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Urban green infrastructure: bridging biodiversity conservation and sustainable urban development through adaptive management approach

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Urban green infrastructure (UGI) is pivotal in reconciling biodiversity conservation with sustainable urban development through adaptive management approaches. This paper introduces a comprehensive conceptual framework integrating ecological principles, urban planning strategies, and adaptive management methodologies to nurture resilient and biodiverse urban landscapes. The essence of UGI lies in its capacity to bolster ecological connectivity, restore ecosystem functions, and provide habitats for diverse flora and fauna within urban settings. Fundamental principles governing UGI design underscore its multifunctionality, connectivity, diversity, and accessibility, emphasizing the importance of adaptive management marked by its iterative and participatory nature. Despite challenges posed by urbanization, such as habitat loss, pollution, and climate change, UGI interventions offer promising avenues for enhancing habitat quality, connectivity, and ecosystem resilience. Global case studies demonstrate the effectiveness of UGI in biodiversity conservation, leveraging initiatives like green roofs, urban forests, and community gardens. UGI significantly contributes to sustainable urban development by offering diverse ecosystem services across various domains. Adaptive management is critical for effective UGI planning and implementation, ensuring flexibility amidst evolving environmental conditions. However, UGI encounters hurdles, including funding constraints, institutional fragmentation, and equity issues. Addressing these challenges necessitates innovative financing mechanisms, community involvement, and policy innovations. UGI presents a transformative pathway towards fostering resilient, biodiverse, and sustainable urban landscapes, imperative for cities to thrive in the 21st century.

KEYWORDS

urban green infrastructure, biodiversity conservation, sustainable urban development, adaptive management, ecosystem services

1 Introduction

Urbanization is a defining trend of the 21st century, with over half of the global population residing in urban areas. While cities offer economic opportunities and cultural vibrancy, rapid urban expansion often leads to habitat loss, fragmentation, and degradation, posing threats to biodiversity and ecosystem health (Liu et al., 2022; Jena and Utete, 2024). Additionally, urbanization exacerbates environmental challenges such as air and water pollution, heat island effects, and the loss of green spaces, impacting the well-being of urban residents (Grimm et al., 2008; Kassouri, 2021). Addressing these interconnected challenges requires innovative approaches integrating biodiversity conservation with sustainable urban development.

Urban green infrastructure (UGI) has emerged as a multifunctional strategy to reconcile urbanization with biodiversity conservation and ecosystem services provision (Chen and Hu, 2015). UGI comprises a network of green spaces, including parks, green roofs, urban forests, wetlands, and green corridors, integrated within the urban fabric to support ecological processes, enhance biodiversity, and provide multiple benefits to urban communities. By mimicking natural ecosystems and enhancing green spaces in cities, UGI offers opportunities to mitigate urban environmental degradation, improve urban resilience, and promote human well-being.

2 Conceptual framework

UGI's conceptual framework integrates ecological principles, urban planning strategies, and adaptive management approaches to foster resilient and biodiverse urban landscapes (Liu and Russo, 2021). Central to UGI is the goal of bolstering ecological connectivity, reinstating ecosystem functions, and furnishing habitats for diverse flora and fauna within urban settings. Achieving this demands a comprehensive strategy for the spatial layout, functional interconnections, and ecological integrity of green spaces spanning various scales, from individual sites to citywide networks (Chen and Hu, 2015; Korkou et al., 2023). The fundamental principles underpinning the design and execution of UGI encompass the following Figure 1.

Multifunctionality. To maximize its societal and ecological benefits, UGI should serve multiple purposes, such as biodiversity conservation, climate regulation, stormwater management, recreation, and cultural enrichment (Shade et al., 2020; Kassouri, 2021; Awad and Jung, 2022; Jena and Utete, 2024). By integrating these functions, UGI can address various urban challenges simultaneously. For example, green roofs and walls can mitigate urban heat islands, manage stormwater, and provide habitats for urban wildlife. Parks and urban forests can function as recreational spaces, support mental health, and enhance community well-being while serving as carbon sinks and biodiversity hotspots.

Connectivity. The green spaces within UGI should be interconnected via green corridors, wildlife corridors, and ecological networks to facilitate species movement, maintain genetic diversity, and bolster ecosystem resilience (Fu et al., 2022; Zhao et al., 2024a; Misbari et al., 2024). Connectivity ensures the linkage of fragmented habitats, enabling species to migrate, locate food, and reproduce, all essential for sustaining healthy urban ecosystems. For example, greenways and riparian buffers can connect larger green spaces, forming a network supporting wildlife movement and human recreation.

Diversity. UGI should incorporate diverse habitats, vegetation types, and landscape features to support various species and ecological processes, including pollination, seed dispersal, and nutrient cycling. Diversity within UGI enhances ecosystem

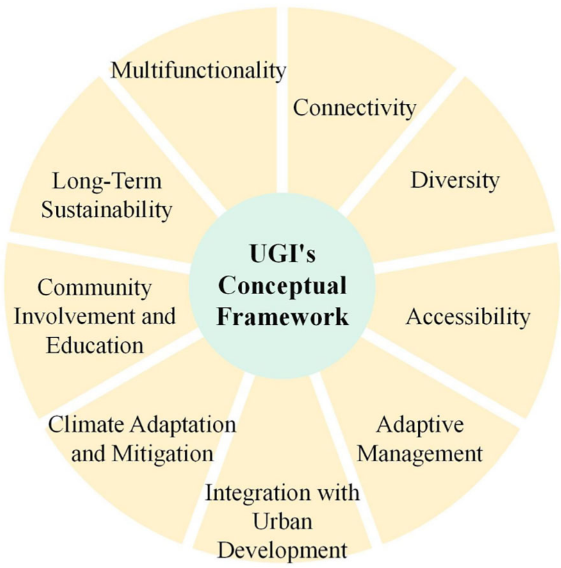

FIGURE 1
Conceptual framework of UGI.

resilience, rendering it more adept at enduring environmental changes and disturbances (Calderón-Contreras and Quiroz-Rosas, 2017; Huchler et al., 2023). Urban planners should strive to integrate wetlands, meadows, woodlands, and grasslands into the urban landscape to craft a mosaic of habitats that address the needs of various species. Planting native species and establishing diverse microhabitats can augment ecological richness and stability (Suárez et al., 2024).

Accessibility. UGI should be accessible and inclusive, offering equitable access to green spaces, recreational opportunities, and environmental education for diverse urban populations, including marginalized communities (Spulerová et al., 2022). Accessibility ensures that all city residents can avail themselves of green spaces' ecosystem services and health benefits. Design considerations should encompass safe pathways, disability access, and amenities like benches and information boards (Korkou et al., 2023; Ruiz-Apilanez et al., 2023). Community gardens and urban farms can foster food security and social cohesion, while educational programs can raise awareness about the significance of urban biodiversity and conservation (Szczepanska et al., 2021).

Adaptive Management. UGI planning and management should be adaptive, iterative, and participatory, integrating monitoring, feedback mechanisms, and stakeholder engagement to address uncertainties, draw lessons from experience, and refine management strategies over time. Adaptive management offers flexibility and responsiveness to evolving conditions and new insights (Hsu et al., 2020; Zeng et al., 2024; Zhang et al., 2024). For instance, routine biodiversity and ecosystem services monitoring can guide management practices and policy formulation. Engaging local communities, scientists, policymakers, and other stakeholders in the planning and management ensures that UGI initiatives are rooted in local knowledge and needs, cultivating a sense of ownership and stewardship.

Integration with Urban Development. UGI must integrate with broader urban development plans to preserve and enhance green spaces amidst urban growth and evolution. This necessitates coordination across various governmental sectors and levels and integrating green infrastructure principles into zoning laws, land-use planning, and building codes (Girma et al., 2019; Zhang et al., 2024). Green infrastructure should not be an afterthought but a central element of urban design, influencing everything from transportation networks to housing developments (Rezvani et al., 2023).

Climate Adaptation and Mitigation. UGI plays a pivotal role in climate adaptation and mitigation by reducing greenhouse gas emissions, managing urban heat islands, and enhancing urban resilience to extreme weather events (Grimm et al., 2008; Sharifi, 2021). Green spaces serve as carbon sinks, absorbing CO2 from the atmosphere, and their cooling properties can diminish the need for air conditioning, thereby reducing energy demand. Integrating green infrastructure into urban planning can aid cities in adapting to climate change impacts, such as heightened rainfall and flooding, by enhancing water infiltration and mitigating surface runoff (Kassouri, 2021; An et al., 2023).

Community Involvement and Education. Involving communities in the development and upkeep of UGI cultivates a sense of ownership and responsibility toward local green spaces. Educational programs can heighten awareness about the benefits of UGI and promote sustainable practices among urban residents. Citizen science initiatives involving residents in data collection and monitoring can advance scientific comprehension of urban ecosystems and bolster more effective management practices (Russo and Cirella, 2020; Spulerová et al., 2022).

Long-Term Sustainability. UGI's long-term sustainability relies on secure funding, effective governance, and ongoing evaluation. Investing in UGI should be prioritized in urban infrastructure development, with allocated budgets and funding mechanisms to ensure its maintenance and expansion. Transparent governance structures that engage multiple stakeholders can ensure the efficient and equitable management of UGI initiatives (Fors et al., 2022; Isendahl et al., 2024).

3 Biodiversity conservation in urban environments

3.1 Deductive analysis

Urban environments host a surprising diversity of species, encompassing plants, animals, fungi, and microorganisms, all of which have adapted to thrive amidst human-altered landscapes. These organisms find niches in the varied habitats that cities provide, from the cracks in sidewalks to the canopies of urban forests (Felappi et al., 2020; Wang et al., 2022). However, urbanization presents significant challenges to biodiversity, including habitat loss, fragmentation, pollution, the spread of invasive species, and the impacts of climate change (Grimm et al., 2008; Wang et al., 2022). Despite these challenges, cities also present unique opportunities for biodiversity conservation through UGI interventions that enhance habitat quality, connectivity, and ecosystem resilience (Velázquez et al., 2023).

The foremost challenge, habitat loss, is particularly acute in urban areas where buildings, roads, and other infrastructure supplant natural landscapes (Grabowski et al., 2023; MacKinnon et al., 2023). This transformation often entails the destruction of native vegetation and the displacement of wildlife. Habitat fragmentation exacerbates this issue by isolating patches of green space, impeding species migration, food procurement, and mating. Pollution, encompassing air, water, and soil contamination, detrimentally affects urban biodiversity by degrading habitats and compromising the health of flora and fauna. Invasive species introduced through human activity can outcompete native counterparts, leading to declines in local biodiversity. Climate change introduces additional stressors by altering temperature and precipitation patterns, affecting urban species' survival and distribution.

Despite these significant challenges, cities can emerge as biodiversity hotspots through innovative UGI strategies (Wang et al., 2022). Green roofs and walls, for instance, provide critical habitats for birds, insects, and plants in densely built urban areas. These structures offer wildlife refuge and contribute to temperature regulation and air quality improvement. Urban forests, comprising parks, street trees, and larger forested areas within cities, play a crucial role in enhancing biodiversity. They offer habitat and food resources for various species and create corridors facilitating movement and genetic exchange among wildlife populations. Riparian corridors along riverbanks and waterways are vital for biodiversity maintenance, supporting a range of aquatic and terrestrial species while filtering pollutants from urban runoff.

Community gardens, pocket parks, and urban farms are examples of UGI promoting biodiversity while providing social and ecological benefits (Szczepanska et al., 2021). These green spaces support local food production, potentially mitigating the urban heat island effect and offering habitats for pollinators such as bees and butterflies. Moreover, they serve as hubs for cultural exchange and community engagement, fostering social cohesion and ecological stewardship among urban residents. Community involvement in these projects can increase awareness and appreciation of biodiversity and more sustainable urban living practices.

The multifunctionality of UGI is crucial for effective biodiversity conservation in urban environments. By harnessing positive interactions among its functions, UGI enhances ecosystem services and adds value for urban residents. Integrating various functions within UGI maximizes its effectiveness, including providing critical habitats for species, promoting urban biodiversity, mitigating urban heat island effects, sequestering carbon, aiding stormwater management, reducing flooding risks, and offering recreational opportunities that enhance human well-being. These positive interactions create synergistic effects, known as the multiplier effect. For example, vegetated areas provide habitats and cool the environment, benefiting biodiversity and urban dwellers. Wetlands and green roofs manage stormwater while offering aesthetic and recreational benefits (Velázquez et al., 2019). High biodiversity areas in cities enhance mental health and provide educational opportunities. The multifunctionality of UGI enhances ecosystem services, making urban ecosystems more resilient. Integrated UGI solutions are often more cost-effective than single-function interventions. Multifunctional UGI can increase property values, reduce healthcare costs, and foster social cohesion by expanding green spaces and engaging communities.

UGI plays a pivotal role in biodiversity conservation within urban environments, offering ecological, social, and economic benefits. However, its implementation and maintenance entail significant costs. Establishing UGI requires substantial initial investment, particularly in acquiring or leasing land, especially in densely populated urban areas. Professional services from landscape architects and urban planners also contribute to upfront costs. Constructing green infrastructure, such as parks, green roofs, and urban forests, involves significant materials, labor, and equipment expenditures. Ongoing costs are critical for ensuring UGI's sustainability and functionality. Regular maintenance, including watering, pruning, and pest control, is necessary to maintain the health and aesthetics of green spaces. Infrastructure elements may require periodic replacement or repair due to wear and tear, vandalism, or extreme weather events. Effective UGI management involves administrative expenses such as staff salaries, monitoring, and community engagement activities. Despite these expenses, UGI offers substantial economic benefits. Direct economic benefits include increased property values near well-maintained green spaces, benefiting homeowners and boosting municipal tax revenues. Appealing green spaces also attract tourists and visitors, stimulating the local economy through increased spending on recreational activities, food, and accommodation. Indirect economic benefits are significant as well. UGI provides essential ecosystem services such as air and water purification, climate regulation, and flood mitigation, all with substantial economic value. Access to green spaces promotes physical and mental health, potentially reducing healthcare costs and enhancing productivity. UGI supports biodiversity by providing habitats for various species, enhancing ecological resilience, and contributing to the long-term sustainability of urban environments. Various funding mechanisms can support UGI implementation and maintenance. Governments can offer financial assistance through grants and subsidies to promote UGI development. Public-private partnerships mobilize additional resources and expertise for UGI projects. Green bonds can attract investment from environmentally conscious investors to fund UGI initiatives. Engaging local communities in fundraising efforts, such as crowdfunding and local sponsorships, can generate financial support and foster community ownership of UGI projects.

3.2 Case studies

Case studies from cities worldwide demonstrate the effectiveness of UGI in supporting biodiversity conservation in urban environments.

In Chicago, the city's green roof initiative has established over 500 green roofs to provide wildlife habitats and manage stormwater (Sharma et al., 2018), successfully bolstering urban biodiversity and ecological services. These roofs support wildlife such as birds and insects, enhancing urban ecological resilience and mitigating urban flooding risks while improving downstream water quality through effective stormwater runoff management. These ecological benefits underscore the initiative's alignment with sustainable urban development goals. Despite its achievements, several challenges warrant consideration. Firstly, the financial burden of installing and maintaining green roofs poses a significant obstacle. High initial costs and ongoing maintenance expenses may hinder scalability, particularly in economically disadvantaged communities or cities with differing financial priorities. Addressing this challenge necessitates innovative financing mechanisms and cost-effective design solutions to enhance accessibility and economic viability. Secondly, the effectiveness of green roofs can vary due to local climatic conditions, building structures, and maintenance practices. Issues such as inadequate irrigation, insufficient substrate depth, or improper plant selection can compromise their ecological and stormwater management functionalities. Site-specific design considerations and adaptive management strategies are crucial to optimize performance and durability. Ensuring the long-term sustainability of green roofs requires continuous monitoring and management efforts, including assessing biodiversity impacts, evaluating stormwater retention rates, and promptly addressing maintenance needs. Given the complexity of integrating green roofs into broader UGI frameworks, robust governance structures, and stakeholder engagement are essential to foster sustained commitment and community support. While Chicago's green roof initiative has made notable strides in enhancing urban biodiversity and stormwater management, cost, technical feasibility, and sustainability challenges remain significant.

Urban agriculture initiatives have gained momentum worldwide as strategies to support biodiversity and sustainability. In Poland, the transformation of vacant lots into urban farms has emerged as a prominent example, combining fresh food production with wildlife habitat creation and community development (Szczepanska et al., 2021). This initiative has proven successful on multiple fronts. Repurposing vacant lots addresses urban blight while enhancing local food security and promoting sustainable agricultural practices in urban environments. Urban farms have effectively restored wildlife habitats, enriching urban biodiversity and creating new ecological niches in densely populated areas. These dual benefits underscore the initiative's capacity to integrate ecological and social goals. However, alongside these achievements, several challenges warrant consideration. Land availability, regulatory complexities, and competing urban development priorities may constrain the scalability of urban agriculture initiatives on vacant lots. Issues related to land access and zoning regulations could limit the expansion of such initiatives across diverse urban contexts or neighborhoods with differing socioeconomic conditions. Ensuring the sustainability of urban farms requires addressing technical challenges such as water resource management, soil quality maintenance, and pest control in urban settings. Long-term success hinges on robust community engagement and sustainable management practices, necessitating continuous support from local governments, community organizations, and residents to sustain infrastructure, education, and maintenance efforts. Critical to this effort is resolving issues surrounding land tenure, resource access, and equitable distribution of benefits to foster social inclusivity and mitigate disparities in urban food access. While Poland's urban agriculture initiatives have effectively utilized vacant lots to promote biodiversity, sustainability, and community development through urban farming, they encounter challenges related to scalability, resource management, and social equity.

Singapore's extensive network of green spaces, including parks, nature reserves, and green buildings, is pivotal in preserving the city-state's rich biodiversity (Zhang et al., 2022). This approach has yielded substantial successes in biodiversity conservation and urban sustainability. The interconnected parks and nature reserves serve as critical habitats for diverse flora and fauna, crucial for maintaining Singapore's biodiversity. These green spaces also function as ecological corridors, facilitating wildlife movement across urban landscapes and supporting native species populations. Integrating green buildings, such as green roofs and vertical gardens, enhances urban sustainability by improving aesthetics, boosting energy efficiency, sequestering carbon, and creating favorable urban microclimates. These initiatives underscore Singapore's commitment to integrating ecological and environmental considerations into urban planning. However, despite these achievements, several challenges and limitations persist. The effectiveness of green spaces in biodiversity conservation faces pressures from urbanization, habitat fragmentation, and the introduction of invasive species. Managing these issues amid Singapore's rapid urban expansion requires careful planning to maintain the ecological integrity of green spaces. While green buildings offer environmental benefits, barriers such as high costs, technical complexity, and regulatory hurdles hinder their widespread adoption across diverse sectors and economic contexts, limiting their overall impact on urban sustainability. Effective maintenance and management of green spaces and buildings necessitate sustained financial investment, a skilled workforce, and community engagement. Ensuring their long-term viability demands addressing funding sustainability, enhancing stakeholder coordination, and promoting public awareness to foster environmental stewardship. Singapore's extensive network of green spaces has significantly contributed to biodiversity conservation and urban sustainability. Nevertheless, addressing urbanization, cost-effectiveness, and sustainable management challenges requires integrated strategies and innovative solutions in UGI planning and implementation.

4 Sustainable urban development through UGI

UGI contributes to sustainable urban development by conserving biodiversity and providing a spectrum of ecosystem services crucial for bolstering human well-being and fortifying urban resilience. These multifaceted contributions make UGI integral to urban landscapes' resilience, livability, and sustainability, enriching the quality of life for urban inhabitants and reducing their susceptibility to environmental hazards and calamities (Figure 2).

4.1 Regulation services

UGI is pivotal in enhancing urban regulatory services, which is crucial for mitigating environmental impacts and improving urban resilience. The principle of multifunctionality underscores that green spaces can simultaneously serve flood control, improve air quality, and mitigate urban heat islands. Connectivity ensures that green spaces are interconnected, facilitating effective water management and pollution reduction. Adaptive management and climate adaptation strategies enable UGI to respond dynamically to changing environmental conditions, enhancing the city's capacity to regulate and sustain environmental quality. Integration with urban development ensures that these regulatory functions are incorporated into city planning and design, promoting a balanced and sustainable urban ecosystem.

Regulatory services provided by UGI are crucial in addressing multifaceted environmental challenges prevalent in urban landscapes. The integration of UGI facilitates the regulation of various ecological processes essential for sustaining urban environments (Rolhauser et al., 2023). Primarily, UGI significantly contributes to ameliorating the adverse impacts of the urban heat island effect, characterized by elevated temperatures

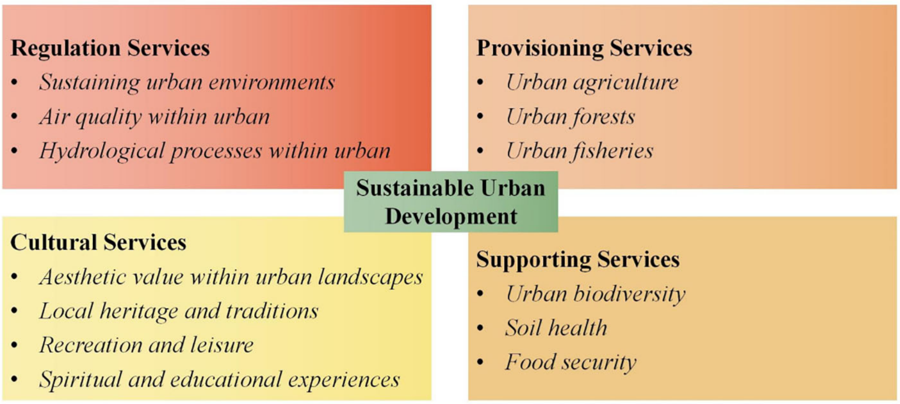

FIGURE 2
Sustainable urban development through UGI.

in urban areas compared to their rural counterparts. UGI helps attenuate heat absorption and radiation through evapotranspiration and shading, moderating local climate conditions and fostering thermal comfort within urban spaces.

UGI plays a pivotal role in enhancing air quality within urban settings by acting as a natural filtration system for pollutants (Sebastiani et al., 2021). Vegetation in green infrastructure components, such as green roofs and rain gardens, serves as a sink for airborne particulate matter and absorbs gaseous pollutants like carbon dioxide and nitrogen oxides. Consequently, the implementation of UGI aids in mitigating air pollution levels, thereby contributing to the overall improvement of public health and well-being in urban communities.

In addition to climate and air quality regulation, UGI is vital in managing hydrological processes within urban landscapes (Wang et al., 2023). Urbanization often leads to increased impervious surfaces, disrupting natural hydrological cycles and exacerbating stormwater runoff and flooding issues. However, by incorporating green infrastructure practices such as permeable pavements and rain gardens, UGI helps attenuate the adverse effects of stormwater runoff by promoting infiltration, retention, and slow release of rainwater into the soil. This reduces the burden on conventional drainage systems, mitigates the risk of urban flooding, and alleviates pressure on downstream water bodies.

4.2 Provisioning services

Provisioning services offered by UGI are essential for maintaining the supply of resources upon which urban populations rely. The diversity of plant and animal species supported by UGI contributes to the availability of food, fresh water, and raw materials. Access to green spaces enables communities to utilize these resources sustainably. Adaptive management practices ensure that these resources are managed to maintain availability for future generations. Integration with urban development plans optimizes and sustains these provisioning services, reducing the city's reliance on external resources and enhancing its self-sufficiency.

The provisioning services provided by UGI encompass a range of essential benefits that contribute to the sustenance and well-being of urban populations while mitigating the ecological impacts associated with conventional provisioning activities. Urban agriculture, forestry, and fisheries, facilitated by the integration of UGI, play a pivotal role in meeting the diverse resource needs of urban residents, from food to timber and fiber, while fostering the sustainable management of renewable resources within urban environments.

Urban agriculture, facilitated by UGI, involves cultivating crops and rearing livestock within urban areas, bolstering local food production, and enhancing food security for urban populations (Evans et al., 2022). Practices such as rooftop gardens, community gardens, and vertical farming provide opportunities for urban dwellers to engage in agricultural activities, reducing dependency on external food sources and enhancing self-sufficiency. Additionally, urban agriculture reduces food miles associated with conventional agricultural supply chains, minimizing the carbon footprint and energy consumption related to food production and distribution.

UGI supports urban forestry initiatives aimed at the sustainable management and utilization of urban tree resources (Cobbinah et al., 2023). Urban forests serve as repositories of biodiversity and carbon sinks, providing provisioning services such as timber, fuelwood, and non-timber forest products to urban residents. Initiatives like agroforestry and urban reforestation programs enhance the availability of forest-derived resources in urban settings, reducing pressure on natural forest ecosystems and promoting biodiversity conservation.

UGI provides fisheries resources within urban areas by creating and restoring aquatic habitats such as wetlands, ponds, and urban water bodies (Ghofrani et al., 2020). These ecosystems support cultivating freshwater fish and aquatic plants, diversifying protein sources available to urban residents, and promoting sustainable aquaculture practices. Integrating UGI into urban water management strategies enhances the resilience of urban fisheries resources to environmental stressors and anthropogenic pressures, ensuring their long-term viability.

4.3 Cultural services

UGI significantly enhances cultural services by improving urban residents' quality of life and well-being. The principles of multifunctionality and biodiversity ensure that green spaces offer a range of recreational, aesthetic, and spiritual benefits. Community involvement and education play crucial roles in fostering a sense of ownership and stewardship of these spaces, promoting social cohesion and cultural enrichment. Accessibility ensures that all community members can benefit equitably from these services. Integration with urban development helps preserve and enhance cultural services as cities expand and develop, contributing to a vibrant and dynamic urban culture.

UGI enhances cultural services primarily by augmenting aesthetic value within urban landscapes (Cengiz and Boz, 2020). Green spaces, such as parks, gardens, and tree-lined boulevards, serve as visual focal points, enhancing the aesthetic appeal of urban environments and providing respite from the monotony of built infrastructure. UGI elements like flowering plants, ornamental trees, and landscaped features imbue urban spaces with beauty and tranquility, fostering a sense of pride and attachment among residents while attracting visitors and tourists.

UGI serves as a vital space for recreation and leisure, offering opportunities for physical activity, relaxation, and social interaction (Kalinauskas et al., 2023). Parks, playgrounds, and recreational trails provided by UGI enable urban residents to engage in various recreational pursuits such as jogging, cycling, picnicking, and outdoor sports. These green spaces serve as social hubs where individuals from diverse backgrounds come together to socialize, connect with nature, and forge community bonds, promoting social inclusion and well-being.

UGI contributes to providing spiritual and educational experiences within urban settings (Hegetschweiler et al., 2017). Green spaces, particularly those with significant natural or historical value, serve as sanctuaries for contemplation, meditation, and spiritual rejuvenation. Additionally, UGI provides opportunities for environmental education and interpretation, fostering a deeper understanding of ecological processes, biodiversity conservation, and sustainable living practices among urban residents, particularly children and youth.

UGI promotes social equity, health, and well-being by ensuring equitable access to green spaces across diverse urban communities. In cities where UGI initiatives prioritize underserved neighborhoods, such as developing community gardens and accessible parks, residents experience improved mental and physical health. These spaces mitigate environmental inequalities and foster social cohesion through shared recreational areas, facilitating community interaction and cultural exchange. However, implementing UGI initiatives involves navigating complex stakeholder interests and potential conflicts. For instance, urban planners must balance preserving green spaces with urban development pressures, ensuring conservation efforts do not compromise socioeconomic development goals. Stakeholders, including residents, developers, and environmental advocates, may prioritize UGI use and management aspects. Therefore, inclusive decision-making processes are necessary to prioritize community input and achieve sustainable outcomes. Effectively managing UGI requires strategies that reconcile these competing interests and ensure equitable distribution of benefits.

4.4 Supporting services

Supporting services offered by UGI are essential for sustaining the ecosystem processes that underpin all other services. Biodiversity conservation, soil formation, and nutrient cycling benefit from the principles of connectivity and diversity. Long-term sustainability guarantees the maintenance of these supporting services, securing the ecological foundations of the urban environment. Adaptive management practices enable continual assessment and enhancement of these services, ensuring resilience in response to environmental changes. Integration with urban development ensures consideration and preservation of these essential ecological processes, promoting the overall sustainability of the urban ecosystem.

A primary function of UGI is the preservation and enhancement of urban biodiversity (Grabowski et al., 2023). Green spaces, including parks, belts, urban forests, and refuges for various plant and animal species, promote species richness and genetic diversity within urban ecosystems. The presence of UGI elements such as native vegetation, habitat corridors, and wildlife-friendly landscapes facilitates the movement and dispersal of species, mitigating the negative impacts of habitat fragmentation and promoting ecosystem connectivity.

UGI is crucial in maintaining soil fertility and promoting soil health within urban environments (Spanò et al., 2017). Green infrastructure practices such as urban agriculture, composting, and soil remediation enrich organic matter, nutrient cycling, and microbial activity, enhancing soil structure, fertility, and productivity. Additionally, UGI helps mitigate soil erosion and compaction, reducing the risk of land degradation and enhancing the resilience of urban soils to environmental stressors.

UGI supports providing critical ecosystem services for agricultural productivity and food security (Cilliers et al., 2020). Pollination, facilitated by urban green spaces and diverse plant communities, is vital for reproducing many flowering plants, including food crops, ensuring crop yield and agricultural sustainability. Similarly, UGI contributes to natural pest control by providing habitat and resources for natural enemies of pests, reducing reliance on synthetic pesticides, and promoting sustainable pest management practices.

4.5 Ecosystem service valuation based on RPCS

To establish an ecosystem value assessment framework for UGI across four dimensions—RPCS (regulation services, provisioning

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services, cultural services, and support services)—we identify primary indicators for each dimension and select corresponding secondary indicators (Table 1). Below is a detailed breakdown of these indicators and the rationale behind their selection.

Regulation services of UGI encompass climate, water, and air quality. Climate regulation is assessed through indicators like temperature control, carbon sequestration, and climate stability, evaluating UGI's role in mitigating urban heat islands, its impact on the carbon cycle, and overall climate regulation. Water regulation includes stormwater management, flood control, and water purification, highlighting UGI's ability to manage runoff, reduce flood risks, and improve water quality. Air quality regulation involves pollutant removal, oxygen production, and health risk reduction, showing how UGI contributes to air purification, increases oxygen levels, and improves urban health outcomes.

Provisioning services of UGI include food, raw materials, water, and energy provision. Food and raw materials are supported by indicators such as food production, timber supply, and medicinal plants, facilitated by urban farms and community gardens integrated into UGI to meet urban residents' needs. Water provision includes drinking water supply, irrigation sources, and groundwater recharge, where UGI serves as a vital water supply and replenishment source. Energy provision involves bioenergy production, solar energy utilization, and energy efficiency improvements, with specific UGI designs generating renewable energy and enhancing overall efficiency.

Cultural services provided by UGI encompass recreation, aesthetic value, education, inspiration, and spiritual and mental health benefits. Recreation and aesthetic value are enhanced by park facilities, landscape beautification, and cultural activities within UGI, enriching urban residents' recreational experiences and quality of life. Educational and inspirational value is supported by environmental education, cultural heritage preservation, and artistic displays within UGI spaces, serving as platforms for public education on nature and cultural diversity. Spiritual and mental health benefits are facilitated through psychological healing spaces, spiritual retreat areas, and community cohesion promotion, improving mental well-being and fostering stronger community bonds.

Supporting services provided by UGI include soil formation, nutrient cycling, biodiversity support, and primary production. Soil formation and nutrient cycling are promoted by UGI through activities such as soil improvement, nutrient recycling, and soil protection, thereby enhancing urban soil quality and safeguarding groundwater resources. UGI facilitates biodiversity support through measures like species protection, habitat provision, ecological connectivity promotion, creating habitats, and fostering biodiversity in urban environments. Primary production within the urban ecosystem is supported by UGI through plant growth, biomass production, and energy flow indicators, contributing to biological productivity and energy dynamics crucial for urban ecological balance.

This comprehensive set of indicators enables a robust evaluation of UGI's ecosystem services, assisting decision-makers in scientifically optimizing and managing urban green spaces.

TABLE 1 Ecosystem service valuation based on RPCS.

Primary Indicator	Secondary Indicator	Tertiary Indicator
Regulation Services	Climate Regulation	Temperature Regulation
		Carbon Sequestration
		Climate Stability
	Water Regulation	Stormwater Management
		Flood Control
		Water Purification
	Air Quality Regulation	Pollutant Removal
		Oxygen Production
		Health Risk Reduction
Provisioning Services	Food and Raw Materials	Food Production
		Timber Supply
		Medicinal Plants
	Water Provision	Drinking Water Supply
		Irrigation Sources
		Groundwater Recharge
	Energy Provision	Bioenergy Production
		Solar Energy Utilization
		Energy Efficiency
Cultural Services	Recreation and Aesthetic Value	Park Facilities
		Landscape Beautification
		Cultural Activities
	Educational and Inspirational Value	Environmental Education
		Cultural Heritage
		Artistic Displays
	Spiritual and Mental Health Benefits	Psychological Healing
		Spiritual Retreats
		Community Cohesion
Supporting Services	Soil Formation and Nutrient Cycling	Soil Improvement
		Nutrient Cycling
		Soil Protection
	Biodiversity Support	Species Protection
		Habitat Provision
		Ecological Connectivity
	Primary Production	Plant Growth
		Biomass Production
		Energy Flow

5 Adaptive management of UGI

Adaptive management is a cornerstone principle in orchestrating and executing UGI initiatives. It offers a structured approach to navigating uncertainties, assimilating insights from practical endeavors, and flexibly tailoring management strategies to environmental variables. Within its framework is a cyclical modus operandi, moving through phases of planning, implementation, monitoring, evaluation, and adjustment, guided by feedback mechanisms and stakeholder involvement. Several indispensable components are central to the essence of adaptive management within UGI, each fostering resilience and efficacy within the framework (Figure 3).

5.1 Monitoring and evaluation

The importance of monitoring and evaluation in ecological conservation, particularly within UGI, cannot be overstated. Rigorous and systematic monitoring practices are essential for assessing the ecological performance of UGI sites, tracking progress toward conservation objectives, and identifying emerging threats or opportunities requiring intervention (Feingold et al., 2018; Gasparovic and Dobrinic, 2021).

Monitoring and evaluation entail systematically collecting data on various indicators to assess the health and functionality of UGI sites. Standardized protocols are crucial for ensuring consistency and comparability across different monitoring initiatives. These protocols specify the parameters to measure, methodologies to employ, and data collection frequency. Standardization facilitates the creation of robust datasets suitable for meaningful analysis. Following data collection, rigorous statistical analysis is essential to uncover trends and patterns, providing actionable insights for informed decision-making. By identifying statistical significance and interpreting trends, conservation practitioners gain valuable information on the effectiveness of conservation interventions, resilience of UGI sites, and efficacy of management strategies. Disseminating monitoring findings to stakeholders is integral to the process. Given diverse stakeholders—including policymakers, academics, community members, and advocacy groups—presenting findings in an accessible manner is crucial. This may involve creating user-friendly reports, interactive dashboards, or tailored informational workshops. Such efforts ensure broad dissemination and acceptance of monitoring results, empowering stakeholders with knowledge to support UGI conservation. Integrating monitoring and evaluation into adaptive management frameworks is fundamental for fostering iterative learning and refining conservation strategies.

Adaptive management strategies were implemented in a city's urban wetlands restoration project to enhance biodiversity and improve water quality. Initial monitoring identified invasive species and water contamination as primary challenges. Management interventions included removing invasive species and introducing native plants. Ongoing monitoring and evaluation demonstrated notable enhancements in water quality and increased native biodiversity. When new invasive species emerged, the management plan promptly adjusted to mitigate these threats, showcasing the efficacy of adaptive management in sustaining urban wetland health. In another municipal initiative to install green roofs on public buildings, adaptive management was employed to optimize plant selection and maintenance practices. Initial assessments highlighted issues with plant growth and stormwater retention. The management strategy was refined through trials with diverse plant species and soil compositions.

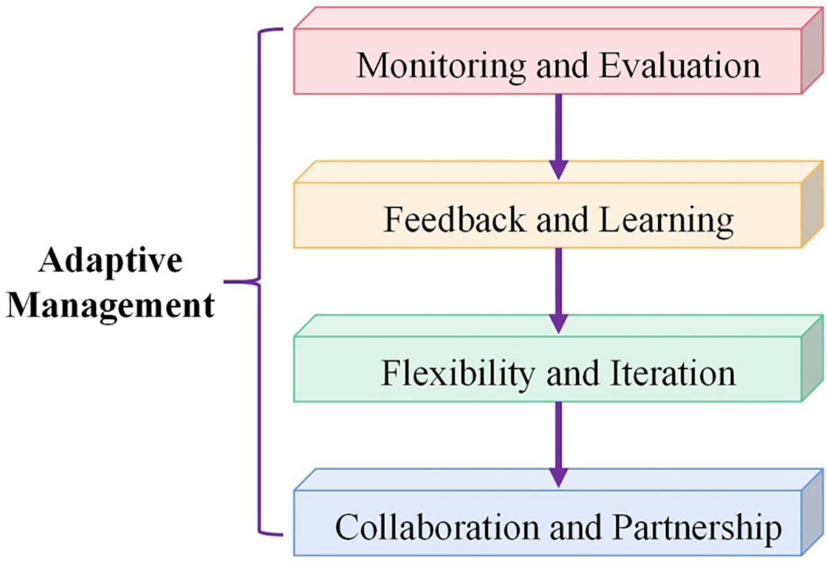

FIGURE 3
Adaptive management of UGI.

Subsequent evaluations indicated improved plant health and enhanced stormwater management capabilities.

5.2 Feedback and learning

Integrating feedback mechanisms and learning processes is crucial for developing adaptive management strategies that respond to dynamic environmental challenges in ecological conservation and sustainable management. Within the UGI context, monitoring data alongside stakeholder feedback is essential for the iterative adaptive management process (Krasny et al., 2014; Castro, 2022).

Central to this paradigm is the recognition that monitoring data provides crucial insights into the performance and resilience of UGI sites. Stakeholder feedback offers valuable perspectives on conservation initiatives' on-the-ground implementation and effectiveness. By synthesizing these complementary sources of information, managers can refine and recalibrate their approaches in response to evolving ecological dynamics and societal needs. Feedback mechanisms play a dual role: they provide insights for informed decision-making and cultivate a culture of engagement, collaboration, and shared responsibility among stakeholders. Designing and implementing effective feedback mechanisms necessitates transparency, participatory processes, and inclusivity to ensure diverse voices and perspectives are heard and integrated into decision-making. Government agencies, NGOs, community groups, and academic researchers contribute unique expertise, resources, and perspectives, highlighting the importance of inclusive, multi-stakeholder approaches to feedback and learning. Collaborative platforms, such as multi-stakeholder forums, working groups, or advisory committees, foster dialogue, knowledge exchange, and collective problem-solving. The iterative nature of adaptive management requires a commitment to continuous learning and improvement. Successful strategies and best practices identified through monitoring and stakeholder feedback should be systematically documented, shared, and disseminated to inform future decision-making and guide the replication of successful approaches in other contexts. Integrating feedback and learning into adaptive management processes signifies a move toward more dynamic, responsive, and collaborative approaches to ecological conservation and sustainable management.

Adaptive management practices addressed biodiversity and public use concerns in restoring an urban park. Initial assessments identified areas with low biodiversity and significant human impact. Stakeholder feedback from residents and park users highlighted the demand for increased green spaces and amenities. In response, the management strategy focused on planting native species to enhance biodiversity and designating recreational areas to balance conservation and public enjoyment. Continuous monitoring and periodic stakeholder consultations facilitated adjustments, such as incorporating educational signage and revising maintenance schedules. These adaptations underscored the efficacy of adaptive management in simultaneously achieving ecological conservation and meeting social needs. Adaptive management was utilized in a riverbank stabilization project in a metropolitan area to combat erosion and enhance habitat quality. Initial data revealed extensive erosion and habitat loss for aquatic species, with community feedback emphasizing flood risk and recreational river access. The management approach integrated bioengineering solutions, such as live staking and coir logs, alongside planting riparian vegetation. Early monitoring indicated initial success in erosion reduction; however, subsequent data highlighted new erosion challenges downstream. Adaptations to the management plan included expanding stabilization measures and enhancing community involvement through volunteer planting initiatives.

5.3 Flexibility and iteration

Flexibility and iteration support the adaptive management framework in ecological conservation and sustainable management. This approach acknowledges the inherent uncertainty and complexity of ecological systems, emphasizing the need for managers to be agile and responsive to dynamic environmental conditions and emerging challenges. Within the context of UGI, applying flexible and iterative approaches is crucial for optimizing the effectiveness and resilience of conservation initiatives (Suleiman et al., 2020; Ramyar et al., 2021).

Adaptive management's flexibility entails the readiness and capability to adjust management strategies and interventions based on new information, shifting priorities, and evolving environmental dynamics. This approach requires moving from rigid, prescriptive methods to more dynamic, context-sensitive strategies that adapt to changing circumstances and uncertainties. Managers must have the autonomy and resources to make timely, informed decisions guided by a commitment to achieving conservation goals while remaining responsive to emerging threats and opportunities. Central to flexibility is iterative planning processes, which offer experimentation, innovation, and learning opportunities. Viewing failures as valuable learning experiences rather than setbacks fosters a culture of continuous improvement and adaptive capacity within UGI programs and projects. Iterative planning enables managers to test hypotheses, pilot new approaches, and refine strategies based on real-world feedback, thereby enhancing the effectiveness and efficiency of conservation interventions over time. Iterative approaches also facilitate the integration of stakeholder perspectives and local knowledge into decision-making processes, promoting ownership and empowerment among diverse stakeholders. Engaging stakeholders in collaborative planning and co-design processes allows managers to leverage their insights and expertise to co-create solutions tailored to local contexts and responsive to community needs and aspirations. The iterative nature of adaptive management necessitates ongoing monitoring, evaluation, and feedback loops to track progress, identify emerging issues, and assess the effectiveness of interventions.

An urban stream restoration project utilized adaptive management practices to improve water quality and aquatic habitat. Initial assessments identified elevated pollutant levels and degraded habitat conditions, with community feedback emphasizing concerns over water quality and recreational access.

The management strategy included implementing vegetative buffers and bio-retention systems to filter pollutants and create recreational access points. Continuous monitoring and community engagement indicated improvements in water quality and habitat complexity. Upon detecting new pollutant sources during subsequent monitoring, the management plan swiftly adapted to mitigate these issues, illustrating the efficacy of adaptive management in sustaining and enhancing urban stream ecosystems. A citywide initiative to install green roofs on public buildings employed adaptive management to optimize plant selection and maintenance practices. Initial monitoring revealed varying plant survival rates and stormwater retention capacities across different sites, with feedback from building managers and maintenance personnel emphasizing the need for simplified maintenance and enhanced plant resilience. The management approach involved trialing different plant species and soil compositions alongside adjusting maintenance routines. Follow-up monitoring demonstrated improved plant health and superior stormwater management capabilities.

5.4 Collaboration and partnership

Collaboration and partnership are crucial in adaptive management, facilitating practical conservation actions and sustainable management practices. This necessity is particularly evident within the context of UGI, where the complexity of environmental challenges demands concerted efforts from diverse stakeholders across governmental, non-governmental, community, private sector, and academic sectors (Donnell et al., 2018; Rottle et al., 2023).

Collaboration involves pooling resources, expertise, and perspectives from multiple stakeholders to address shared conservation goals and challenges collectively. By harnessing different actors' complementary strengths and resources, collaborative initiatives can leverage synergies and achieve unattainable outcomes through individual efforts alone. Collaboration fosters a sense of shared ownership and responsibility among stakeholders, promoting a collective commitment to the long-term sustainability and resilience of UGI initiatives. Partnership denotes the establishment of formal or informal alliances between stakeholders based on mutual interests, objectives, and values. Partnerships serve as vehicles for fostering trust, building relationships, and promoting mutual understanding among diverse stakeholders. Through partnerships, stakeholders can align their efforts, coordinate actions, and leverage each other's networks and resources to achieve shared conservation objectives. Partnerships facilitate the exchange of knowledge, best practices, and innovative solutions, thereby enhancing the effectiveness and efficiency of conservation interventions. Collaborative governance structures are pivotal in facilitating collaboration and partnership among multiple stakeholders. These structures encompass formal mechanisms such as inter-agency committees, multi-stakeholder platforms, collaborative decision-making processes, informal networks, and alliances. By providing forums for dialogue, information sharing, and collective decision-making, collaborative governance structures enable stakeholders to work together toward shared goals while respecting diverse perspectives and interests. Key features of effective collaborative governance include transparency, inclusivity, and accountability. Transparent decision-making processes and open communication channels foster trust and confidence among stakeholders, while inclusivity ensures that all stakeholders' voices and perspectives are heard and valued.

Collaboration and partnership played pivotal roles in the adaptive management approach in an urban park revitalization project. Government agencies, local NGOs, community groups, and academic researchers established a multi-stakeholder platform to guide project initiatives. Initial assessments identified areas requiring ecological restoration and enhancements for community use. Stakeholder input shaped a strategy focused on restoring native plants and creating recreational spaces. Continuous monitoring and feedback loops facilitated adjustments, including the introduction of educational programs and modifications to maintenance practices, underscoring the effectiveness of adaptive management through collaborative efforts. A citywide initiative to enhance green infrastructure for flood management exemplified extensive collaboration among municipal authorities, private developers, and local communities. This partnership formed a formal alliance to address urban flooding using adaptive management principles. Initial evaluations identified critical flood-prone zones and stakeholder priorities, such as flood mitigation and the integration of recreational green spaces. The management strategy included implementing rain gardens, permeable pavements, and green roofs. Ongoing monitoring and stakeholder engagement highlighted opportunities for enhancement, particularly in increasing public awareness and involvement in maintenance activities. The iterative process of adaptation and collaboration significantly bolstered flood resilience, showcasing the efficacy of adaptive management within urban green infrastructure initiatives.

6 Challenges and opportunities

6.1 Challenges

Despite its potential benefits, UGI faces several challenges and barriers to implementation (Figure 4).

6.1.1 Limited funding and resources

Limited funding and resources pose significant challenges to the successful planning, development, execution, and upkeep of UGI projects, which are critical for sustainable urban development (Mell and Whitten, 2021). Ensuring adequate financial backing and resources is essential for the efficacy and longevity of UGI initiatives. However, many cities struggle to allocate sufficient financial resources to UGI endeavors due to competing priorities, stringent budgetary constraints, and short-term planning perspectives. Identifying and addressing these challenges is pivotal in adaptive management for UGI projects. Adaptive management necessitates a proactive approach to recognizing and mitigating barriers that could hinder project success.

Municipalities frequently prioritize UGI projects amidst competing demands such as public safety, infrastructure maintenance, social welfare, and education. Conducting stakeholder analyses and thorough budget reviews is imperative to address this challenge comprehensively. Engaging with municipal decision-makers and scrutinizing budget allocations reveals how UGI projects are prioritized relative to other municipal needs. Fiscal conservatism and budget constraints often limit funding for UGI initiatives, necessitating reviews of financial reports and budget plans. Interviews with financial planners and city officials provide further insights into budget constraints and potential flexibility. Municipalities' tendency to prioritize short-term gains over long-term sustainability may marginalize UGI initiatives, as evident in analyses of planning documents and policy statements. Engaging with planners and policymakers clarifies how the planning horizon impacts UGI funding. UGI projects heavily depend on funding from various government agencies with diverse priorities and budget cycles. Identifying this challenge involves mapping the funding landscape, consulting with funding agencies, and reviewing application processes and historical funding patterns to understand criteria and timelines comprehensively.

The effectiveness of adaptive strategies in addressing funding challenges is demonstrated through two examples. Firstly, in a project focused on expanding the urban tree canopy, adaptive management was utilized to confront funding obstacles. Initial assessments revealed competition between tree planting initiatives and other city priorities. Stakeholder workshops and budget reviews led to developing a funding strategy that integrated public-private partnerships and community fundraising campaigns. Continuous monitoring and feedback mechanisms were established to assess funding sufficiency and refine strategies, ensuring consistent financial support and project success. Secondly, in a citywide initiative to install green roofs on public buildings, adaptive management was employed to navigate stringent budget constraints and fragmented funding sources. A comprehensive analysis of the funding landscape identified challenges, prompting the project team to engage multiple funding agencies. A coordinated funding application strategy was developed, supported by a centralized database to monitor funding opportunities and allocations. Regular monitoring and evaluation of funding statuses enabled timely adjustments, ensuring the financial sustainability of the green roof initiative. These projects effectively identified and resolved funding challenges through adaptive management practices, facilitating the successful implementation of green infrastructure initiatives across urban environments.

6.1.2 Institutional fragmentation and coordination

Institutional fragmentation and coordination pose significant challenges to the planning and management of UGI projects (Li et al., 2017). These initiatives typically involve multiple government agencies, departments, and stakeholders, each with distinct mandates, jurisdictions, and decision-making processes. The complexity of UGI projects and the diversity of stakeholders underscore the critical importance of fostering cohesive institutional collaboration and coordination mechanisms. Identifying and addressing these challenges is crucial within the adaptive management framework to develop effective strategies for overcoming them.

Institutional fragmentation within governmental entities often results in fragmented decision-making and disjointed policy implementation in UGI management. Responsibilities for UGI planning and management are typically dispersed among various

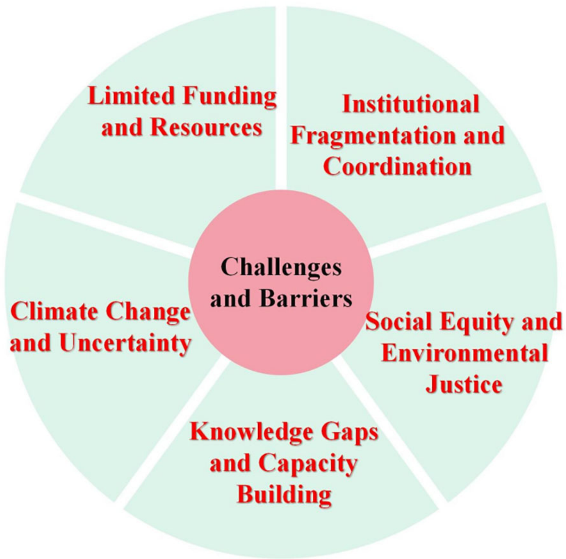

FIGURE 4
Challenges and barriers.

agencies and departments, each operating within its organizational silo. This fragmentation can lead to divergent priorities, conflicting strategies, and disjointed efforts, compromising the coherence and effectiveness of UGI initiatives. Identifying this challenge involves mapping the organizational structure and responsibilities of involved entities and assessing the alignment of their strategic goals and policies. The lack of coordination among these entities hampers information sharing and knowledge dissemination critical for informed decision-making and integrated policy development. Establishing robust mechanisms for information exchange and activity coordination is essential to ensure that valuable insights and best practices are shared across agencies. Assessing existing communication channels and knowledge-sharing practices among stakeholders is necessary to address this challenge effectively. Institutional fragmentation challenges aligning regulatory frameworks and streamlining permitting processes essential for timely UGI project implementation. Diverse regulatory requirements and permitting procedures across jurisdictions can create bureaucratic hurdles and administrative delays, thereby increasing project timelines and costs. Identifying this challenge involves analyzing regulatory requirements, identifying inconsistencies, and addressing bottlenecks in permitting processes. Coordinated efforts are crucial to overcoming these challenges and enhancing the efficiency and effectiveness of UGI management practices across governmental entities.

The effectiveness of adaptive strategies in addressing institutional and regulatory challenges is exemplified through two case studies. In a river restoration project, adaptive management addressed institutional fragmentation. Initial assessments revealed involvement from multiple agencies in water management, environmental protection, and urban planning, highlighting coordination gaps and overlapping responsibilities. A multi-agency task force was established through stakeholder analysis and mapping exercises with structured communication protocols and regular meetings. This approach facilitated enhanced information sharing, aligned strategies, and improved policy implementation, effectively resolving institutional fragmentation. Significant delays in an urban wetland conservation initiative stemmed from fragmented regulatory frameworks and permitting processes. Adaptive management practices addressed these challenges through comprehensive reviews of regulatory requirements and engagement with permitting authorities. Inconsistencies and bottlenecks in the approval process were identified, leading to the development of a unified permitting framework. Continuous feedback loops and stakeholder consultations ensured ongoing refinement and adaptation of the permitting process. This adaptive approach streamlined regulatory compliance and accelerated project timelines, demonstrating the efficacy of adaptive management in overcoming regulatory obstacles.

6.1.3 Social equity and environmental justice

Social equity and environmental justice are pivotal considerations in planning and implementing UGI interventions (Derickson et al., 2024). Although UGI projects strive to improve urban livability and environmental quality, inadequate management can worsen social disparities and environmental injustices. Addressing these challenges is crucial within the adaptive management framework to ensure that UGI initiatives contribute to equitable and just urban environments.

One of the significant challenges in UGI planning is the potential for interventions to benefit privileged communities while disproportionately marginalizing or displacing vulnerable populations. This issue, often termed "green gentrification," arises when efforts to enhance green spaces and environmental amenities increase property values and revitalization, potentially displacing low-income residents and communities of color. Addressing this challenge requires comprehensive socioeconomic assessments and robust stakeholder engagement to understand and mitigate potential impacts on diverse communities. Inclusive planning processes prioritizing community participation are essential to mitigate the risk of exacerbating social inequities. Ensuring meaningful involvement of stakeholders from underserved neighborhoods and vulnerable populations is crucial to aligning UGI projects with urban residents' needs, preferences, and aspirations. Evaluating these processes involves assessing the quality and extent of stakeholder engagement throughout the planning and implementation phases. Historically marginalized communities often face barriers to accessing quality green spaces, contributing to disparities in health outcomes, environmental quality, and overall well-being. Addressing this challenge involves spatial analysis to map UGI benefits distribution and assess disparities across socioeconomic and demographic groups. Surveys and community feedback provide additional insights into perceptions of access and utilization of green spaces, which is essential for informing equitable UGI planning and management strategies.

The effectiveness of adaptive strategies in addressing social equity and environmental justice challenges is demonstrated through two case studies. In a community-led park revitalization project, adaptive management practices were employed to tackle social equity issues. Initial assessments highlighted potential risks of green gentrification, which could displace low-income residents due to planned park improvements. Socioeconomic impact studies were conducted to mitigate this, and extensive engagement with the local community was pursued through workshops and focus groups. These efforts identified the needs and concerns of vulnerable populations, leading to the formulation of policies for affordable housing and inclusive zoning regulations. Continuous monitoring and feedback loops were established to adapt the project to emerging issues, showcasing the effectiveness of adaptive management in promoting social equity. In another initiative focused on improving green space access in underserved neighborhoods, adaptive management practices were utilized to address challenges related to equitable distribution. Spatial analyses and community surveys revealed significant disparities in green space access among socioeconomic groups. In response, the project prioritized green space development in areas with the greatest need and implemented participatory planning processes to engage residents in decision-making. Regular evaluation of green space usage and ongoing community feedback facilitated continuous adaptation and improvement of the initiative, illustrating how adaptive management can effectively address environmental justice concerns.

6.1.4 Knowledge gaps and capacity building

Addressing knowledge gaps and enhancing capacity among practitioners, policymakers, and researchers is essential for advancing the field of UGI amidst increasing interest and investment (Castelo et al., 2023). Despite growing enthusiasm for UGI projects, substantial global disparities in technical expertise, data infrastructure, and institutional capacity among cities persist. These disparities challenge the effective design, implementation, and evaluation of UGI initiatives. Therefore, it is crucial to identify and address these challenges within an adaptive management framework to support evidence-based decision-making in UGI planning and management.

A primary challenge in UGI management is a comprehensive understanding of the diverse benefits and trade-offs associated with different interventions. Despite UGI's potential to address urban challenges such as stormwater management, heat island mitigation, and biodiversity conservation, empirical research, and data-driven analyses are essential to fully elucidate its social, environmental, and economic impacts. Addressing this challenge involves conducting systematic literature reviews, fostering interdisciplinary research collaborations, and utilizing knowledge exchange platforms to integrate varied perspectives and expertise. Capacity constraints often hinder cities' ability to plan, implement, and manage UGI projects effectively. Many municipalities lack the technical know-how and human resources necessary for UGI planning and design, leading to suboptimal outcomes and missed innovation opportunities. Identifying this challenge requires assessing the current capacities of local governments and practitioners, pinpointing specific training and development needs, and implementing targeted capacity-building initiatives such as training programs, workshops, and professional development opportunities. The absence of robust data infrastructure poses a significant barrier to evidence-based UGI planning and decision-making. Many cities struggle with accessing spatial data, monitoring networks, and analytical tools essential for evaluating UGI performance and informing policy choices effectively. Addressing this challenge involves evaluating existing data systems, identifying data availability and quality gaps, and prioritizing investments in developing comprehensive data infrastructure and decision support systems tailored to UGI requirements. These efforts are crucial for enhancing the effectiveness and sustainability of UGI initiatives in urban settings.

The effectiveness of adaptive strategies in enhancing technical capacity and developing data infrastructure is demonstrated through two case studies. Adaptive management practices were employed in a city facing significant capacity constraints to address technical knowledge gaps among municipal staff. A comprehensive capacity assessment revealed deficiencies in UGI design and implementation expertise. In response, the city collaborated with academic institutions and professional organizations to design and implement targeted training programs and workshops. These initiatives successfully equipped practitioners with essential skills and knowledge, resulting in improved project outcomes and innovative UGI solutions. Continuous feedback mechanisms ensured the relevance and effectiveness of the training programs, highlighting the utility of adaptive management in capacity building. In another municipality, inadequate data infrastructure posed a critical challenge to effective UGI planning and management. The city thoroughly assessed existing data systems, identifying significant gaps in spatial data availability and monitoring capabilities. The municipality prioritized investments in developing a comprehensive data infrastructure, including advanced monitoring networks and analytical tools. Collaborative efforts with research institutions and technology providers facilitated the creation of tailored decision support systems to meet UGI planning needs. Regular evaluation and iterative improvements ensured the robustness and responsiveness of the data infrastructure, showcasing the effectiveness of adaptive management in overcoming data-related challenges.

6.1.5 Climate change and uncertainty

Climate change poses significant challenges for the planning and management of UGI, introducing increased levels of uncertainty and risk (Grimm et al., 2008). With shifting climatic patterns and more frequent and severe extreme weather events, UGI projects must adapt to evolving environmental conditions while meeting urban population needs. Uncertainties about future climate projections and the magnitude of ecological changes further complicate UGI planning, requiring proactive strategies to enhance climate resilience and adaptive capacity.

One of the primary concerns in UGI management relates to the impacts of climate change, mainly the increased frequency and intensity of extreme weather events such as heavy rainfall, heat waves, and droughts. These events can overwhelm conventional infrastructure systems, exacerbating urban flooding, water scarcity, and heat-related health risks. Addressing this challenge involves monitoring climatic trends and assessing the vulnerabilities of existing UGI systems to extreme weather events. Proactive strategies include integrating UGI elements such as permeable pavements, green roofs, and bioswales into urban landscapes to enhance stormwater absorption, manage urban heat island effects, and bolster overall climate resilience. Climate change-induced shifts in ecological conditions pose challenges for UGI projects that rely on specific plant species, habitats, and ecosystem functions. Changes in temperature, precipitation patterns, and species distributions can disrupt UGI systems and compromise their ability to deliver essential ecosystem services. Addressing this challenge requires comprehensive ecological assessments and scenario planning to anticipate and mitigate the impacts of climate change. UGI planning must prioritize ecological resilience and biodiversity conservation, incorporating climate-adaptive plant species, resilient ecosystem designs, and dynamic management approaches responsive to environmental shifts. The uncertainty surrounding future demand for ecosystem services adds complexity to UGI planning and management. As urban populations grow and societal priorities evolve, demand for UGI amenities such as recreational spaces, wildlife habitats, and aesthetic enhancements may fluctuate. Addressing this challenge involves stakeholder engagement and participatory planning processes to understand evolving community needs and preferences. UGI projects must

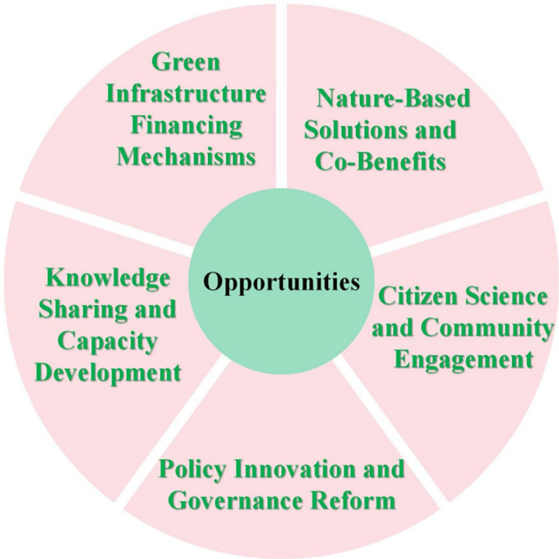

FIGURE 5
Opportunities.

embody flexibility and adaptability to effectively respond to societal changes while continuing to provide desired ecosystem services in a changing climate context.

The effectiveness of strategies in enhancing resilience to climate change and ecological shifts is illustrated through two examples. In response to increased flooding from extreme rainfall, Copenhagen implemented adaptive management to enhance its stormwater management capacity. This involved integrating UGI elements such as green roofs, permeable pavements, and urban wetlands to improve stormwater absorption and management. Continuous monitoring and feedback facilitated real-time adjustments, ensuring the city's resilience to future climatic extremes. This example demonstrates the efficacy of adaptive management in addressing challenges posed by extreme weather events through innovative UGI solutions. In Melbourne, UGI projects encountered challenges concerning plant species vulnerable to rising temperatures and altered precipitation patterns. The city conducted comprehensive ecological assessments and scenario planning to identify climate-resilient plant species and ecosystem designs. Incorporating native and drought-tolerant species enhanced the resilience and functionality of UGI projects, enabling them to continue providing ecosystem services such as air quality improvement and urban cooling despite climatic changes. This example underscores the value of adaptive management in responding to ecological shifts and ensuring the long-term sustainability of UGI initiatives.

6.2 Opportunities

Despite these challenges, UGI presents numerous opportunities for innovation, collaboration, and transformative change in urban landscapes (Figure 5).

6.2.1 Green infrastructure financing mechanisms

Green infrastructure financing mechanisms are critical in addressing funding challenges associated with UGI projects. Innovative approaches such as green bonds, impact investing, public-private partnerships, and ecosystem service payments offer promising avenues for mobilizing capital and unlocking new sources of investment to support UGI implementation and maintenance. By diversifying funding sources and revenue streams, these mechanisms help overcome constraints and enhance the long-term sustainability and resilience of UGI investments.

Green bonds are a recent and effective financing tool designed to support projects with environmental benefits, including UGI initiatives to improve urban resilience, enhance biodiversity, and mitigate climate change impacts. Identifying opportunities for green bonds involves recognizing the increasing demand for environmentally responsible investments and aligning UGI projects with investors' sustainability objectives. For instance, Paris successfully issued green bonds to finance green roofs, urban parks, and other UGI projects, raising substantial capital while promoting environmental sustainability.

Impact investing represents another promising avenue for financing UGI projects, particularly those delivering measurable social, environmental, and economic benefits. Impact investors seek positive societal outcomes alongside financial returns, making them ideal partners for funding UGI initiatives. Showcasing the potential benefits of UGI projects is essential to attract impact investors. For example, New York utilized impact investments to fund the MillionTreesNYC initiative, enhancing urban green spaces, air quality, and community well-being.

Public-private partnerships offer opportunities to leverage private sector expertise and capital for UGI projects. By pooling resources and sharing risks between public and private entities, these partnerships enable cities to access additional funding sources and expedite UGI implementation. Establishing collaborative frameworks and aligning stakeholder interests are crucial in leveraging public-private partnerships. Singapore has successfully implemented various UGI projects through such partnerships, promoting innovation and sustainability in urban development.

Ecosystem service payments present a novel approach to financing UGI projects by monetizing ecological benefits such as carbon sequestration and flood mitigation. Assigning economic value to these services incentivizes private investment in UGI and generates revenue for ongoing maintenance. Quantifying UGI benefits and developing compensation mechanisms are crucial to implementing ecosystem service payments. For example, Bogotá implemented a payment scheme to restore urban wetlands, compensating landowners for preserving ecosystem services and ensuring sustainable funding for UGI projects.

6.2.2 Nature-based solutions and co-benefits

Integrating nature-based solutions (NBS) into UGI planning and design offers a strategic approach to addressing urban challenges while delivering multiple co-benefits across various domains (Zhao et al., 2024b). NBS encompasses strategies and interventions that leverage natural processes and ecosystems to achieve sustainable development objectives, including enhancing resilience to climate change, promoting biodiversity conservation, and improving urban livability.

One key advantage of integrating NBS into UGI planning is its potential to enhance the resilience and sustainability of urban infrastructure systems. By leveraging the inherent resilience of natural ecosystems, NBS interventions can help cities better withstand and adapt to environmental shocks and stressors, such as extreme weather events, urban heat islands, and flooding. Identifying this opportunity involves assessing the urban landscape to determine areas most vulnerable to climate impacts and implementing suitable NBS strategies. For example, Copenhagen has successfully implemented green roofs and permeable pavements to manage stormwater and reduce urban heat island effects. The city's Cloudburst Management Plan includes green roofs that absorb rainwater, reducing runoff and mitigating flooding risks during heavy rainfall events. Permeable pavements allow rainwater to infiltrate the ground, reducing surface runoff and replenishing groundwater. These interventions illustrate how integrating NBS can enhance urban resilience and sustainability by addressing specific environmental challenges while providing additional benefits, such as improved air quality and urban aesthetics.

NBS interventions also have the potential to promote social equity and environmental justice by ensuring equitable access to green spaces and ecosystem services across diverse urban communities. Identifying this opportunity requires a thorough analysis of urban areas to identify underserved neighborhoods with limited access to green infrastructure. Strategically locating NBS interventions in these areas can address disparities in environmental quality and enhance the well-being of vulnerable populations. The Lower Eastside Action Plan (LEAP) focuses on converting vacant lots into community gardens and green spaces in Detroit. This initiative involves residents in the planning and implementation, empowering them and fostering a sense of ownership and stewardship over shared green spaces. The project addresses social equity by providing green spaces in underserved neighborhoods, promoting environmental justice, and enhancing community well-being. This approach demonstrates how community engagement and strategic NBS implementation can effectively address urban challenges and promote social equity.

6.2.3 Citizen science and community engagement

Citizen science and community engagement are critical components in effectively planning, implementing, and monitoring UGI projects. Involving citizens, community groups, and stakeholders in decision-making leverages local knowledge, promotes social cohesion, and enhances environmental stewardship, leading to more effective and sustainable UGI interventions.

Citizen science initiatives and community engagement provide invaluable access to local knowledge and expertise within communities. Residents possess unique insights into their neighborhoods' environmental conditions, biodiversity hotspots, and areas of concern. By actively involving residents in UGI planning and design processes, cities can utilize this local knowledge to inform decision-making, identify priority intervention areas, and co-design solutions tailored to community needs and preferences. For instance, the Green Map System in New York City engages local communities in mapping green spaces, environmental resources, and potential areas for UGI interventions. This participatory mapping tool empowers residents to contribute spatial data on local environmental assets and challenges, facilitating dialogue and collaboration among diverse stakeholders. The Green Map System has proven effective in identifying opportunities for new green spaces and enhancing existing ones, illustrating how citizen science can inform and improve UGI planning within an adaptive management framework.

Moreover, citizen science initiatives and volunteer monitoring programs empower residents to actively monitor and evaluate UGI projects, contributing to data collection, analysis, and interpretation. Engaging citizens as "citizen scientists" expands monitoring networks, collects real-time UGI performance data, and identifies emerging issues requiring attention. This collaborative monitoring approach enhances data quality and accuracy and fosters a sense of ownership and accountability among residents. For example, the Streamkeepers Program in Seattle involves community volunteers monitoring the health of urban streams and riparian zones. Volunteers collect data on water quality, biodiversity, and habitat conditions, providing critical information for managing and improving UGI interventions. This program demonstrates how citizen science can effectively identify and address environmental issues, contributing to the adaptive management of UGI projects and ensuring their long-term success and sustainability.

6.2.4 Policy innovation and governance reform

Policy innovation and governance reform are essential for creating an enabling environment for successfully implementing and mainstreaming UGI across various government sectors and scales. Strengthening policy frameworks, regulatory incentives, and governance structures allows cities to integrate UGI into urban planning processes, land use policies, and development regulations, ensuring widespread adoption and long-term sustainability.

One approach to policy innovation involves developing and implementing green zoning ordinances that designate specific areas within cities for UGI development and conservation. These ordinances establish guidelines and regulations to encourage incorporating green infrastructure elements into new developments and redevelopment projects, such as parks, green roofs, and permeable surfaces. By mandating UGI integration into urban landscapes, green zoning ordinances promote environmental sustainability, enhance resilience to climate change, and improve overall urban livability. New York City's Green Infrastructure Program illustrates the effective use of green zoning ordinances. The city mandates incorporating green infrastructure into new developments and significant renovations, focusing on managing stormwater runoff and reducing the burden on the city's sewer system. This policy has led to the widespread adoption of green roofs, permeable pavements, and rain gardens, showcasing the potential of green zoning ordinances to create opportunities for UGI implementation and ensure compliance through adaptive management practices.

Urban biodiversity strategies offer a comprehensive framework for integrating UGI into city planning and governance. These strategies include habitat restoration, green space enhancement, and community engagement initiatives to promote biodiversity conservation and ecosystem service provision in urban areas. By adopting holistic approaches to urban biodiversity management, cities can enhance the ecological functionality of green infrastructure, improve urban biodiversity, and support the well-being of both human and non-human communities. Melbourne's Urban Forest Strategy is a prime example of an urban biodiversity strategy effectively integrated into UGI planning. The strategy aims to increase the city's tree canopy cover to improve biodiversity, reduce the urban heat island effect, and enhance residents' quality of life. By prioritizing habitat restoration and green space enhancement, Melbourne has successfully created a more resilient and biodiverse urban environment, demonstrating the importance of adaptive management in identifying and leveraging UGI opportunities.

Governance reform is crucial in mainstreaming UGI and fostering collaboration across different levels of government and sectors. Establishing interagency task forces, coordinating committees, and stakeholder partnerships enables cities to streamline decision-making processes, enhance stakeholder coordination, and facilitate UGI project implementation. Participatory governance mechanisms, such as citizen advisory boards and community forums, ensure diverse perspectives are considered in UGI planning and decision-making processes, fostering transparency, accountability, and public trust. Toronto's Green Roof Bylaw exemplifies successful governance reform to promote UGI. The bylaw mandates green roofs for new commercial, institutional, and residential developments, with provisions for exemptions and incentives. This collaborative approach, involving various stakeholders, has resulted in increased green roof installations, improving stormwater management, energy efficiency, and urban biodiversity. Toronto's experience highlights the effectiveness of governance reforms in identifying opportunities and overcoming challenges through adaptive management frameworks.

6.2.5 Knowledge sharing and capacity development

Knowledge sharing and capacity development are crucial for advancing UGI initiatives, fostering sustainability, and enhancing resilience in urban environments. Establishing networks, partnerships, and knowledge-sharing platforms enables cities, regions, and countries to engage in peer-to-peer learning, exchange best practices, and collectively enhance their capacity to implement and manage UGI projects effectively.

International initiatives such as the Urban Biodiversity and Ecosystem Services Partnership, Cities4Forests initiative, and Biophilic Cities Network facilitate collaboration, research, and advocacy on UGI and urban biodiversity conservation. These platforms provide valuable opportunities for cities to share experiences, access resources, and collaborate on joint projects to enhance green infrastructure and biodiversity conservation efforts. The Urban Biodiversity and Ecosystem Services Partnership illustrates the power of international collaboration. Cities involved can exchange knowledge on integrating biodiversity into urban planning best practices. For instance, Singapore and Berlin have shared experiences creating urban wildlife corridors, which are crucial for enhancing biodiversity.

Partnerships forged through initiatives enable cities to leverage collective expertise, resources, and experiences to address common challenges and advance shared goals related to UGI and urban biodiversity conservation. Collaborating with academic institutions, research organizations, and NGOs enhances cities' access to cutting-edge research, technical expertise, and funding opportunities, strengthening their capacity to address complex urban challenges. The Cities4Forests initiative provides a framework for cities to collaborate with academic and research institutions. For example, Portland, Oregon, has partnered with local universities to develop innovative green infrastructure projects, such as green streets and urban forests, serving as living laboratories for ongoing research. This collaboration helps cities implement evidence-based UGI solutions and monitor their effectiveness over time.

Knowledge-sharing platforms and capacity-building initiatives enable cities to access training, technical assistance, and resources to strengthen UGI planning, implementation, and management capabilities. Participating in workshops, webinars, and peer-to-peer exchanges allows cities to enhance their understanding of UGI principles, learn about emerging trends and technologies, and gain practical insights into effective UGI practices. The Biophilic Cities Network facilitates extensive knowledge sharing among member cities. For instance, Washington, D.C., has benefited from the network's webinars and workshops on incorporating biophilic design into urban planning. These events have provided practical insights and case studies that Washington, D.C., has used to enhance its green infrastructure projects, such as expanding green roofs and increasing tree canopy coverage.

7 Conclusions and future research directions

UGI is a crucial mechanism for harmonizing biodiversity conservation and sustainable urban development, employing adaptive management paradigms. This paper presents a comprehensive conceptual framework integrating ecological principles, urban planning strategies, and adaptive management methodologies to cultivate resilient and biodiverse urban landscapes.

The essence of UGI lies in its ability to enhance ecological connectivity, restore ecosystem functions, and provide habitat for diverse flora and fauna within urban areas. This requires a holistic approach considering spatial configuration, functional connectivity, and ecological quality across various scales, from individual sites to citywide networks. Fundamental principles governing the design and implementation of UGI emphasize its multifunctionality, connectivity, diversity, and accessibility while highlighting the importance of adaptive management characterized by its iterative, participatory, and flexible nature. Furthermore, examining biodiversity conservation in urban environments reveals numerous challenges resulting from urbanization, including habitat loss, fragmentation, pollution, invasive species, and climate change. However, UGI interventions offer promising opportunities to improve habitat quality, connectivity, and ecosystem resilience. Global case studies demonstrate the effectiveness of UGI in enhancing biodiversity conservation through various initiatives, such as green roofs, urban forests, riparian corridors, community gardens, pocket parks, and urban farms.

In addition to its role in biodiversity conservation, UGI significantly contributes to sustainable urban development by providing diverse ecosystem services across regulation, provisioning, cultural, and supporting domains. Adaptive management is crucial for effectively planning and implementing UGI projects, ensuring adaptability to changing environmental conditions. Despite its potential, UGI faces challenges such as funding constraints, institutional fragmentation, equity concerns, and knowledge gaps. Overcoming these obstacles requires innovative financing mechanisms, nature-based solutions, community engagement, policy innovation, and capacity development initiatives. UGI represents a transformative approach to fostering resilient, biodiverse, and sustainable urban landscapes, essential for cities to thrive amidst the challenges of the 21st century.

UGI is crucial in integrating biodiversity conservation with sustainable urban development through adaptive management frameworks. This study proposes future research priorities and directions based on a comprehensive conceptual framework. Firstly, future research should prioritize strategies to enhance ecological connectivity and restore ecosystem functions in urban areas. This involves optimizing spatial configurations and functional connectivity across scales, from individual UGI sites to citywide networks. Assessing the ecological quality and resilience of UGI components such as green roofs, urban forests, riparian corridors, community gardens, pocket parks, and urban farms is essential. To effectively implement UGI, research must refine adaptive management practices characterized by iterative, participatory, and flexible approaches. This includes developing methodologies for continuously monitoring and assessing UGI projects to adapt to changing environmental conditions. Engaging community stakeholders in participatory frameworks for planning, implementation, and maintenance of UGI is crucial. Further research should address urbanization challenges such as habitat loss, fragmentation, pollution, invasive species, and climate change. Evaluating the effectiveness of different UGI interventions in enhancing habitat quality, connectivity, and ecosystem resilience is necessary. Longitudinal studies are recommended to measure the long-term impacts of UGI on urban biodiversity. Quantifying the ecosystem services UGI provides across regulatory, provisioning, cultural, and supporting domains is pivotal for understanding its multifaceted contributions to sustainable urban development. Developing integrated assessment models to evaluate the socioeconomic benefits of UGI, including improvements in public health, well-being, and social equity, is essential. Examining global case studies can offer valuable insights into best practices and lessons learned from diverse contexts. Compiling and analyzing case studies demonstrating UGI's effectiveness in enhancing biodiversity conservation and sustainable urban development will be beneficial. Developing a repository of best practices and guidelines tailored to different urban contexts for UGI implementation is recommended to support future initiatives.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: The datasets used and analyzed during the current study available from the corresponding author on reasonable request. Requests to access these datasets should be directed to B-WA, agony08@126.com.

Author contributions

DW: Writing – original draft, Writing – review & editing. P-YX: Writing – original draft, Writing – review & editing. B-WA: Writing – original draft, Writing – review & editing. Q-PG: Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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