

Urban green infrastructure for insect functional diversity and standardised monitoring under global change

Urbana zelena infrastruktura za funkcionalnu raznolikost kukaca i standardizirano praćenje u uvjetima globalnih promjena

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ABSTRACT

Insects represent a fundamental component of biodiversity and play a crucial role in ecosystem functioning through pollination, biological pest control, decomposition, nutrient cycling, and soil formation. However, increasing evidence indicates widespread declines in insect abundance and diversity driven by climate change, habitat fragmentation, urbanisation, and intensive land use. This review synthesises current knowledge on the role of urban ecosystems and ecological infrastructure in supporting entomofaunal biodiversity. Urban green infrastructure contributes to entomofauna conservation through structurally complex vegetation, flower-rich habitats, native and drought-tolerant plant species, wildlife-friendly design, and water-related features, all of which enhance habitat availability, ecological connectivity, and functional biodiversity. The assessment of such systems is based on a broad spectrum of entomofauna monitoring methods, including traditional techniques such as the use of visual, food-based or sexual attractants, as well as molecular, digital, and automated approaches, including smart traps, computer vision, acoustic monitoring, and radar-based systems. The integration of the “citizen science” approach further expands spatial and temporal data coverage while strengthening connections between scientific research and society. By bringing these elements together, this review provides a coherent basis for integrated and multidisciplinary strategies that link ecological infrastructure, standardised long-term monitoring, biodiversity-friendly management, and public engagement, thereby supporting the maintenance of functional and resilient ecosystems under ongoing global change.

Keywords: ecological infrastructure, ecosystem services, entomofauna monitoring methods, functional biodiversity, urban ecosystems

SAŽETAK

Kukci predstavljaju temeljnu sastavnicu bioraznolikosti te imaju ključnu ulogu u funkcioniranju ekosustava kroz oprašivanje, biološku regulaciju štetnika, razgradnju organske tvari, kruženje hranjiva i promjenama fizikalno-kemijskih svojstava tla. Međutim, sve je više dokaza o izraženom padu brojnosti i raznolikosti kukaca, potaknutom klimatskim promjenama, fragmentacijom staništa, urbanizacijom i intenzivnom obradom tla. Ovaj pregledni rad obuhvaća postojeće spoznaje o ulozi urbanih ekosustava i ekološke infrastrukture u potpori bioraznolikosti entomofaune. Urbana zelena infrastruktura doprinosi očuvanju entomofaune putem strukturno složene vegetacije, cvjetno bogatih staništa, autohtonih i na sušu otpornih biljnih vrsta, dizajna prilagođenog divljim organizmima te vodenih elemenata, čime se povećava dostupnost staništa, ekološka povezanost i funkcionalna bioraznolikost. Procjena takvih sustava temelji se na širokom spektru metoda praćenja entomofaune, koje obuhvaćaju tradicionalne tehnike poput korištenja vizualnih, hranidbenih ili seksualnih atraktanata, kao i molekularne, digitalne i automatizirane pristupe, uključujući pametne

lovke, računalni vid, akustični nadzor i radarske sustave. Uključivanje pristupa “građani znanstvenici” dodatno proširuje prostorni i vremenski obuhvat prikupljanja podataka te jača povezanost znanstvenih istraživanja i društva. Objedinjavanjem navedenih elemenata, ovaj pregledni rad pruža koherentnu podlogu za integrirane i multidisciplinarnе strategije koje povezuju ekološku infrastrukturu, standardizirano dugoročno praćenje, upravljanje prilagođeno bioraznolikosti i aktivno uključivanje javnosti, čime se podupire očuvanje funkcionalnih i otpornih ekosustava u uvjetima trajnih globalnih promjena.

Ključne riječi: ekološka infrastruktura, ekosustav, metode praćenja entomofaune, funkcionalna bioraznolikost, urbani ekosustavi

INTRODUCTION

Biodiversity represents a fundamental prerequisite for ecosystem stability and functionality, as it underpins key ecological processes and interactions among organisms and their environment (Morse, 2017). In terrestrial ecosystems, insects constitute the dominant component of biological diversity and play a role in maintaining ecosystem processes, including pollination, biological pest regulation, organic matter decomposition, nutrient cycling, and soil formation (Weisser and Siemann, 2008). Owing to their high diversity, abundance, and sensitivity to environmental change, insects are widely recognised as contributors to ecosystem resilience and sustainability (Morse, 2017).

Despite their ecological and economic importance, a continuous decline in insect abundance and diversity has been documented over recent decades. This decline has been associated with multiple, often interacting drivers, including habitat loss and fragmentation, agricultural intensification, pesticide use, climate change, urbanisation, and environmental pollution (Skendžić et al., 2021; Abassi, 2025). Climate change, in particular, has emerged as a major pressure on entomofauna, as rising temperatures and altered precipitation patterns directly affect insect development, phenology, and survival. Over the last 50 years, atmospheric carbon dioxide concentrations have increased substantially, contributing to global temperature rise and placing additional stress on insect populations and the ecosystems they support (Abir et al., 2018; Skendžić et al., 2021).

Urbanisation is one of the most pronounced forms of land-use change at the global scale and has traditionally been viewed as a significant threat to biodiversity. Ur-

ban environments are characterised by extensive grey infrastructure, habitat fragmentation, altered microclimatic conditions, soil sealing, and simplified vegetation structure, all of which negatively affect insect communities (Li et al., 2017). Additional pressures, such as artificial lighting, intensive management of green spaces, and the frequent use of chemical inputs, further contribute to biodiversity loss and biotic homogenisation in cities (Theodorou, 2022).

Nevertheless, recent research increasingly highlights the potential of urban areas to support substantial levels of biodiversity when ecological principles are integrated into spatial planning and management. The conservation and restoration of urban biodiversity have therefore become integral components of broader sustainability strategies, particularly within the framework of European environmental policy (Lanzas et al., 2019). The European Union has recognised biodiversity loss as a critical challenge and has addressed it through strategic documents such as the EU Biodiversity Strategy for 2030 (European Commission, 2020), which emphasises the need to improve monitoring systems, protect species and habitats, and integrate ecological infrastructure into urban and agricultural landscapes (Köninger et al., 2021).

Urban green and ecological infrastructure is increasingly recognised as a key tool for mitigating biodiversity loss and enhancing ecosystem functionality in cities. By conserving and reconnecting fragmented habitats, ecological infrastructure supports species persistence, dispersal, and gene flow, while simultaneously maintaining ecosystem services and socio-economic benefits (Lanzas et al., 2019). In this context, cities may function not only as centres of anthropogenic pressure but also as refuges

and stepping-stone habitats for insects, particularly in highly fragmented landscapes.

Given the documented drivers of insect decline and the growing importance of urban environments, systematic monitoring of entomofauna has become essential. Reliable and timely data on insect diversity and population trends are necessary for the development and implementation of effective conservation measures. A wide range of traditional and modern monitoring methods is currently employed, including visual and pheromone traps, molecular techniques such as DNA barcoding, and emerging digital technologies, all of which contribute to improved understanding of insect biodiversity patterns and responses to environmental change (Weisser and Siemann, 2008). In the context of accelerating global change, understanding biodiversity patterns and processes represents a fundamental prerequisite for assessing ecosystem resilience and informing sustainable management strategies.

To ensure a structured and integrative synthesis, this review follows a narrative-integrative approach aimed at analysing current knowledge on the relationship between urban ecological infrastructure, functional insect diversity, and entomofauna monitoring under global change. The literature was selected using major scientific databases, including Web of Science, Scopus, and Google Scholar, with combinations of keywords such as “urban green infrastructure”, “urban ecological infrastructure”, “insect biodiversity”, “functional diversity”, “entomofauna monitoring”, “pollinators”, “biological control”, “citizen science”, and “global change”. Priority was given to peer-reviewed publications addressing urban ecosystems, insect functional groups, ecological infrastructure, and monitoring methods, while earlier seminal works and policy-related documents were included where relevant. The selected literature was analysed thematically to identify links among urban ecological infrastructure elements, functional insect groups, ecosystem services, and monitoring approaches. Accordingly, the review is structured around three main components: (i) key drivers of insect decline, (ii) the role of urban ecological infra-

structure in supporting functional insect diversity, and (iii) monitoring approaches required for evaluating and improving biodiversity-friendly urban management.

BIODIVERSITY AND FUNCTIONAL DIVERSITY OF INSECTS

Biodiversity, derived from the term “biological diversity”, became widely used in the mid-1980s in response to increasing concerns about environmental degradation (Lévêque and Mounolou, 2004). It encompasses genetic diversity within species, species diversity, ecosystem diversity, and the interactions among organisms and their environment. The concept was further formalised through international frameworks such as the Convention on Biological Diversity, which emphasises conservation, sustainable use, and equitable benefit-sharing (Herczeg, 2013). From an ecological perspective, biodiversity underpins ecosystem functioning by maintaining key processes such as pollination, nutrient cycling, climate regulation, and soil formation (Weisser and Siemann, 2008). These processes support ecosystem stability, resilience, and the provision of ecosystem services essential for human well-being. Biodiversity is closely linked to human activities, both as a result of anthropogenic pressures such as habitat destruction, pollution, and land-use change, and through conservation efforts aimed at mitigating these impacts (Lévêque and Mounolou, 2004). Insects (Insecta) represent one of the most diverse and functionally important groups of organisms in terrestrial ecosystems, accounting for a substantial proportion of described animal species (Treer and Tucak, 2004). Their ecological importance is reflected in their involvement in multiple ecosystem functions, including pollination, biological pest control, decomposition, and nutrient cycling (Lazar, 2022; Weisser and Siemann, 2008). Due to their high diversity, abundance, and sensitivity to environmental change, insects play a key role in maintaining ecosystem stability and are widely recognised as indicators of environmental conditions (Morse, 2017). Scientific evidence indicates a global decline in insect abundance and diversity, driven by multiple interacting pressures, including climate change, habitat loss, and land-use in-

tensification (Skendžić et al., 2021; Harvey et al., 2020; Abir et al., 2018). As ectothermic organisms, insects are particularly sensitive to temperature, which regulates their physiology, behaviour, geographic distribution, and number of generations per year (voltinism), resulting in shifts in species ranges and changes in community composition under changing climatic conditions (Harvey et al., 2020; Skendžić et al., 2021; Lazar, 2022).

Among ecosystem services, pollination is one of the most important, with approximately 35% of global crop production dependent on insect-mediated processes (Getanjaly et al., 2015). In addition to pollinators, predatory and parasitoid insects contribute to biological pest control, while soil-dwelling taxa such as springtails (Collembola), ground beetles (Carabidae), and rove beetles (Staphylinidae) support soil formation, nutrient cycling, and overall soil health (Bažok et al., 2015; Maceljski, 2002). Certain groups, such as ground beetles, are also widely used as bioindicators of habitat quality and environmental contamination (Holland, 2002; Viric Gasparic et al., 2025). In this context, increasing attention is given to functional diversity, which reflects the range of ecological roles performed by organisms and their contribution to ecosystem processes. Unlike taxonomic diversity, functional diversity provides a more direct link to ecosystem functioning and allows for a more comprehensive assessment of ecological resilience, particularly under conditions of environmental change.

The conservation of insect biodiversity, therefore, requires integrative approaches that consider both taxonomic and functional dimensions, as well as their interactions with environmental drivers across spatial and temporal scales. In landscapes subject to intensive land use and urbanisation, maintaining functionally diverse insect communities is essential for sustaining ecosystem processes and services. Despite their ecological importance and functional versatility, insect populations are increasingly exposed to multiple anthropogenic pressures that threaten their diversity and long-term persistence, with potential cascading effects on ecosystem functioning and stability. Importantly, these functional groups do

not respond equally to environmental pressures, and their relative representation can shift depending on habitat structure, management intensity, and resource availability (Weisser and Siemann, 2008; Harvey et al., 2020). As a result, changes in functional composition may have more direct implications for ecosystem functioning than changes in species richness alone, highlighting the importance of integrating functional perspectives into biodiversity assessment.

Threats to entomofaunal biodiversity

Biodiversity and its changes are inevitably linked to anthropogenic pressures. Through various forms of land use, resource exploitation, and environmental modification, humans exert the most significant influence on the biosphere, and these activities represent the primary source of negative factors threatening other organisms. Numerous studies have documented a continuous global decline in biodiversity (Butchart et al., 2010; Wu, 2010; Hallmann et al., 2017; Rhodes, 2019).

The loss of plant species reduces primary production, which in turn affects carbon and nitrogen cycles and ultimately undermines the stability of entire ecosystems (Allan et al., 2013). Alongside population growth and economic development, increasing pressure is placed on natural resources, resulting in land-use change, deforestation, and agricultural intensification (Orešković, 2015).

Insects, as the most numerous and diverse group of animals, are particularly affected by these changes. As illustrated in Figure 1, these pressures do not act independently but interact across multiple scales, leading to simultaneous declines in abundance, species richness, and functional diversity, with cascading effects on ecosystem services. Although global environmental change does not affect all species equally, significant declines have been recorded in numerous insect groups, including pollinators, decomposers, and predators, as confirmed by recent studies (Didham et al., 2020). Climate change represents one of the most serious contemporary threats, with effects including range shifts, disrupt

tions in voltinism, physiological stress, and changes in population dynamics. Although insects exhibit a high degree of adaptability, extreme weather events and rising temperatures disrupt their development, metabolism, and reproduction (Harvey et al., 2023).

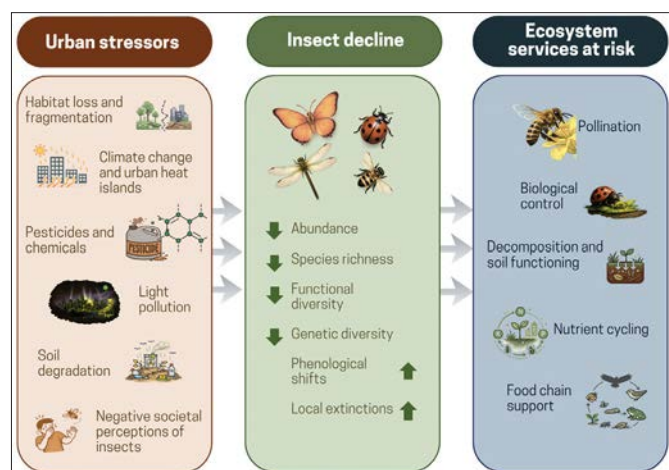


Figure 1. Conceptual representation of urban stressors affecting entomofauna and associated ecosystem services (Sandra Skendžić)

Long-term monitoring conducted in the Netherlands provides a clear example of these trends. Hallmann et al. (2020) reported declines of 40–60% in abundance and biomass of moths and beetles following decades of systematic monitoring of terrestrial and aquatic insects. Although not all species were equally affected, the results indicate that land use and management practices exert a strong influence on insect community structure.

Anthropogenic pressures are also reflected in societal perceptions of insects. Despite their ecological roles, insects are often perceived as unpleasant, dangerous, or harmful organisms (Nash, 2004). Such negative perceptions reduce public awareness of their importance and hinder the implementation of conservation measures. Samways et al. (2020) therefore emphasise the need to develop a “psychology of insect conservation”, an approach that promotes understanding and protection of insects through education and societal change. This social dimension further interacts with ecological drivers by shaping management decisions and conservation priorities.

Habitat loss and fragmentation further contribute to species decline, particularly in tropical regions where entomofaunal diversity is exceptionally high and a large proportion of species remains scientifically undescribed (Pires and Maués, 2020). In temperate regions, intensive pesticide use, nitrogen pollution, and soil degradation substantially affect the stability of insect communities.

Entomofauna is also highly sensitive to changes in the atmosphere, soil, and water. The effects of environmental stressors may be additive, synergistic, or antagonistic, depending on the combination of factors involved. For example, increased vegetation cover can induce microclimatic cooling that mitigates warming effects, whereas habitat fragmentation can negate the benefits of otherwise favourable climatic conditions (Pires and Maués, 2020). These interactions highlight that environmental pressures rarely act independently, but rather through complex feedbacks.

Finally, temperature increases exceeding the optimal range for a given species may result in a series of adverse effects, including developmental disturbances, reduced fertility, impaired dispersal capacity, increased mortality, and overall declines in population fitness (Harvey et al., 2023). Owing to these interlinked threats, the conservation of entomofauna requires a multidisciplinary and integrated approach.

These interacting pressures highlight that changes in insect communities are not driven by single factors, but by complex combinations of environmental and anthropogenic drivers, which complicates both prediction and management of biodiversity responses.

In response to these interconnected ecological and societal pressures, the European Union adopted the Biodiversity Strategy for 2030 as part of the European Green Deal (European Commission, 2019), with the overarching goal of achieving climate neutrality by 2050. The strategy proposes the protection of at least 30% of EU land and sea areas, restoration of degraded ecosystems, and a 50% reduction in pesticide use by 2030. Particular emphasis is placed on sustainable soil management and agroecological practices within the Common Agri-

cultural Policy, including regenerative agriculture and the conservation of pollinator habitats. Despite progress, studies indicate that only one third of EU Member States systematically address threats to soil biodiversity, underscoring the need for stronger integration of soil protection into EU legislation (Köninger et al., 2022; European Commission, 2013). These policy measures provide a framework for addressing the multiple pressures acting on entomofaunal biodiversity. However, the effectiveness of these policy measures depends on their practical implementation and integration with locally adapted management strategies.

Entomofauna in urban environments

Urbanisation is recognised as one of the major global drivers of biodiversity loss, with particularly pronounced effects on entomofauna, a group that is highly sensitive to environmental change (Theodorou, 2022). Urban environments, characterised by high human population density and extensive impervious surfaces, are associated with habitat fragmentation and reduced availability of natural habitats, resulting in reduced insect abundance and diversity (Theodorou, 2022). Changes in land use, light pollution, pesticide application, and the loss of food resources further exacerbate stress on numerous insect groups. For example, many firefly species (family Lampyridae) are declining due to urbanisation, while populations of solitary bees are negatively affected by the loss of suitable nesting substrates and limited floral resources. In contrast, some eusocial bees, such as bumblebees, have shown a degree of adaptation to urban environments by exploiting buildings as alternative nesting sites (Butchart et al., 2010; Sánchez-Bayo and Wyckhuys, 2021).

Urban green spaces, including parks, tree-lined streets, roadside grasslands, and green roofs, can support insect populations; however, their ecological value depends on vegetation quality, resource availability, and microclimatic conditions. In this context, Nature-based Solutions (NBS), defined as interventions that use natural processes to address environmental and societal

challenges, are increasingly applied to support urban biodiversity (Cohen-Shacham et al., 2016).

In addition to supporting entomofauna, these measures provide multiple co-benefits by improving air quality, regulating temperature, reducing noise, and enhancing the aesthetic value of urban environments, thereby positively influencing human health and well-being (Marselle et al., 2021). Despite the promotion of biodiversity integration within urban planning at global and European levels, including frameworks such as the Convention on Biological Diversity and the European Green Deal, local authorities often face limited resources and varying capacities for implementation. Consequently, the importance of locally adapted strategies, interdisciplinary collaboration, and public education on the ecological roles of insects is increasingly emphasised.

At the level of the European Union, certain measures within the Common Agricultural Policy also include agri-environmental interventions relevant to urban and peri-urban areas, such as flower strips designed to support pollinators, predators, and parasitoids, thereby contributing to increased entomofaunal biodiversity and ecological stability (Kowalska et al., 2022). However, the effectiveness of urban green spaces varies considerably depending on their design, management, and spatial configuration, highlighting that not all urban habitats contribute equally to entomofaunal biodiversity. As urban expansion continues and climate change further intensifies environmental stressors affecting insects, the conservation of entomofaunal biodiversity in cities is becoming an increasingly significant challenge, as well as a responsibility, in the planning of sustainable and resilient urban spaces.

ECOLOGICAL INFRASTRUCTURE IN URBAN ENVIRONMENTS

More than half of the global population currently lives in cities, and this proportion is expected to reach 60% by 2030 (Zhang, 2016). The expansion of urban infrastructure, including transport networks, energy systems, and drainage systems, often occurs at the expense

of natural habitats, contributing to fragmentation and reduced ecological resilience (Li et al., 2017). To mitigate these effects, the concept of green infrastructure has been developed, referring to the integration of natural and semi-natural elements such as parks, urban forests, green roofs, and water bodies within urban areas. These elements support entomofauna by providing resources for feeding, reproduction, and overwintering (Li et al., 2017). However, their ecological effectiveness depends on design and management, as intensively maintained green spaces may also have negative impacts, including eutrophication and the spread of invasive species.



Figure 2. Indoor urban green infrastructure integrated into a public transport hub, providing vegetation-based ecosystem functions (Ivana Pajač Živković, Atocha Tropical Garden, Madrid, Spain)

The concept of urban ecological infrastructure (UEI) extends this approach by emphasising not only structural elements but also the ecological processes they support, such as nutrient cycling and organic matter decomposition (Childers et al., 2019). UEI includes a wide range of

interconnected elements, from large parks to small-scale features such as residential gardens and green roofs, with a key requirement being the integration of structural and functional roles.

Given projections that up to 80% of the global population will live in cities by 2050, urban ecological infrastructure represents a critical opportunity for integrating biodiversity conservation into urban development (Childers et al., 2019). Its implementation enables the design of resilient and multifunctional urban systems that support both human well-being and insect-mediated ecosystem functions (Figure 2).

Supporting functional insect groups

Pollination represents one of the most important ecosystem services at the global scale, supporting both agricultural production and ecosystem functioning. Insect pollinators enable plant reproduction and genetic exchange, thereby maintaining plant diversity and ecosystem stability (Gill et al., 2016). Urban environments are increasingly recognised as important habitats for pollinators, as green spaces can provide diverse floral resources, nesting sites, and microhabitats. When appropriately designed and managed, urban areas may sustain pollinator diversity comparable to surrounding rural landscapes (Braman and Griffin, 2022). However, pollinators face multiple pressures in urban environments, including habitat fragmentation, intensive management, chemical inputs, and climate-driven phenological mismatches (Skendžić et al., 2021). Additional stressors such as pathogens and competition with non-native species further contribute to population declines (Hane and Korfmacher, 2022).

Beyond pollinators, functional biodiversity includes predatory, parasitoid, and decomposer insects that contribute to ecological regulation and nutrient cycling. These groups depend on structurally complex vegetation, resource continuity, and the presence of organic matter, highlighting the importance of habitat heterogeneity and reduced disturbance for sustaining functional insect diversity (Weisser and Siemann, 2008).

Structural and management elements of urban ecological infrastructure

The capacity of urban environments to support entomofaunal biodiversity largely depends on the structural characteristics and management of green spaces. Ecological infrastructure that incorporates spatial heterogeneity, diverse vegetation layers, and continuity of resources throughout the year provides substantially greater ecological value than simplified or intensively managed green areas. Supporting pollinators and other functional insect groups therefore requires an integrated approach that combines habitat provision, reduced disturbance, and informed management practices. The incorporation of such ecological infrastructure into urban planning offers a practical pathway for sustaining insect-mediated ecosystem services and mitigating biodiversity loss under conditions of increasing urbanisation and environmental change (Gill et al., 2016; Braman and Griffin, 2022). While individual elements of urban ecological infrastructure contribute differently to insect biodiversity, their relative importance depends on ecological function, spatial scale, and management context. Some elements primarily support resource availability (e.g. flower-rich habitats), whereas others enhance connectivity (e.g. linear vegetation and tree networks) or provide critical microhabitats (e.g. dead wood and artificial nesting structures). Therefore, their effectiveness should be evaluated comparatively and in relation to specific functional groups and environmental conditions. Accordingly, the prioritisation of urban ecological infrastructure elements should be context-dependent and guided by site-specific biodiversity assessments, as different elements support different functional groups and ecological processes. Table 1 provides a comparative overview of the main urban ecological infrastructure elements according to their ecological roles, supported functional insect groups, and key limitations. The following subsections further elaborate these categories and discuss how individual elements contribute to entomofaunal biodiversity under different urban and management contexts.

Linear and structurally complex vegetation elements

Linear and structurally complex vegetation elements, such as hedgerows, shrub belts, and vegetated strips, represent components of ecological infrastructure due to their capacity to support diverse arthropod communities. Increased vertical and horizontal vegetation complexity provides a greater range of microhabitats and resources, benefiting both pollinators and natural enemies of pests. Structurally heterogeneous vegetation enhances arthropod abundance and diversity, thereby strengthening ecological regulation processes. The ecological effectiveness of these elements is strongly influenced by management intensity, as simplified vegetation structures reduce habitat suitability, while structurally diverse, low-disturbance management promotes functional biodiversity. Consequently, linear vegetation elements should be considered functional components of urban ecological infrastructure rather than purely aesthetic features (Rosas-Ramos et al., 2019).

Urban trees, tree-lined streets and vertical greening

Urban trees and tree-lined streets constitute key structural elements of urban ecological infrastructure, contributing to habitat availability and ecological connectivity in highly fragmented urban landscapes. Functioning as linear corridors or “green arteries”, these elements facilitate insect movement between isolated green spaces and enhance landscape-scale connectivity, particularly in densely built environments where continuous natural habitats are limited (Aronson et al., 2017).

Empirical studies indicate that tree-lined streets can support high insect abundance and species richness when vegetation structure is sufficiently complex. Urban green spaces combining tree canopies with shrub and herbaceous layers harbour greater invertebrate biomass and diversity than simplified plantings, owing to increased habitat heterogeneity and microclimatic buffering (Goddard et al., 2010). Tree-associated structures such as bark, leaves, and epiphytes provide feeding, breeding, and refuge sites for a wide range of arthropod taxa.

Table 1. Comparative overview of urban ecological infrastructure elements and their roles in supporting entomofaunal functional diversity

Urban ecological infrastructure element	Ecological role	Supported functional insect groups	Key limitations/ constraints	References
Flower-rich habitats (meadows, strips, green walls)	Resource provision (nectar, pollen), temporal continuity of food	Pollinators, some natural enemies	Limited nesting/ overwintering sites if isolated; dependent on management	Baldock et al., 2019; Tschumi et al., 2016; Dicks et al., 2015
Linear and structurally complex vegetation (hedgerows, strips)	Habitat connectivity, structural heterogeneity	Pollinators, predators, parasitoids	Effectiveness depends on management intensity and spatial continuity	Rosas-Ramos et al., 2019
Urban trees and vertical greening	Connectivity, microclimatic buffering, habitat provision	Multiple functional groups (pollinators, herbivores, predators)	Requires long-term planning; effectiveness depends on species selection and configuration	Goddard et al., 2010; Aronson et al., 2017
Wildlife-friendly design and microhabitats (dead wood, insect hotels)	Nesting and overwintering sites, life-cycle completion	Solitary bees, parasitoids, saproxylic insects	Limited spatial extent; requires proper design and maintenance	Gaston et al., 2005; Davies et al., 2009; Liu et al., 2024
Rain gardens and water-related elements	Water regulation, microclimate, habitat heterogeneity	Moisture-dependent taxa, pollinators, generalist insects	Effectiveness depends on design and hydrological conditions	Burszta-Adamiak et al., 2023; Jia et al., 2016
Urban orchards	Multifunctional (resources, habitat, cultural services)	Pollinators, predators, decomposers	Management-dependent; variable intensity affects outcomes	Rada et al., 2022, 2023; Liu et al., 2024
Native and drought-tolerant vegetation	Resource continuity, climate resilience	Pollinators, herbivores, generalist insects	Limited availability in urban planning; slower establishment	Gómez-Baggethun and Barton, 2013; Matias et al., 2025
Management practices (low mowing, reduced chemicals)	Regulation of habitat quality and disturbance	All functional groups	Requires policy support and changes in management practices	Muratet and Fontaine, 2015; Watson et al., 2020; de Montaigne and Goulson, 2023

The ecological value of urban trees is strongly influenced by species selection and spatial configuration. Native tree species and spatially connected arrangements (rows or clusters) are more effective in supporting native insect communities than isolated ornamental plantings. Vertical greening systems, including green walls (Figure 3) and vegetated facades, can further increase habitat complexity and complement ground-level vegetation, particularly in densely urbanised areas, when integrated into broader green networks (Goddard et al., 2017).

Overall, urban trees, tree-lined streets, and vertical greening should be regarded as functional components of ecological infrastructure rather than aesthetic elements. Their contribution to entomofaunal biodiversity depends on vegetation diversity, structural complexity, and spatial connectivity, which together determine their

effectiveness in supporting insect populations and enhancing the resilience of urban ecosystems (Goddard et al., 2010; Aronson et al., 2017).

Flower-rich habitats and continuity of floral resources

Flower-rich habitats and vertical green walls (Figure 4) constitute a functional component of urban ecological infrastructure, as the diversity, abundance, and temporal continuity of nectar, pollen, and shelter resources contribute to the persistence of beneficial insect communities in fragmented urban landscapes. Well-designed urban wildflower meadows and flowering strips can support pollinator abundance and species richness comparable to semi-natural habitats, even at small spatial scales, provided that flowering resources are available throughout the growing season (Baldock et al., 2019).



Figure 3. Green wall integrated into a building façade as a vertical greening system, increasing structural habitat complexity and contributing to urban ecological infrastructure by supporting insect habitat availability in densely built environments (Ivana Pajač Živković, Madrid, Spain)



Figure 4. Flower-rich urban habitat illustrating the role of flowering strips and ornamental plantings in supporting pollinators in fragmented urban landscapes (Helena Viric Gasparic, El Retiro, Madrid, Spain)

Continuity of floral resources is particularly important for pollinator species with extended or multiple activity periods. Species-rich flowering strips composed of plants with staggered blooming phenology enhance pollinator visitation rates and simultaneously support natural enemies, thereby contributing to biological pest control and functional biodiversity (Tschumi et al., 2016).

Certain plant species provide disproportionate ecological benefits by supporting insects across multiple life stages and seasonal bottlenecks. The common nettle (*Urtica dioica* L.) is a well-documented example, as it serves as a larval host plant for several butterfly species and also provides habitat for predatory and saprophagous insects, thereby increasing overall habitat value (Barić and Pajač Živković, 2020). In contrast, ivy (*Hedera helix* L.), as a late-flowering species, plays a complementary role by

providing a valuable source of nectar and pollen in late autumn, when other floral resources are scarce, thereby supporting diverse pollinator assemblages in urban and semi-natural habitats (Antić, 2025).

The effectiveness of flower-rich habitats depends strongly on management practices. Reduced mowing, avoidance of chemical inputs, and maintenance regimes that allow plants to complete their flowering cycles enhance resource availability and reproductive success of insects. When implemented as permanent or semi-permanent elements of urban ecological infrastructure, flower-rich habitats contribute to pollinator resilience and the sustained provision of ecosystem services in cities (Baldock et al., 2019; Tschumi et al., 2016). Compared to structurally complex woody vegetation, flower-rich habitats primarily enhance resource availability for polli-

nators but may provide comparatively limited nesting or overwintering opportunities if not combined with other habitat elements (Dicks et al., 2015; Božek et al., 2023).

Native and drought-tolerant vegetation in urban ecosystems

The selection of plant species strongly influences the ecological functionality and long-term sustainability of urban green infrastructure. In Mediterranean urban environments, where high temperatures and prolonged summer droughts are common, the use of native and drought-tolerant vegetation is particularly important for maintaining ecosystem performance under water-limited conditions (Matias et al., 2025). Native species, adapted to local climatic and soil conditions, provide high-quality habitat and food resources for native fauna, including pollinators and other beneficial insects, reflecting long-term coevolutionary relationships and offering greater functional value than ornamental or exotic plantings (Gómez-Baggethun and Barton, 2013).

Deep-rooted, perennial, and structurally diverse native vegetation enhances urban resilience by improving soil stabilization, moderating microclimatic extremes, and reducing irrigation demand. By supplying nectar, pollen, fruits, seeds, and shelter, such vegetation supports the continuity of plant-insect interactions and stabilizes entomofaunal communities during periods of environmental stress, thereby reducing the risk of population bottlenecks and local extinctions under drought conditions (Gómez-Baggethun and Barton, 2013). Representative drought-tolerant native plant species include: *Quercus ilex* L., *Arbutus unedo* L., *Ceratonia siliqua* L., *Phillyrea latifolia* L., *Olea europaea* var. *sylvestris* (Mill.) Lehr, *Cistus* spp., *Lavandula angustifolia* Mill., *Rosmarinus officinalis* L., *Thymus vulgaris* L., *Salvia officinalis* L., *Helichrysum italicum* (Roth) G. Don, *Verbascum* spp., *Achillea millefolium* L., *Festuca* spp., *Poa* spp., and *Brachypodium retusum* (Pers.) P. Beauv. The integration of native and drought-adapted plant species into urban green systems therefore represents an effective strategy for enhancing biodiversity, increasing climate resilience, and supporting sustainable urban landscape management (Gómez-Baggethun and Barton, 2013; Matias et al., 2025).

Wildlife-friendly design and microhabitat provision

Wildlife-friendly design enhances urban entomofaunal biodiversity by compensating for the loss of natural microhabitats caused by intensive management practices, particularly the removal of dead wood and leaf litter (Hane and Korfmacher, 2022; Ferlauto and Burghardt, 2025). The retention of decaying organic material and the incorporation of artificial nesting structures, such as insect hotels within parks (Figure 5), rooftops, and building facades, provide essential nesting and overwintering sites for insects. The effectiveness of these measures depends on appropriate design and placement, including sunny and sheltered locations, the use of natural, untreated materials, integration with flower-rich vegetation, and periodic cleaning and monitoring to maintain functionality and limit pathogen accumulation (Hane and Korfmacher, 2022; Ferlauto and Burghardt, 2025).



Figure 5. Example of wildlife-friendly design in urban ecological infrastructure: Artificial nesting structure ("insect hotel") used as a supplementary microhabitat in urban green spaces (Ivana Pajač Živković, Sveti Ivan Zelina, Croatia)

Compared to larger vegetation-based elements of urban ecological infrastructure, microhabitat features operate at smaller spatial scales but fulfil distinct and non-substitutable ecological functions. They directly support critical stages of insect life cycles by providing nesting substrates, overwintering refugia, and protection from environmental stressors, which are often not adequately supplied by structurally simplified green spaces. In this context, their ecological importance is disproportionate to their spatial extent, as even small-scale features can significantly influence local population persistence and community composition, particularly in fragmented urban environments (Gaston et al., 2005; Davies et al., 2009; Liu et al., 2024). When implemented as part of integrated urban ecological infrastructure rather than as isolated interventions, microhabitat provision supports insect life cycles and contributes to the ecological functionality of urban green spaces.

Rain gardens and water-related elements

Rain gardens are shallow, vegetated depressions designed to collect stormwater runoff from impervious surfaces, such as roofs, sidewalks, and roads, allowing water to temporarily pond and gradually infiltrate into the soil. As multifunctional elements of urban ecological infrastructure, they mitigate altered urban water cycles by reducing peak runoff and delaying runoff response during rainfall events, thereby decreasing local flooding and supporting groundwater recharge (Burszta-Adamiak et al., 2023). Their simple design and low maintenance requirements make them an effective nature-based solution for urban stormwater management under increasing rainfall variability associated with climate change.

Beyond their primary hydrological role, rain gardens may also contribute to urban biodiversity when planted with native and insect-friendly vegetation. By integrating stormwater retention with vegetated, moist microhabitats, they create conditions that can further support hydration, reproduction, and thermoregulation, helping to complete insect life cycles. Hydrologically optimised designs that account for infiltration capacity, runoff contribution, and storm characteristics enable the integration of water regulation and vegetated habitat features with-

in compact urban spaces (Jia et al., 2016). When embedded within broader green infrastructure networks, such systems enhance habitat heterogeneity and contribute to the ecological resilience of urban landscapes (Burszta-Adamiak et al., 2023).

Urban orchards as multifunctional ecological infrastructure

Urban orchards represent a multifunctional element of urban ecological infrastructure by integrating biodiversity conservation with provisioning, cultural, and educational ecosystem services. In contrast to intensively managed ornamental green spaces, urban and peri-urban orchards are characterised by structurally diverse vegetation, including fruit trees, herbaceous ground cover, and semi-natural margins, which creates favourable conditions for a wide range of insect taxa and enhances habitat quality in urban landscapes (Rada et al., 2022, 2023; Liu et al., 2024).

Fruit trees provide important nectar and pollen resources for pollinators during flowering, while tree bark, cavities, leaf litter, and spontaneous vegetation offer shelter and microhabitats for insects and other wildlife. Traditional orchard systems have been shown to support higher biodiversity levels than simplified green spaces, with particularly positive effects on insect and bird communities due to increased structural complexity and reduced management intensity (Rada et al., 2022). Such conditions also favour natural enemies of pests, thereby enhancing functional biodiversity and biological control potential.

Beyond their ecological role, urban orchards contribute to cultural, educational, and social values by strengthening connections between urban residents and food production and increasing awareness of biodiversity conservation. When integrated into urban green infrastructure networks and managed with low chemical inputs and tolerance of spontaneous vegetation, urban orchards function as local biodiversity hotspots and represent an effective nature-based solution for combining food production with conservation objectives (Rada et al., 2022, 2023).

Management intensity, chemical inputs and habitat connectivity

Management intensity strongly determines the ecological value of urban green spaces and their capacity to support entomofaunal biodiversity. Intensively managed lawns and ornamental plantings, characterised by frequent mowing and vegetation removal, typically sustain low plant and insect diversity, whereas reduced management intensity allows the development of structurally and floristically diverse vegetation that provides a wider range of resources and microhabitats for insects (Muratet and Fontaine, 2015). Reduced mowing regimes have been shown to increase plant species richness and insect abundance and diversity, while simultaneously lowering maintenance costs and greenhouse gas emissions, making them ecologically and economically beneficial management strategies (Watson et al., 2020).

Chemical inputs, including insecticides and herbicides, represent a major pressure on urban insect communities, with documented negative effects on insect abundance, species richness, and functional composition even at low application intensities. Empirical evidence links pesticide use in urban environments to declines in pollinator populations, underscoring the importance of minimising or eliminating chemical inputs within urban ecological infrastructure (de Montaigu and Goulson, 2023).

Habitat connectivity contributes to the long-term persistence of urban insect populations in fragmented landscapes. Connected networks of green spaces facilitate dispersal and gene flow, support higher species richness, and enhance population stability (Schlaepfer et al., 2018; Theodorou et al., 2020). The integration of vegetated corridors and other linear green elements further strengthens functional connectivity and ecological resilience by reducing isolation effects and enabling recolonisation following local disturbances (Aleixo et al., 2024).

MONITORING OF ENTOMOFAUNA

Monitoring of entomofauna provides a basis for understanding insect population dynamics, spatial and temporal distribution patterns, and long-term trends

in biodiversity. Systematic monitoring provides the basis for detecting population declines, shifts in species composition, and phenological changes, which may indicate broader ecological disturbances driven by climate change, land-use change, urbanisation, or intensive agricultural practices (Montgomery et al., 2021).

Given the high taxonomic diversity of insects and the wide range of ecological functions they perform, entomofauna monitoring requires carefully designed and methodologically consistent approaches. A major challenge lies in the lack of standardisation among monitoring methods, which often differ in sensitivity, selectivity, spatial coverage, and temporal resolution. Fragmented or short-term data collection is frequently insufficient to meet scientific and conservation objectives, whereas long-term, standardised, and repeatable monitoring schemes enable meaningful comparisons across sites and time periods (Montgomery et al., 2021).

Despite increasing recognition of cities as important environments for biodiversity conservation, insect monitoring in urban areas remains comparatively underdeveloped and is often fragmented across locations, projects, and target taxa. Existing monitoring efforts in urban environments frequently focus on economically relevant or nuisance species, particularly pests associated with urban trees and ornamental vegetation, while broader biodiversity-oriented monitoring remains less systematically implemented (Bowler et al., 2024). Recent urban studies further demonstrate that insect responses are shaped by interacting environmental factors, including vegetation structure, impervious surface cover, habitat configuration, and local microclimatic conditions, emphasising the need for context-specific monitoring in urban landscapes (Buenrostro and Hufbauer, 2022; Chen and Neoh, 2022). For example, standardised monitoring across urban gradients has shown that arthropod richness, diversity, and community composition vary among vegetation layers and urban conditions, highlighting the importance of multi-scale monitoring approaches capable of capturing spatial and temporal variability within cities (Chatelain et al., 2023). Strengthening systematic monitoring in urban environments would therefore im-

prove understanding of insect abundance, functional diversity, and temporal dynamics and provide an evidence base for designing and adapting urban conservation and management measures. In this context, monitoring approaches already widely applied in agriculture and forestry may offer transferable methodological frameworks for urban biodiversity assessment when adapted to heterogeneous urban conditions. Such approaches may additionally support the evaluation of urban ecological infrastructure measures described in previous sections and provide an evidence base for improving biodiversity-sensitive urban management under changing environmental conditions. In practice, entomofauna monitoring serves multiple purposes depending on the context. In ecological and conservation studies, it can be used to assess biodiversity patterns, identify indicator species, and evaluate the effectiveness of habitat management and ecological infrastructure measures. Greater integration of such approaches into urban environments could facilitate assessment of ecological interventions and support adaptive management of urban green spaces. In applied contexts, particularly in agriculture and urban green space management, monitoring focuses on tracking population dynamics of key pest species and their natural enemies in order to support evidence-based decision-making (Barić and Pajač Živković, 2020; van Klink et al., 2022).

A wide range of monitoring methods is currently employed, each targeting different components of insect diversity, abundance, and activity. Their complementary application is increasingly recognised as necessary for achieving comprehensive entomofauna assessment, particularly under complex and rapidly changing environmental conditions and within heterogeneous urban landscapes. Different approaches vary in their suitability depending on monitoring objectives, target taxa, available resources, and spatial scale. To facilitate comparison among monitoring approaches and support their application in urban biodiversity assessment and management, the main methods, together with their key advantages and limitations, are summarised in Table 2.

Visual methods in entomofauna monitoring

Visual methods represent the oldest and most widely applied approaches in entomofauna monitoring and remain fundamental in both ecological research and applied monitoring programmes. These methods are based on direct observation or passive capture of insects using visually attractive or interceptive devices and are particularly valuable for long-term datasets and comparative studies across habitats and seasons.

Light traps are among the most important visual tools for monitoring nocturnal insects, especially moths (Lepidoptera), flies (Diptera), beetles (Coleoptera), and other

Table 2. Overview of main entomofauna monitoring approaches, including their key advantages and limitations

Monitoring approach	Main advantages	Limitations	Target/scale
Visual and trapping methods	Standardised, widely used	Taxonomic bias, labour-intensive	Flying and ground-dwelling insects, long-term monitoring
Active sampling	High taxonomic resolution	Observer bias	Visible/mobile taxa
Attractant-based methods	High selectivity	Species-specific	Target pest species
Molecular methods	Accurate identification	Database-dependent, costly	All taxa (sample-based)
Digital methods	Automated, scalable	Technical requirements	Continuous monitoring
Radar-based monitoring	Large-scale coverage	Low taxonomic resolution	Migration, landscape scale

night-active taxa (Montgomery et al., 2021). These traps typically consist of a light source, most commonly ultraviolet lamps, combined with a funnel or deflector and a collecting container. Insects attracted to the light collide with the structure and fall into the collecting vessel. Robinson and Heath traps are among the most commonly used designs. Trap efficiency is influenced by lamp type, light intensity, weather conditions, seasonal timing, and sampling duration, all of which must be standardised to ensure data comparability (Macgregor et al., 2017; Jonsson et al., 2014).

Mercury vapour UV lamps have been shown to attract a broader range of insect taxa and higher numbers of individuals compared to other light sources, but they require access to mains electricity and involve higher operational costs. Light-emitting diode (LED) technology represents a more energy-efficient alternative, although its attractiveness may vary depending on wavelength and target taxa (White et al., 2016). Recent developments include automated traps that integrate image acquisition and artificial intelligence-based species recognition, substantially reducing manual inspection and enabling continuous long-term monitoring (Čirjak et al., 2023).

Sticky traps, typically coloured yellow, blue, or white, are widely used for monitoring diurnal insects and specific taxonomic groups (Barić and Pajač Živković, 2020). Yellow sticky cards are commonly used to monitor aphids (Aphididae) and flies (Diptera), whereas blue cards are particularly effective for thrips (Thysanoptera), and white cards are attractive to sawflies (Hymenoptera). These traps are inexpensive, easy to deploy, and suitable for large-scale monitoring, usually of pest populations; however, they are non-selective and may also capture beneficial insects. Moreover, they require manual counting and identification of captured individuals, which can be time-consuming and taxonomically demanding (Barić and Pajač Živković, 2020).

Malaise traps are tent-like interception traps designed for the passive collection of flying insects. Insects encountering the vertical mesh tend to move upwards

towards the light and are guided into a collecting container (Figure 6). Malaise traps are especially effective for Diptera and Hymenoptera and are widely used in biodiversity surveys. Their performance depends on correct placement along natural flight corridors, as well as environmental factors such as wind exposure and surrounding vegetation structure (Montgomery et al., 2021).



Figure 6. Malaise trap for entomofauna monitoring in experimental station Maksimir (Darija Lemic, Zagreb, Croatia)

Active visual sampling, including sweep netting and manual collection, is frequently applied for larger, mobile, or easily recognisable insect taxa such as butterflies, ladybirds, and dragonflies. While this approach allows detailed observation and targeted sampling, it requires a high level of taxonomic expertise and strict adherence to standardised protocols to minimise observer bias and ensure repeatability (Montgomery et al., 2021). In addition, pitfall traps are commonly used for sampling ground-dwelling arthropods and are considered a practical and standardised approach for biodiversity assessment and long-term ecological monitoring (Ahmed et al., 2023). Urban applications of visual and trapping methods further demonstrate their value for biodiversity assessment. For example, a seven-year monitoring study con-

ducted across different urban habitat types in Phoenix combined pitfall trapping and sweep-net sampling and showed that arthropod community composition differed substantially among landscape categories, highlighting the importance of standardised and repeated sampling for understanding urban biodiversity dynamics (Bang and Faeth, 2011). Similarly, pitfall trapping conducted on green roofs in Portland revealed that structurally more diverse roofs supported higher parasitoid diversity, indicating that standardised monitoring can support evaluation of urban ecological infrastructure measures (Diethelm and Masta, 2023).

Importance of attractants in population monitoring

Attractants are substances that selectively attract insects through olfactory or gustatory cues and are primarily used in entomological research for monitoring the presence and abundance of specific species. According to their mode of action, attractants can be divided into two main groups: sexual (pheromonal) and feeding attractants.

Sexual attractants, i.e. sex pheromones, are species-specific chemical signals released by individuals to attract mates for reproduction. In most cases, pheromones are emitted by females to attract males; however, in some species pheromones are produced by males and may have an aggregative function, attracting individuals of both sexes to a particular area (Landolt and Phillips, 1997). Insects detect pheromones via olfactory receptors located on the antennae, and the signal elicits specific behavioural responses such as courtship or directed movement toward the odour source (Cattaneo et al., 2017). Although pheromones are highly selective and usually target a single species, in some cases they may attract non-target species due to shared chemical components or impurities arising during synthesis or formulation (Hrudová, 2003).

Feeding attractants represent another important group of attractants. They are based on substances that mimic food sources, thereby attracting insects that naturally orient towards nutritional cues (Bjeliš, 2006). This

group includes fermented sugars, protein-based compounds, and various fruit or plant extracts. Their application in insect monitoring relies on the fact that many adult insects spend a substantial portion of their lifespan searching for food, which makes them particularly responsive to feeding-related signals (Bjeliš, 2006).

Both sexual and feeding attractants are used in combination with different types of traps (e.g. pheromone traps, sticky traps), and their effectiveness depends on proper placement, duration of activity, type of attractant, and the target species. Standard monitoring protocols typically involve deploying a defined number of traps per unit area, which are checked regularly, while attractant dispensers are replaced every 3–4 weeks to ensure consistent efficacy (Ražov, 2010).

Overall, attractant-based methods provide efficient and selective tools for insect population monitoring and are most effective when integrated with visual and digital approaches.

DNA-based methods in entomofauna monitoring

DNA-based methods have become an important tool in entomofauna monitoring, particularly for morphologically similar or cryptic insect species. DNA barcoding most commonly relies on the mitochondrial cytochrome c oxidase subunit I (COI) marker, which enables rapid and reliable species identification, especially when processing large numbers of samples (Hebert et al., 2004). The effectiveness of DNA-based identification, however, depends on the quality and completeness of reference databases, as insufficient representation of certain taxa may lead to misidentifications (Ekrem et al., 2007). In addition to classical barcoding, environmental DNA (eDNA) approaches are increasingly used to detect insect presence from environmental samples such as soil or water, providing a non-invasive method for biodiversity assessment. Despite remaining methodological limitations, eDNA represents a valuable complementary tool when combined with traditional and molecular identification methods (Ekrem et al., 2007).

Digital methods in entomofauna monitoring

Digital monitoring systems provide more efficient, precise, and often non-invasive tools for data collection, making them particularly suitable for long-term monitoring programmes and the early detection of changes in insect populations.

One of the most significant developments in this field is the introduction of automated monitoring systems and so-called “smart traps”, which integrate pheromone or food attractants with cameras, sensors, and wireless data transmission. These systems enable continuous, real-time monitoring of target species without the need for frequent field inspections. Their application in apple production has demonstrated high potential for improving monitoring efficiency, reducing labour requirements, and supporting timely decision-making within integrated pest management programmes (Pajač Živković et al., 2020; Čirjak et al., 2022; Čirjak et al., 2023). A key technological component underpinning the functionality of smart traps is computer vision, one of the fastest-growing approaches in automated insect monitoring. Computer vision systems employ machine learning algorithms for the automatic recognition and classification of insect species from digital images and video recordings (van Klink et al., 2022). These algorithms are trained on libraries of pre-classified images and can achieve classification accuracies exceeding 90% for certain genera (Čirjak et al., 2022; Čirjak et al., 2023); however, their performance strongly depends on morphological similarity among species and the availability of sufficiently large and representative training datasets. Camera-based computer vision systems are most commonly integrated with visual traps, such as light, sticky, or pheromone traps (Figure 7), thereby improving detection efficiency and standardisation of data collection (van Klink et al., 2022). In addition, these approaches allow the monitoring and classification of both live and dead insects, while the use of standardised lighting conditions and controlled backgrounds further enhances identification accuracy (Wührl et al., 2021). Recent developments in computer vision demonstrate the potential of AI-sup-

ported monitoring. For example, a YOLOv8-based model was developed for large-scale insect classification across multiple environments and may support more scalable and continuous biodiversity monitoring; however, such approaches should complement rather than replace conventional monitoring methods (Venverloo and Duarte, 2024).



Figure 7. Camera-based smart trap used for automated insect monitoring and data collection under field conditions (Helena Viric Gasparic, Zagreb, Croatia)

Acoustic monitoring uses bioacoustic signals produced by insects during communication or as a by-product of movement (Penone et al., 2013; Kawakita and Ichikawa, 2019). This approach is particularly suitable for monitoring taxa such as cicadas (Cicadidae) and orthopterans (Orthoptera), and recordings can be obtained using stationary sensors or mobile devices mounted on vehicles (Jeliaskov et al., 2016). Sound recognition algorithms enable not only species-level detection but also the identification of behaviours such as courtship, sea-

sonal activity patterns, and phenological changes (van Klink et al., 2022). Although bioacoustic reference databases remain limited, the increasing availability and affordability of recording equipment significantly enhance the potential of acoustic monitoring for broader application in entomofauna studies (Montgomery et al., 2021).

The most technologically advanced digital approach to insect monitoring is radar-based surveillance. It relies on the use of radio waves to detect flying individuals, enabling the estimation of body size, flight speed, direction, and altitude, and, in the case of larger species, wingbeat frequency (Rhodes et al., 2022). Specialised entomological radars can detect insects at heights of up to 150 m above ground level, while integration with existing meteorological radar networks allows continuous monitoring of large-scale insect movements and migrations, such as those of aphids or butterflies (van Klink et al., 2022). The main advantages of radar-based approaches include extensive spatial coverage, the ability to operate during nighttime, and non-invasive data collection, although taxonomic resolution remains limited. Radar-based approaches, therefore, offer strong potential for systematic and spatially extensive insect monitoring, particularly for detecting large-scale movement patterns and improving temporal continuity of biodiversity observations (Noskov et al., 2021).

Despite ongoing challenges, including the need for extensive reference datasets and reliable energy supply (which can be partly addressed through the use of solar-powered systems), digital monitoring technologies represent a major step forward in the modernisation of entomological monitoring. Their application enables precise, long-term, and scalable assessment of insect dynamics across different habitats, which is critically important in the context of global environmental change and widespread biodiversity decline (Bjerger et al., 2022; van Klink et al., 2022).

Role of citizens and local communities in entomofauna monitoring

Given the scale and complexity of insect monitoring in urban environments, complementary approaches that engage non-professionals have gained increasing relevance. Citizen science has become an increasingly important component of entomofauna monitoring, complementing expert-led and institutionally driven programmes by enabling large-scale and long-term data collection. In Europe and North America, public participation has been widely applied in biodiversity and phenological monitoring, particularly in the context of climate change and habitat alteration (Donnelly et al., 2014). One of the earliest long-term examples of citizen involvement in insect monitoring is the Rothamsted Insect Survey light-trap network, established in the United Kingdom in 1968, in which most traps are operated by volunteers who contribute data to the national monitoring programme, providing invaluable insights into long-term population trends of nocturnal Lepidoptera (Conrad et al., 2004).

Well-established citizen science initiatives demonstrate that, when supported by appropriate protocols and training, data collected by volunteers can be scientifically robust and suitable for integration into research and conservation planning. Initial concerns regarding the reliability of volunteer-collected data have been addressed through standardised methodologies, validation procedures, and expert oversight, allowing such data to be effectively incorporated into scientific research and conservation policies (Dickinson et al., 2012).

Several national programmes illustrate the value of citizen involvement in insect monitoring. In Ireland, structured schemes such as butterfly and bumblebee monitoring rely on standardised transect walks and repeated observations throughout the growing season, generating long-term datasets on species distribution and abundance (Donnelly et al., 2014). Short-term intensive initiatives such as BioBlitz events further contribute to rapid biodiversity inventories by combining expert knowledge with broad public participation.

In the United States, large-scale initiatives such as *The Great Sunflower Project* have enabled the collection of extensive datasets on pollinator activity in private gardens since 2008, providing valuable insights into pollinator declines and habitat use. Technological developments have greatly facilitated citizen science participation through the use of smartphones with GPS, online databases, and dedicated platforms that allow real-time recording and sharing of observations. Applications such as iNaturalist and SciStarter integrate georeferenced data with community-based or expert-supported species identification (Kobori et al., 2016).

Beyond data collection, citizen science plays an important educational and societal role by increasing scientific literacy, raising awareness of biodiversity loss, and fostering engagement with nature (Roche et al., 2020; Viric Gasparic et al., 2022). Participation is primarily motivated by intrinsic factors, such as interest in nature and the desire to contribute to science and conservation, whereas financial incentives tend to have limited or even negative effects on engagement (Richter et al., 2021). Effective citizen science programmes therefore require clear communication, accessible protocols, and ongoing feedback to participants in order to maximise both data quality and societal impact (Roche et al., 2020).

CONCLUSIONS

This review addressed the role of urban ecological infrastructure in supporting functional insect diversity and the importance of monitoring approaches under conditions of global change. Climate change, urbanisation, habitat fragmentation and management intensity are major drivers of changes in insect abundance, diversity and community structure. Because insects contribute to pollination, biological control, decomposition and nutrient cycling, these changes have implications for ecosystem functioning and the delivery of ecosystem services in cities.

This review indicates that urban areas can contribute to entomofauna conservation when urban ecological infrastructure is designed and managed to increase habitat availability and connectivity. The reviewed evidence suggests that no single infrastructure element is sufficient on its own; rather, combinations of structurally diverse vegetation, resource continuity, microhabitat provision, and reduced disturbance are required to sustain functional insect diversity. Their effectiveness remains context-dependent and should be prioritised according to site conditions, target functional groups, and implementation constraints within urban environments.

Effective conservation and management require long-term, standardised monitoring. No single method captures the full range of taxa and functions; therefore, integrated monitoring approaches are needed. Traditional trapping and active sampling should be combined with molecular approaches (DNA barcoding, eDNA) and digital methods (smart traps, acoustic monitoring and radar-based systems) to improve taxonomic coverage, temporal resolution and spatial extent. Citizen science may further support implementation and expand monitoring capacity when combined with standardised protocols and data validation procedures.

Overall, maintaining insect biodiversity in cities depends on integrating ecological infrastructure design with monitoring frameworks capable of evaluating ecological outcomes over time. Future research should prioritise comparative assessment of infrastructure effectiveness across urban contexts and development of evidence-based management strategies that support resilient and functional urban ecosystems under global change.

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