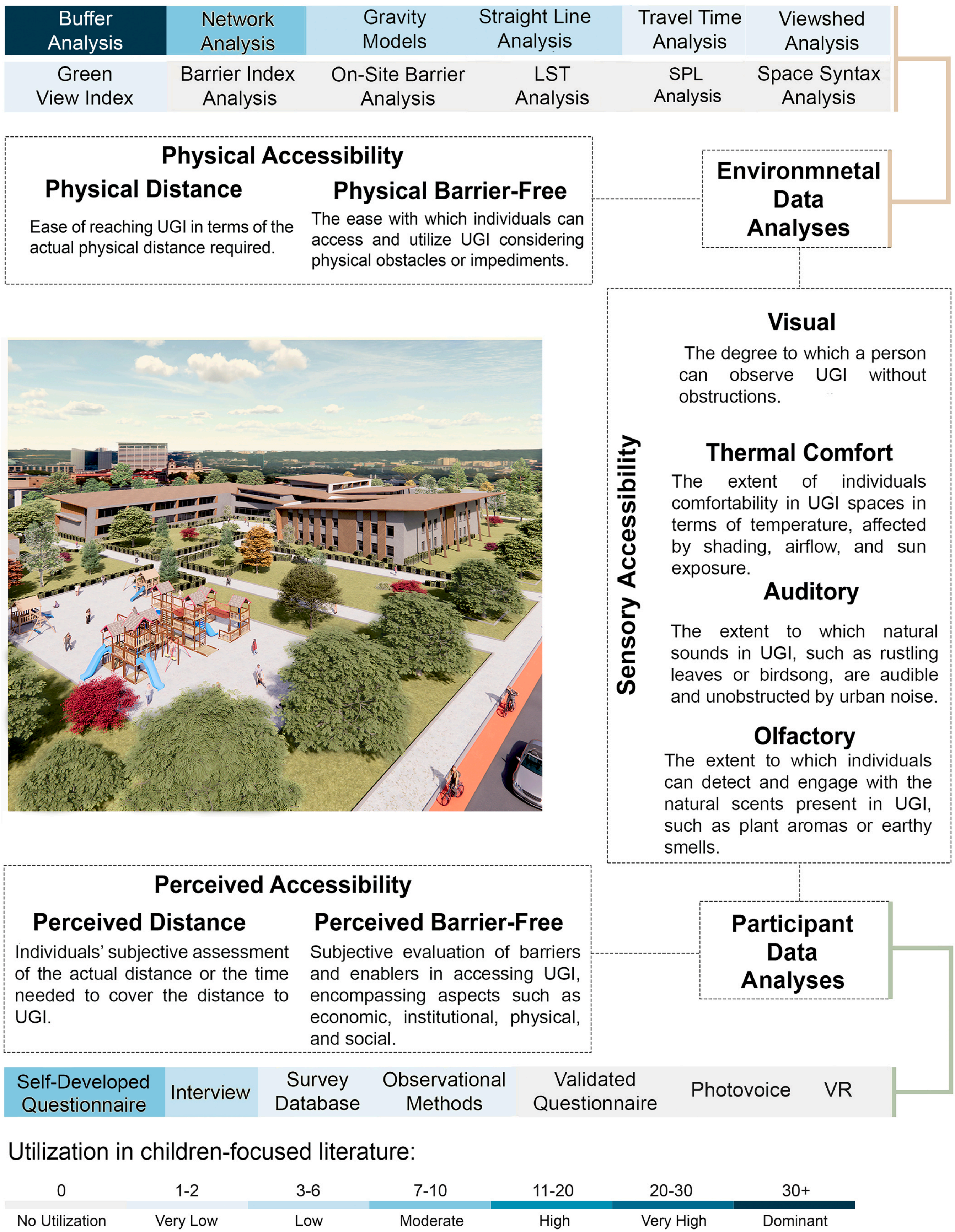

Fig. 7. Conceptual framework of UGI accessibility assessment for children.

barriers affecting children's mobility. In contrast, three-dimensional geospatial analyses improve the representation of such barriers from a child's perspective. To capture the complexity of children's interactions with green infrastructure, combining environmental data analyses (e.g., geospatial methods) with participant data analyses (e.g., questionnaires and interviews) offers a more comprehensive perspective. Altogether, these insights lay the foundation for inclusive, equitable, and child-friendly approaches to planning and assessing urban green infrastructure, ultimately fostering environments that support children's development and well-being.

Ethical compliance

- The study adheres to the ethical guidelines outlined in Elsevier's *Publishing Ethics Policy*.
- If applicable, necessary ethical approvals and informed consent were obtained.

CRediT authorship contribution statement

Ahmadreza Irajpour: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Francesc Baró:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sareh Moosavi:** Writing – review & editing. **Emilie Lacroix:** Writing – review & editing. **Maider Llaguno-Munitxa:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Martin Edwards:** Writing – review & editing.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the authors used ChatGP-4o to check the grammar, punctuation, and clarity. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2025.129040.

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