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Urbanization and Anthropogenic Impacts on Fungal Diversity: Implications for Ecosystem Health and Sustainability

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Abstract

Macroscopic fungal species forming fruiting bodies are vital for the proper functioning of ecosystems due to their roles in decomposition and nutrient cycling, soil formation, and plant fungal symbiosis. Urbanization and human intervention lead to significant alterations in fungal communities in soil, water, atmosphere, and artificial ecosystems through changes in diversity, ecological functional groups, and ecosystem stability. This review presents a critical synthesis of the available information on the influence of urbanization processes and anthropogenic impacts on mushroom diversity and examines the importance of fungi as ecological bioindicators. The review was carried out via a comprehensive literature analysis focusing on urban mycology, fungal ecology, environmental monitoring, and biodiversity conservation. Key topics covered in this paper include habitat fragmentation, pollution-induced stress, climate change-related impacts, changes in fungal community structure, and the ecological value of mycoindicators of environmental conditions. In addition, special attention is paid to the relevance of fungal conservation in light of global environmental challenges such as the implementation of the UN Sustainable Development Goals. The study recommends establishing a comprehensive system of monitoring the mycobiome in urban areas, developing strong conservation policies for fungi, and raising public awareness regarding the importance of fungi for urban sustainability.

Keywords: Fungi, Bioindicators, Mycoindicators, Ecosystem Health, SDGs, Mycorrhizae

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Introduction

Biodiversity and ecosystems are highly affected by urbanization (Baldrian et al., 2022). Macroscopic and microscopic fungal saprotrophs, pathogens, and mycorrhizal fungi are essential in regulating the processes of decomposition, nutrient cycling, soil composition, and pollutant degradation (Ryan et al., 2019). Loss in ecto-mycorrhizal and lienotropic fungal species, and the increasing dominance of generalist saprotrophic and airborne fungi, are all indicative of the taxonomic and functional homogenization of fungal communities that are caused by urbanization (Netherway & Bahram, 2021; Ahmad et al., 2023I). All plant-fungus interactions, soil, nitrogen, and overall ecosystem stability can be adversely affected by this (Ullah et al., 2022). Fungal indicators are highly sensitive and can monitor urban degradation early, and their neglect during planning poses the risk of undermining the critical function provided by them to urban green spaces (Sultana et al., 2007; Peay et al., 2022). The dynamics of fungal populations, their poor representation in biological databases, their geographic and seasonal biases, and methodological issues are all barriers to the use of fungi as indicators (Maula et al., 2022). The use of fungal indicators would enhance urban resilience against increasing urbanization and is expected to support several Sustainable Development Goals, including health, sustainable cities, biodiversity, and water (Mitchell, 2022; Bahram et al., 2018). Impartial long-term and multi-regional observations are required to mitigate all these challenges.

The process of urbanization may influence the diversity, communities, and functioning of fungi via the destruction of habitats, contamination of environments, and modification of land. It has been increasingly researched how fungi can be used as biological indicators because of their high sensitivity to disturbances in their environments and their functions in cycling nutrients and breaking down organic matter (Li & Dong, 2025). It was assumed that urbanization would cause homogenization of ecologies where fungal disturbance generalists outcompete fungal habitat specialists (Zheng et al., 2025).

The diverse types of fungal populations that inhabit urban soils, flora, water sources, man-made ecosystems, and air are collectively known as urban mycobiomes. Since these fungi play an important role in regulating ecosystem processes such as nutrient cycles, decomposition, pollutant degradation, and plant growth, they are increasingly being recognized for their ecological significance within urban ecosystems. While there is growing recognition about their role, urban fungi have yet to be effectively integrated into urban biodiversity assessments and policies as compared to other forms of urban life, like flora and fauna. The reasons for this oversight include the lack of adequate monitoring, taxonomic difficulties, seasonal fruiting cycles of fungi, and low public awareness levels (Ahmed et al., 2022; Egidi et al., 2023). Urbanization leads to the homogenization of ecology by replacing disturbance-tolerant generalist organisms with specialized fungi. Fungal functional diversity reduction might have an adverse effect on plant adaptability and nutrient cycling, making the importance of fungal guild dynamics essential for maintaining ecosystem stability (Tedersoo et al., 2014; Olchowik et al., 2023).

The following theories enhance the theoretical framework of urban fungal ecology because they assist in studying the way an ecosystem can maintain its stability under anthropogenic pressure: First, it is important to incorporate the theory of urban ecological resilience. Functional trait ecology is also relevant as stress tolerance and decomposition are considered as functions of the ecosystem under an urban environment (Li et al., 2025). Second, metacommunity theory will also be incorporated here as it assists in studying the dispersal and composition of the fungi (Costa et al., 2026).

The ectomycorrhizal communities are being negatively affected by habitat fragmentation, changes in forest types, soil deterioration, and high nitrogen levels, whereas the disturbance-tolerant and saprophytic species are becoming more prevalent in urban areas (Brady, 2024; Tedersoo & Nilsson, 2017). The decline in fungal diversity leads to reduced functionality and resilience of the ecosystem (Jiang et al., 2024; Silva et al., 2025). Similarly, freshwater ecosystems and mangrove systems are dominated by pollution-tolerant fungi that do not perform the ecological function well (Leis, 2022; Seena et al., 2023). Fungal sensitivity to environmental change makes it suitable for bioindicating in the urban environment (Vetrovsky et al., 2019; Luo et al., 2025).

Fungi have been recognized as ecosystem engineers that play diverse roles in the ecosystem by belonging to functional guilds (Singh et al., 2024). Decomposers (saprotrophs), such as saprophytic fungi, break down organic material, thereby contributing to nutrient cycling and carbon cycling alongside soil fertility (Abdullahi et al., 2023; Iqbal & Hanif, 2024). Mycorrhizal fungi (including ectomycorrhiza (ECM) and arbuscular mycorrhiza (AM)) enter into relationships with plants, helping to enhance nutrient absorption and provide resistance to environmental stresses such as drought and salt conditions. Moreover, pathogenic fungi play a role in community dynamics and disease development (Shi et al., 2025; De Medeiros et al., 2021). In addition, endophytic and lichenized fungi also play roles in regulating their hosts' ecosystems. Furthermore, certain fungi have the ability to accumulate heavy metals and pollutants in the environment. Thus, fungi are used in assessing the environment and bioremediation processes (Baldrian, 2017).

The primary aim of conducting this literature review is to determine the impacts of urbanization and anthropogenic disturbance on the diversity of fungi and mushrooms, with more emphasis being put on the role played by fungi in maintaining the integrity of ecosystems as bioindicators. In addition to that, this literature review aims to synthesize available literature with regard to the mycobiome, fungal functional groups, resilience of ecosystems, and conservation in urban areas by emphasizing key gaps that need further attention through future monitoring programs. The uniqueness of this literature review lies in its application within urban sustainability and global SDGs.

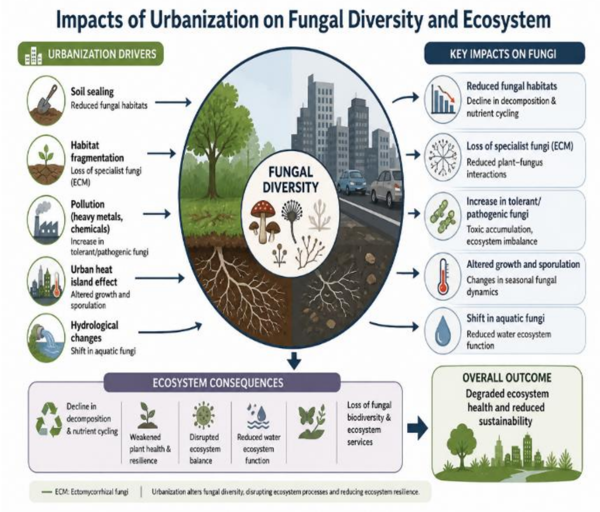
Urbanization and anthropogenic activities

The growth and life cycles of fungi are greatly affected by urbanization-induced factors such as urban heat islands, changing moisture levels, and increasing environmental temperatures. While moderate changes in temperature and humidity will help in the increase of fungi propagation, extreme changes in climate conditions may hinder fungal growth and their biological functions. Other man-made impacts, such as soil compression, habitat destruction, and the heavy application of fertilizers, also affect the survival of fungi. The breakdown of the mycorrhizal relationship will result in reduced ectomycorrhizal (ECM) richness and diversity. The disruption of such ecological relationships is an existing issue in fungal population stability and requires proper measures to address the concern. Another factor that will negatively affect the fungi populations includes biotic pressures, especially when harvesting edible fungi (Abarenkov et al., 2010; Ramos Irizarry et al., 2025).

Table 1: Impacts of Urbanization and Anthropogenic Disturbances on Fungal Diversity, Functional Guilds, and Ecosystem Functioning

Factor	Impact on Fungi	Ecosystem Consequences
Soil sealing	Reduced fungal habitats	Decline in decomposition & nutrient cycling
Habitat fragmentation	Loss of specialist fungi (ECM)	Reduced plant–fungus interactions
Pollution (heavy metals, chemicals)	Increase in tolerant/pathogenic fungi	Toxic accumulation, ecosystem imbalance
Urban heat island effect	Altered growth and sporulation	Changes in seasonal fungal dynamics
Hydrological changes	Shift in aquatic fungi	Reduced water ecosystem function

Figure 1: Pictorial representation of the impacts of urbanization on fungal diversity and the ecosystem



Patterns observed in urban and anthropogenic contexts

As fungal populations in different distant cities converge, biotic homogenization through urbanization also occurs. Just primarily human fungal range invasions and similar environmental filtering through pollution and soil compaction are primarily responsible for this. Airborne fungal assemblages are radically different in urban conditions, and the magnitude and uniformity of airborne spore emissions are totally different and uncharacteristic in the environment and quantity in the countryside. Human health, specifically in terms of allergy and pulmonary function, and also generally and ecologically on dispersion and plant fungi interaction levels, is radically affected. Regardless of this deterioration, parks and roadside tree pockets and regions of still existing vegetation are typical examples of urban pockets and biotopes that may comparatively be considered valuable refuge stations for fungal diversity. Local technical approaches on soil and soil preservation, host tree composition, and inter-physiological connectivity may specifically influence urban refuge stations and their fungal diversity value, utilization levels, and achievements (Calderon et al., 2019; Kumar et al., 2023).

Table 2: Functional Roles of Fungi in Ecosystem Processes, Nutrient Cycling, and Environmental Stability

Functional Group	Role	Ecosystem Service
Saprotrophic fungi	Decomposition of organic matter	Nutrient cycling, soil fertility
Mycorrhizal fungi (ECM & AM)	Symbiosis with plants	Nutrient uptake, stress tolerance
Pathogenic fungi	Disease regulation	Population control

Endophytic fungi	Host support	Stress resistance
Lichenized fungi	Bioindicators	Air quality monitoring
Pollutant-accumulating fungi	Bioremediation	Detoxification

Climate Change Urbanization Interaction

Climate change and urbanization have a significant influence on fungal diversity, composition, and the ecological processes in the urban environment. The development of heat islands through urbanization creates favorable conditions for temperature and moisture, causing stress in fungi and other organisms, thereby influencing their physiological processes (Zhang et al., 2025). Climate change factors such as droughts, unusual rainfall, and high levels of CO_2 in the atmosphere will be able to influence fungi and their interactions in the ecosystem. Ectomycorrhizal fungi are sensitive to drought and are unable to acquire nutrients for plants (Gehring et al., 2020). In comparison, there might be a rise in certain fungi species that thrive opportunistically and have the ability to withstand higher temperatures; therefore, higher temperatures in urban settings may favor their proliferation and would result in ecological homogenization and changes in the functioning of ecosystems (Li & Dong, 2025). In other words, climate change and urbanization must be considered together.

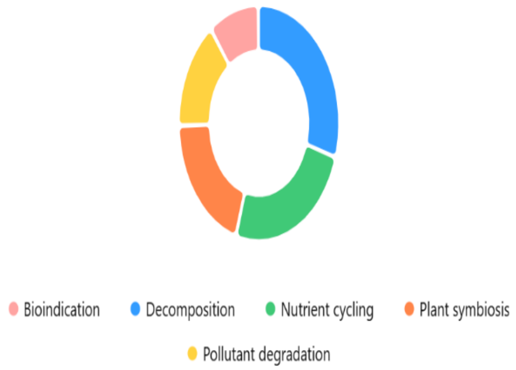
Functional Trait-Based Fungal Ecology

Fungal functional trait ecology investigates the adaptability of fungi to anthropogenic pressures, their resilience, and functionality is fungal functional trait ecology. Functional traits associated with fungi include decomposer abilities, stress tolerance, mode of nutrient uptake, morphology, and dispersal mechanisms, all of which have significance in determining the reactions of some species to changes in their environments as well as their roles in the processes occurring in the ecosystem (Li et al., 2025). It has been found that urbanization may alter the environmental filter, leading to the prevalence of fast-growing decomposers in disturbed areas at the expense of specialized mycorrhiza and symbionts (Averill et al., 2021).

Table 3: combined effects of climate change and urbanization on fungal diversity, ecosystem functioning, and ecological resilience in urban ecosystems.

Environmental Factor	**Impact on Fungal Communities**	**Ecological Consequences**
Urban heat islands	Increase in thermotolerant and stress-resistant fungi	Ecological homogenization and altered species composition
Habitat fragmentation	Reduction in ectomycorrhizal fungal diversity	Decline in nutrient exchange and ecosystem resilience
Drought stress	Disruption of mycorrhizal associations	Reduced plant adaptability and soil fertility
Pollution and land-use change	Dominance of opportunistic saprotrophic fungi	Altered decomposition and nutrient cycling

Figure 2: Major Ecological Functions and Ecosystem Services Provided by Fungal Communities in Urban Ecosystems.



Chronological development of ideas and methods:

The surveys involving fruiting bodies have provided us with basic information concerning the urban macromycetes; however, studies focusing on cryptic fungi, endophytic fungi, and non-fruiting fungi are still in their infancy (Abarenkov et al., 2010; Baldrian, 2017). Culture-based and microscopic methods have made contributions to soil fungi, air fungi, and indoor fungi; however, issues with unculturable taxa and morphological similarity among fungi have limited the effectiveness of this method (Edwards et al., 2025). New technologies in molecular methods, such as next-generation sequencing, eDNA, and metabarcoding, have been very helpful for the study of urban fungal biodiversity and urban to rural shift, especially the trend of specialist fungi and loss of functional diversity (Ooi et al., 2022; Authier et al., 2022). Yet, challenges like database references and marker biases persist. The advancement in aerosol sampling technology, functional traits, culturomics, and remote sensing provides new knowledge concerning the link between urban fungi and human health and predictions about fungal communities (Ferrari et al., 2019; Chen et al., 2023; Zari, 2014).

Fungi as bioindicators

Because of their rapid response to changes in soil chemistry, pollution, vegetation, and other environmental parameters, especially in urban areas, fungi are extremely sensitive indicators of changes in the environment. The fact that many fruiting bodies of macro-fungi are accessible allows observations by both professionals and amateurs, and modern molecular techniques such as DNA analysis/ITS metabarcoding enabled the detection of rare, non-fruiting fungal species (Authier et al., 2022). Fungal communities are very significant in ecological research due to their intense association with plant health and significant soil processes such as nutrient cycling and decomposition (Garcia, 2017; Mersal, 2016). However, seasonality, insufficiencies in fruiting-body surveys, fungal identification difficulties due to morphology, and fungal responses to environmental disturbance can cause complexities in monitoring fungal populations, including the setting of baseline ecological observations, and including molecular analysis techniques. In addition, comparisons of studies are constrained due to the lack of standard global guidelines, thus underlining the importance of coordination for joint monitoring efforts (Hernandez-Moreno, 2009; Oglu-Huseynov, 2011; Tobias et al., 2025).

Case studies

Symbiotrophic fungi, particularly mycorrhizal species essential for nutrient cycling and tree health, decline with increasing urbanisation, whereas saprotrophic and pathogenic fungi increase due to disturbed soils and altered environmental conditions. These changes influence plant communities and ecosystem functioning (Zeb et al., 2023; Yan et al., 2025). Urban environments also show higher concentrations of airborne fungal spores than surrounding areas, with seasonal variation and a shift toward allergenic taxa, raising concerns for ecosystem stability and public health. Airborne fungi further serve as bioindicators of air quality. Similarly, aquatic fungi, such as water hyphomycetes, reflect the ecological status of urban and peri-urban rivers and can complement macroinvertebrate-based indices for water quality assessment.

Despite their ecological importance, many global mycorrhizal fungal diversity hotspots lie outside protected areas, highlighting a major conservation gap. Integrating fungal diversity ("funga") into biodiversity conservation and land-use planning is therefore essential to ensure effective ecosystem protection and management (Wani et al., 2020; Razaq et al., 2014).

Linking fungal monitoring to ecosystem services and SDGs

Fungi participate in numerous ecological and socioeconomic factors contributing immensely to several Sustainable Development Goals (SDGs). While mycorrhizal fungi are involved in improving nutrient acquisition and plant stress tolerance and growth and crop yields improvement, non-cultivated edible fungi contribute immensely to improving livelihoods and providing food security in rural communities covered by SDG 2 (Zero Hunger) (Jansson and Hofmockel, 2020). While bioremediation methods mediated by fungi reduce human contact or exposure to environmental pollution and fungi in the air affecting human respiratory biology contribute immensely to SDG 3 (Good Health and Well-Being) (Tobias et al., 2025), SDG 6 (Clean Water and Sanitation) involves fungi-supportive green infrastructure increasing biodiversity in urban ecosystems and aquatic fungi involved in nutrient cycles acting as indicators of water quality (Mersal, 2016). While nature and fungus-inclusive urban ecosystem designs contribute immensely to improving carbon fixation in soils, climate rehabilitation, and biodiversity in urban ecosystems covered by SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) through urban nature-based designs (Garcia, 2017) and ecosystem rehabilitation through fungi (Zari, 2014), finally conserving various species of fungi to avoid biodiversity damage in terrestrial ecosystems covered by SDG 15 (Life on Land) on earth requires conservation and monitoring of various species of fungi on earth. New policies are rapidly advancing the integration to include "funga" in biodiversity indices. Practical measures requiring fungal inputs in sustainable goals include fungal indicators incorporated in the assessment of all SDGs, like assessments of soil health indexed under SDGs 2 and 13 on climate rehabilitation and biological assessments of biodiversity indexed under SDG 15 on Life on Land (Brandon and Lombardi, 2010; Devuyst, 2001).

Table 4: Contributions of Fungi and Fungal Ecosystem Services to United Nations Sustainable Development Goals (SDGs)

SDG	Contribution of Fungi
SDG 2 (Zero Hunger)	Enhance soil fertility and crop productivity
SDG 3 (Good Health)	Airborne fungi influence respiratory health
SDG 6 (Clean Water)	Aquatic fungi indicate water quality
SDG 11 (Sustainable Cities)	Support urban ecosystem resilience
SDG 13 (Climate Action)	Carbon cycling and sequestration
SDG 15 (Life on Land)	Biodiversity conservation

Fungal bio-monitoring framework for urban ecosystems: recommended approach

A well-established system of three-tiered monitoring could help achieve scalable and cost-effective fungal assessments in urban ecosystems. First, rapid season-based assessments of the fungi fruiting bodies with straightforward baseline data about the host, location, photos, and soil should be performed by professionals and citizen scientists (Ogola and Odhiambo, 2025). Second, ecological assessments of enzyme activity, decomposition speed, soil composition, pollution by metals, and airborne spore sampling should be conducted on urban and rural locations (Opaku, 2019). The third tier comprises more sophisticated approaches, such as long-term monitoring, experiments on microcosms, and biological studies for mapping hotspots (Ferrari et al., 2019). Utilization of all these three-tier approaches will lead to an increase in geographic coverage, participation of citizens, and standardization of data sets in climate change and biodiversity studies in the context of the UN's sustainable development goals. This approach will help set up the fungal indicator, like the Myco-Integrity Index, which includes community structure, functional groups, and biomonitoring of contaminants both globally and through citizen science (Kiran et al., 2021). In addition to that, new technologies, including global fungal mapping platforms such as Mushroom World and other international fungal databases, can enhance data sharing and ecological surveillance (Yaseen et al., 2020).

Table 5: Tiered Framework for Urban Mycobiome Monitoring, Assessment, and Ecosystem Evaluation

Tier	Approach	Key Activities
Tier 1	Rapid assessment	Mushroom surveys, basic metadata
Tier 2	Standard ecological analysis	Soil chemistry, enzyme activity, spore sampling
Tier 3	Advanced monitoring	Long-term studies, bioassays, and contamination mapping

Machine Learning and AI-Based Biodiversity Monitoring

Technological innovations in such fields as machine learning and artificial intelligence have introduced innovations in the process of assessment and monitoring of fungal biodiversity. The utilization of AI in assessing fungal species via image recognition, DNA metabarcoding, and classifying algorithms has made it easier for fungi detection and their identification (Hwang et al., 2025). Remote sensing and environmental modeling have also been used for assessing vegetation cover, habitat fragmentation, urban heat islands, and other environmental factors that impact fungi in urban settings (Pollock et al., 2026). Moreover, the use of AI in ecological modeling of the environment helps predict How climate change and urbanization would impact fungal communities.

Human Health and Aeromycology

The urban fungal population is strongly linked with public health in relation to aeromycological fungi spores and indoor fungi. As per the findings of the study conducted by Ahmed et al. 2023, some of the urban fungi, such as Aspergillus, Penicillium, Cladosporium, and Alternaria, have been found to cause respiratory allergies, asthma, chronic pulmonary disorders, and infections. Due to pollution levels in cities, excess humidity, poor ventilation, and environmental changes owing to global warming, fungal spore concentration and indoor fungi become very high, which pose serious threats to public health in urban areas. The exposure to fungi in urban residences, hospitals, and workplace environments is now emerging as an environmental health problem because of the threat they pose to individual immunity and respiratory health (Barnes et al., 2025).

Table 6: Summarizes recent technological approaches used in fungal biodiversity monitoring and ecological assessment in urban environments.

Technology	Application in Fungal Ecology	Ecological Importance
AI-assisted fungal identification	Automated fungal species recognition using image analysis and DNA metabarcoding	Improves monitoring accuracy and species detection
Remote sensing	Monitoring habitat fragmentation and urban heat islands	Assesses environmental drivers of fungal diversity
Predictive ecological modelling	Forecasting fungal responses to urbanization and climate change	Supports conservation and ecosystem management
Bioaerosol monitoring	Detection of airborne allergenic fungi	Urban air quality and public health assessment

Figure 3: highlights emerging AI-based applications used for fungal biodiversity assessment and ecological monitoring in urban environments.

Conservation, policy, and management implications

In policy texts, identify fungus. Protected area management, urban biodiversity planning, and environmental impact assessments must consider fungi through the "funga" approach. Host plant and habitat continuity conservation. Conserving native trees, remnant soils, and microhabitats is essential for maintaining mycorrhizal and macrofungal diversity. Urban planning for fungal health. By prioritizing native vegetation and soil health and minimizing soil compaction, green infrastructure design supports fungal population conservation. Pollution control and remediation. Using fungal biomonitoring to plan programs of mycoremediation and to delineate hotspots of contamination. Governance of harvest. By working with local populations in the planning of edible wild fungi harvests, the goal is to preserve livelihoods and species survival (Elabed et al., 2017).

Annexure (A)

Annexure (B)

11. Conclusions

Research carried out within the field of fungi shows that urbanization leads to a decrease in the number of species and adversely affects the diversity of specialist fungal communities such as ectomycorrhizal fungi and wood decomposers by promoting the dominance of generalist saprotrophs and allergenic fungi. It is explained by negative effects on the resilience of ecosystems resulting from disturbances in soil, plant-fungal interactions, and biogeochemical cycles. Fungi are highly valuable bioindicators for the monitoring of urban ecosystems; however, their application is not effective due to numerous difficulties, including the lack of long-term studies, seasonal fluctuations, geographical and taxonomic bias, insufficient literature, limitations related to fungi traits, and a lack of standardized methodologies. Therefore, harmonized and comprehensive long-term monitoring should be conducted to solve these issues. Moreover, the implementation of fungal indicators for urban management will contribute to meeting the Sustainable Development Goals, as it will be beneficial for human health and well-being, water resources availability, biodiversity preservation, and the provision of ecosystem services.

Author Contributions

Adeel Mustafa wrote the paper. Uzma Hanif reviewed the paper. Mehar Un Nisa, Hafiza Mehak Munawar, and Nayyab Munir assisted in writing the paper and collecting the data.

Conflict of Interest

The authors declare that they have no conflicts of interest related to the publication of this work.

Data Availability:

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

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Annexure (A)

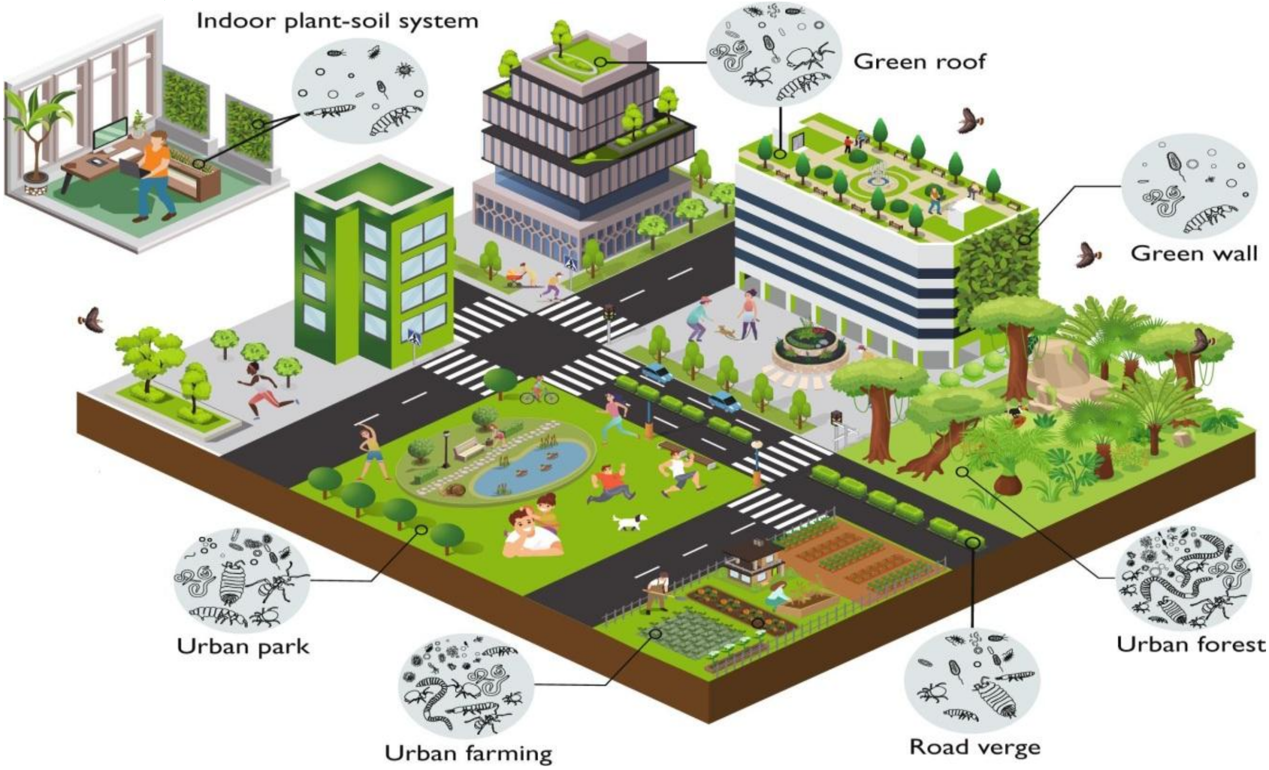

Figure 4: Soil is a primary reservoir of biodiversity in urban ecosystems (Sun et al., 2023).

Annexure (B)

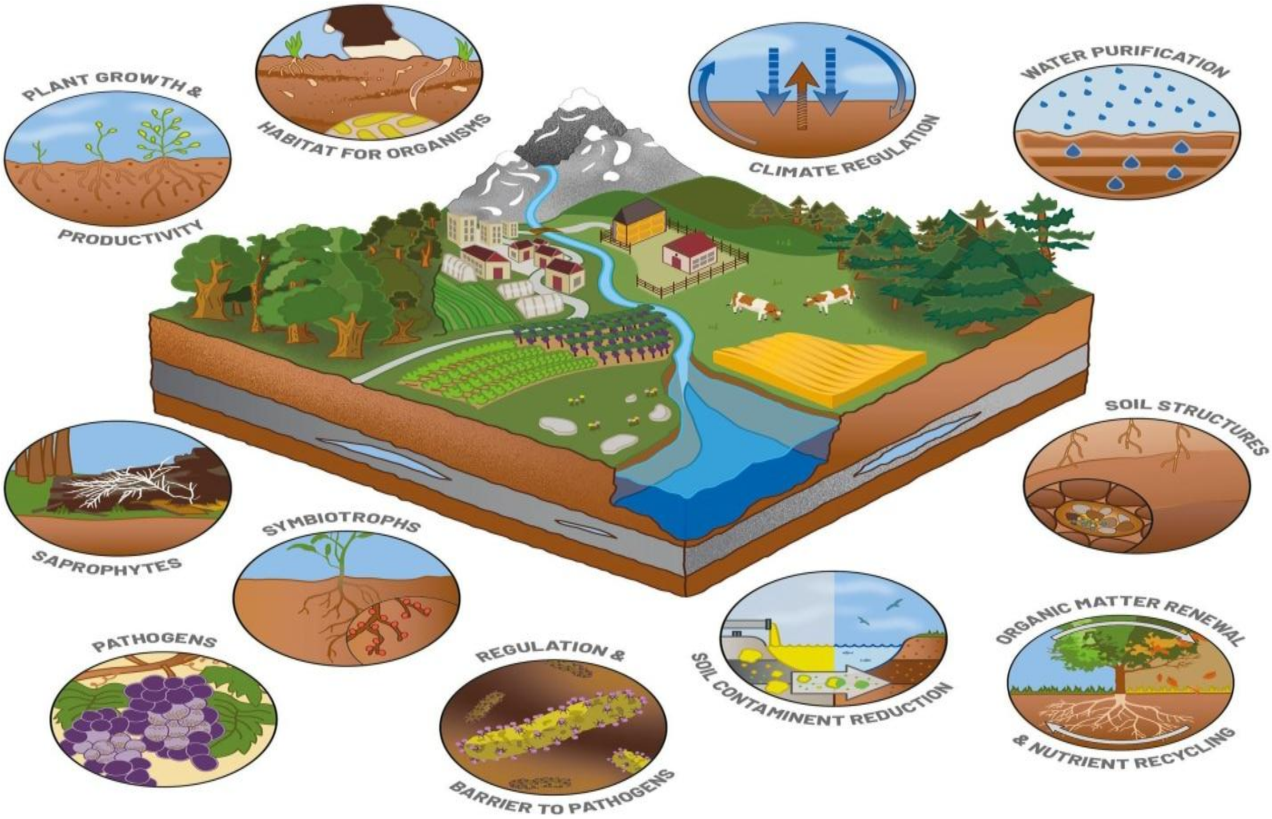

Figure 5: Illustration of the main roles of soil functions and microorganisms as essential players in various ecosystem services (Djemiel et al., 2022).