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"A. ZAMBELLI"

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SOIL APPLICATION OF ORGANIC AMENDMENTS TO PROTECT AND ENHANCE THE BIODIVERSITY OF URBAN ECOSYSTEMS: EVALUATION OF CARBON SEQUESTRATION DYNAMICS BASED ON BOTH SOIL PROPERTIES AND IMPACT ON HERBACEOUS AND TREE SPECIES

Supervisor: ***Prof. Stefano Castiglione*** **Ph.D. student:** ***Annamaria Di Serio***

Co-Supervisor: ***Prof. Domenico Ronga***

Co-Supervisor: ***Prof. Pierluigi Mazzei***

PhD Course Coordinator: ***Prof.ssa Alessandra Lattanzi***

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Abstract

Urbanization during the past decades has profoundly altered the structure and functionality of urban soils, reducing fertility, compromising biodiversity, and limiting carbon sequestration capacity. In this context, the application of organic amendments represents a promising strategy to regenerate urban ecosystems and support plant biodiversity; however, the scientific literature remains fragmented, and studies conducted under truly urban conditions are limited. In addition, the application of organic amendments like compost and biochar on existing urban green areas as turf are not possible. Among the organic amendments, no data is available on the use of micronized ones in urban soils.

Considering these aspects, the present work investigated the application of micronized amendments in urban soils, together with their assessment using high-resolution digital monitoring systems. The experimental work assessed four urban sites with contrasting management characteristics, evaluating the effects of micronized vermicompost, micronized biochar and their combinations on soil chemical properties, water availability, spontaneous vegetation physiology, productivity, and potential carbon sequestration, over three years.

The results show that micronized amendments, particularly when applied in combination, enhance soil fertility, increase nutrient availability, stimulate microbial biomass, and improve water-holding capacity. In addition, increased chlorophyll content, nitrogen use efficiency, and photochemical efficiency and enhancing aboveground biomass. Digital sensors proved to be extremely sensitive tools for detecting differences among the investigated treatments, revealing interesting physiological differences. The most pronounced responses were observed in soils having a low chemical fertility, highlighting the importance of the ecological context.

This thesis directly addresses major gaps in literature by demonstrating that studies conducted under real conditions, using multidisciplinary approaches are essential for a correct assessment on the use of innovative amendments in urban soil. The results provide a solid empirical foundation for future research on carbon stabilization, microbial dynamics, long-term effects, and interactions between micronized amendments and anthropogenic soils. Overall, this thesis contributes to establishing a more robust and realistic scientific framework for the use of innovative organic amendments in urban environments, offering practical guidance for ecological planning and the sustainable management of urban green spaces.

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List of Abbreviations / Acronyms

AnthM: anthocyanin content

BEF: Biodiversity–Ecosystem Functioning

CAS: complex adaptive systems

CH_4: methane

ChlM: chlorophyll content

CO_2: carbon dioxide

DW: dry weight

FlvM: flavonol content

FW: fresh weight

GHG: greenhouse gases

IUSS: international union of soil sciences

LC: lithogenic carbonate

MAOC: mineral-associated organic carbon

MEMS: microbial efficiency–matrix stabilization

MPM-100: multi-pigment meter

NBS: nature-based solutions

NDVI: normalized difference vegetation index

NFI Index: chlorophyll/ flavonol content

PC: pedogenic carbonate

PRI: photochemical reflectance index

SIC: soil inorganic carbon

SOC: soil organic carbon

SOM: soil organic matter

TDR: time domain reflectometry

UHI: urban heat island

VWC: soil volumetric water content

Introduction

General Context: Urbanization, Urban Soils and Climate Change

Urbanization and Its Impact on the Ecosystems

Urbanization is among the most significant and complex phenomena of the contemporary world, resulting not only in higher population densities but also in profound transformations of the territory (Figure 1). Urbanization involves changes in land use, as natural or agricultural areas are converted into infrastructure with direct implications for the economic, social, and environmental functions related to settlements (De Bruin & Holleman, 2023; Angel, 2023).

Figure 1. *Visual contrast between natural and urban systems, emphasizing how land-use changes from vegetated, water-rich environments to highly developed urban areas alters ecological structure, resource flows, and environmental quality. Source: created by the author with assistance from AI.*

Urbanization is a multidimensional phenomenon that can be approached from two complementary perspectives. The first is the processual perspective, which focuses on transformations over time, including demographic growth, expansion of built-up areas, changes in land use, and socio-economic restructuring. The second is the static perspective, often referred to urbanity or urbanicity, that assesses the current state of an area and evaluates the extent of typical urban characteristics, such as density, infrastructure, functional diversity, and availability of services (Vlahov & Galea, 2002; Cyril *et al*., 2013). Tian *et al*. (2022) identify three principal dimensions of urbanization: size, i.e., the

increase in population as areas transition from rural to urban; density**,** i.e., the concentration of people and infrastructure; and heterogeneity, reflecting the growing complexity of economic, social, and spatial functions within urban areas.

Urbanization is not merely a demographic or territorial phenomenon, but a multidimensional challenge that requires integrated strategies for land management and urban ecosystem conservation (Ren *et al*., 2023; Anoling *et al*., 2025). Over the past two centuries, the world has undergone an unprecedented demographic and spatial transformation: the proportion of the global population living in urban areas has risen from a few percentage points to more than half of the world's population (Pouyat *et al*., 2020; Marcotullio *et al*., 2008). This increasing urbanization entails not only higher population densities and larger urban populations but also extensive territorial transformation, as natural or agricultural areas are converted into infrastructure, buildings, roads, and other forms of artificial land use.

According to global-scale data compiled by Ritchie *et al*. (2025), over 4 billion people now live in urban areas, and in 2007, for the first time, the urban population surpassed the rural population. Urban expansion is not uniform: in high-income regions, over 80% of the population resides in urban areas, while in many middle-income countries, the proportion exceeds 50–80%. Projections indicate that this trend will continue, with further growth in urban populations in the coming decades (Ritchie *et al*., 2025; Williams & Duminy, 2025).

From a spatial perspective, urban expansion leads to an increase in urban land cover, the area occupied by settlements, infrastructure, and artificial surfaces, which results in soil sealing, loss of agricultural or natural land, and profound landscape alterations. Recent studies highlight that such expansion poses one of the main challenges to environmental sustainability: widespread growth of urban land increases urban populations' exposure to extreme heat, pollution, and climate-related vulnerabilities (Hu *et al*., 2025).

Urbanization represents one of the most significant threats to the capacity of the ecosystems to provide essential services for human well-being and environmental health, understood as the benefits humans derive from ecosystems, both directly and indirectly (Balvanera & Cotler, 2007; Díaz *et al*., 2015; Gomez-Baggethun & Barton, 2013; Silvestri *et al*., 2013; Assenato *et al*., 2022). Understanding how ecosystem services respond across space and time to complex drivers within socio-ecological systems is critical for assessing the impacts of urbanization on human well-being (Yang *et al*., 2019). In this context, the Millennium Ecosystem Assessment highlights that human activities aimed at economic development and the improvement of well-being have caused significant ecosystem degradation, resulting in a substantial loss of ecosystem services (MEA, 2005; Yang *et al*., 2023).

Urbanization profoundly affects the structure and function of natural ecosystems through land conversion, infrastructure expansion, resource exploitation, and other socio-economic processes (Hasan *et al*., 2020; Kowarik, 2023). Urban development patterns also alter habitat composition, hydrological systems, and nutrient cycles (Alberti, 2005), with significant consequences for biodiversity, urban areas often give rise to "novel ecosystems" characterized by unique species assemblages (Kowarik, 2023; McDonnell, 2015). As urbanization progresses, these effects extend beyond large cities, impacting peri-urban areas and small towns, particularly in developing countries, thereby threatening economic and social stability on a global scale (McDonnell, 2015). One of the most evident impacts is the reduction of ecosystem regulation services, including water cycle control, soil protection, carbon sequestration, water and soil purification, and air quality regulation (Yu *et al*., 2021). Such alterations can also affect the physical and chemical processes that govern the capture, absorption, and transformation of pollutants into less harmful forms during runoff (Sangani *et al*., 2015). The expansion of impervious surfaces, such as roads, buildings, and concrete, impairs rainwater infiltration, reducing groundwater recharge and increasing surface runoff and hydraulic risk (Hasan *et al*., 2020). Simultaneously, the loss of vegetation cover and natural habitats diminishes the capacity of urban ecosystems to retain and filter water, thereby reducing the effectiveness of their hydrological and regulatory services (Aghaloo *et al*., 2025).

Available evidence indicates that, in most cases, human activities tend to exert negative effects on ecosystem services (Li *et al*., 2016; Wang *et al*., 2019a). The expansion of urban areas and transport infrastructure, for instance, can compromise natural habitats, disrupt the continuity of ecological corridors, exacerbate landscape fragmentation, and alter plant dispersal and animal migration processes. Nevertheless, the magnitude and direction of these impacts often remain uncertain, making it difficult to determine whether the effects are significant or negligible, as well as beneficial or harmful.

Accurately identification and measurement of the effects of urbanization on ecosystem services is essential for minimizing their losses in rapidly expanding urban contexts. Various analytical approaches have been employed to quantify the relationship between urban dynamics and ecosystem services, including correlation analysis, multiple regression, exploratory regression, linear and nonlinear models, as well as spatial econometric models (Chen *et al*., 2020a; Wang *et al*., 2022a). Taking account these considerations, methods based on segmented function adaptation have been widely applied to investigate variations in the relationship between urbanization and ecosystem services, as they effectively describe trends and identify turning points (or threshold values) in observed changes (Peng *et al*., 2017). However, these approaches often overlook the spatial heterogeneity associated with different regional contexts, producing results that represent only

average conditions at the study-area level and therefore fail to capture the spatial variability of driving forces (Ma *et al*., 2022). Moreover, due to data availability limitations, much of the research conducted so far has assessed ecosystem service responses to urbanization at a single spatial scale, often based on administrative units, without considering local heterogeneity or the flows of elements between natural units, such as watersheds. This type of framework risks neglecting crucial interactions between urbanization and ecosystem services (Chen & Chi, 2022).

Physical, Chemical, and Biological Transformations of Urban Soil

Urbanization exerts some of the most profound and pervasive transformations on soils, altering their structure, composition, functionality, and capacity to provide ecosystem services. In fact, urban soil is a heterogeneous and heavily anthropized system, resulting from processes such as construction, compaction, removal, replacement, and contamination, which impart physical, chemical, and biological characteristics (Figure 2) distinct from those of natural and agricultural soils (Pouyat *et al*., 2010; Morel *et al*., 2015).

Figure 2. *Conceptual picture of physical, chemical, and biological transformations of urban soils driven by urbanization. The figure summarizes the principal processes through which urbanization modifies soil systems, encompassing physical alterations (compaction, sealing, and disturbance of soil profiles), chemical transformations (decrease in pH and accumulation of contaminants), and biological changes (simplification of microbial communities and decline of soil fauna). Collectively, these processes result in the degradation of essential soil ecosystem services and heightened risks to human health. Source: created by the author with assistance from AI.*

The acceleration of urban expansion in recent decades has intensified these pressures, rendering urban soil a critical, yet often overlooked, resource that is essential for the sustainability of urban ecosystems. Urban soils exhibit unique characteristics due to strong anthropogenic influence. Scientific literature describes them as "technogenic" systems, with often disturbed profiles, mixed or absent horizons, high content of foreign materials (e.g., concrete fragments, metals, plastics, gravel), and marked surface compaction (Lehmann & Stahr, 2007; Pouyat *et al*., 2010).

One of the most evident transformations concerns soil structure alteration like compaction caused by construction activities, vehicles, and pedestrian traffic significantly reduces porosity, thereby limiting air and water circulation. This phenomenon impairs root growth, infiltration, and water retention capacity, all essential for the proper functioning of urban ecosystems. Reduced soil quality translates into lower plant vitality, increased water and thermal stress, higher susceptibility to diseases, decreased native plant diversity, and a simultaneous facilitation of invasive species (Burghardt, 2025).

A well-documented outcome is the tendency of urban soils to exhibit a "convergence" of texture and fine particle content at depth. According to a multi-city study, urbanization "reshapes" soil profiles down to over one meter, leading to relatively fine, uniform soils with carbon (and organic material) content often lower than in pre-urban soils (Herrmann *et al*., 2020). This phenomenon implies that many of the soil's "historical" features, well-differentiated horizons, natural stratifications, and varied textures, are lost or profoundly altered by urbanization (Greinert, 2015).

In many urban areas, soils are "mixed" with materials derived from human activities, including construction debris, concrete, bricks, rock fragments, and imported fill, resulting in urban soils that differ markedly from natural soils in both composition and structure (Burghardt, 2025). Urban soils often exhibit artificial horizons, with sharp boundaries between original and reconstructed or mechanically added layers, reflecting filling, leveling, and imported soil activities (Greinert, 2015). Construction activities, the movement of heavy machinery, and earthworks induce soil compaction, leading to increased bulk density, reduced pore space, and altered pore arrangement. Such compactions can affect not only surface layers but also deeper levels, particularly where underground infrastructure, fill layers, or leveling works are present (Paradelo *et al*., 2025). Urban soils frequently no longer follow natural pedogenic processes: due to repeated anthropogenic interventions, "artificial" soil profiles may develop, in which stratification, particle size distribution, material composition, and porosity no longer reflect those of naturally formed soils. This condition is part of the distinctiveness of urban soils, which are now recognized as a separate category within urban pedology, characterized by high spatial heterogeneity, both horizontally and vertically, and frequent occurrence of anthropogenic artifacts (Burghardt, 2025). One of the most drastic effects of urbanization is soil sealing, considered one of the most extreme forms of degradation. When soil is

permanently covered by artificial materials such as asphalt or concrete, it completely loses its original ecological functions (Naumann *et al*., 2019). The consequences are manifold: water infiltration is reduced or completely blocked, resulting in increased surface runoff and hydraulic risk; gas exchange is interrupted, leading to soil biota mortality; plant growth leave off; critical ecosystem services, such as organic carbon storage, are lost; and the urban heat island effects is intensified (Breure *et al*., 2018; Scalenghe & Marsan, 2009). Notably, ISPRA defines sealed soil as "permanently lost" from an ecological standpoint, and the annual loss of fertile soil due to urbanization remains one of the main environmental threats in Europe. The outcome of these processes is that urban soil cannot be considered merely a degraded version of natural or agricultural soil; rather, it constitutes a distinct pedological entity, characterized by constructed profiles, altered textures, artificial horizons, the presence of anthropogenic materials, and variable compaction levels, which often eliminate or mask natural stratification (Lehmann & Stahr, 2007; Morel *et al*., 2015).

Urban soils exhibit profound chemical alterations and multiple contaminations. Soil pH is a crucial property, as it significantly influences soil functionality, including nutrient availability (Neina, 2019), microbial activity (Abakumov *et al*., 2020; Shi *et al*., 2021; Wang *et al*., 2019b), and plant growth (Gentili *et al*., 2018). In urban contexts, pH is often elevated due to the presence of construction materials such as concrete and lime, while concentrations of heavy metals, including lead, zinc, copper, and cadmium, are generally increased, accompanied by heterogeneous nutrient distributions (Morel *et al*., 2015; Paz-Ferreiro *et al*., 2018).

Soil pH also serves as an important indicator of soil contamination, as its acidity or alkalinity can influence the mobility of heavy metals and the distribution of contaminants (Opekunova *et al*., 2020; Fei *et al*., 2019). For instance, Kicińska *et al*. (2022) demonstrated that soil acidification leads to a significant increase in metal mobility. Urban soils are particularly vulnerable to contamination due to intense anthropogenic pressures, making pH assessment essential for understanding the distribution of contaminants and heavy metals (Kicińska *et al*., 2022).

In natural environments, soil pH tends to be primarily influenced by intrinsic pedological factors, which are more stable and predictable than in urban contexts (Chen *et al*., 2019a). Consequently, pH values in uncontaminated soils often exhibit clear spatial dependence (Bhunia *et al*., 2018). In contrast, in urban landscapes, soil properties are highly heterogeneous, both horizontally and vertically, even over short distances. This complex distribution complicates predictions of spatial variability for pH and heavy metals compared to natural landscapes (Vasenev *et al*., 2014). Elevated pH and chemical alterations in urban soils increase their vulnerability to heavy metal contamination. Indeed, heavy metal-contaminated soils represent one of the main challenges for environmental management and the conservation of urban and peri-urban ecosystems. These elements are

characterized by high chemical persistence and variable mobility, making them particularly insidious over the long term. Their presence alters soil physico-chemical properties, modifies nutrient availability, and interferes with the structure and function of microbial and edaphic communities (Motuzova *et al*., 2014; Breure *et al*., 2018).

Ecologically, heavy metals can exert direct toxic effects on plants, inhibiting germination, reducing root growth, and compromising photosynthesis and biomass production. Soil microbial communities, which are essential for nutrient cycling and organic matter decomposition, undergo selection towards more tolerant species, resulting in a loss of functional biodiversity and decreased natural soil fertility (Paz-Ferreiro *et al*., 2018). Additionally, contamination can accumulate in plant tissues, creating a pathway for metal transfer along the food chain, affecting insects, birds, and mammals in urban ecosystems (Costa, 2019).

From a human health perspective, heavy metal contamination constitutes a significant public health risk, both through direct soil contact and the consumption of crops grown on contaminated soils. Multiple studies have reported carcinogenic and neurotoxic effects of heavy metals, with particularly severe consequences for populations living near industrial sites or areas with high traffic density (Fay *et al*., 2018; Adenuga *et al*., 2022). The issue is of global scale: for example, in China, it is estimated that nearly 20 million hectares of soil are contaminated with heavy metals, compromising food security, agricultural productivity, and environmental quality (Chaoyang & Tongbin, 2001). Similar situations are observed in many industrialized countries, where urban and peri-urban areas exhibit accumulations of heavy metals originating from vehicular traffic, industrial activities, atmospheric deposition, and construction residues (Morel *et al*., 2015).

The ecological and agricultural consequences of contamination are not limited to direct effects on vegetation and soil. The presence of heavy metals reduces the carbon sequestration capacity of soils, disrupts nutrient cycles, and limits the resilience of urban ecosystems to additional environmental stresses, such as drought, extreme weather events, or ongoing anthropogenic pressures (Pouyat *et al*., 2010). This creates a trade-off between urbanization and ecosystem services, highlighting that sustainable management of urban and peri-urban soils must consider not only chemical quality but also ecological functionality and biodiversity protection.

Compounding these challenges is exposure to chemical contaminants from multiple anthropogenic sources, including vehicular traffic, industrial activities, atmospheric deposition, construction waste, and widespread microplastics. These substances negatively affect soil fauna, impair urban plant health, and reduce the productive potential of gardens and green spaces, thereby exacerbating ecological degradation in urban ecosystems (Breure *et al*., 2018).

Alongside chemical changes, significant biological alterations are also observed. Soil biodiversity, including microorganisms, fungi, and invertebrates such as earthworms, tends to decline or become simplified due to unfavorable environmental conditions and fragmentation of urban green spaces. Soil microorganisms represent the most abundant and functionally critical component of soil biodiversity. This loss of diversity results in less efficient biogeochemical cycles and reduced ecological resilience of the entire ecosystem (Ramirez *et al*., 2014).

Numerous studies have documented the negative influence of urbanization on microbial diversity in soils. Loss of organic matter, increased pollutants, and reduced vegetation cover create an environment less conducive to microbial growth and community differentiation (Garcia *et al*., 2020). In some urban areas, microbial communities are often dominated by pollution- or compaction-tolerant species, reducing overall soil functional variability. This phenomenon is particularly pronounced in sealed or heavily disturbed soils, where microbial communities can be drastically impoverished and ecological interactions limited (Zhou *et al*., 2023).

Urbanization also affects fungal diversity, particularly mycorrhizal fungi, which are essential for nutrient transfer between soil and plants. Studies conducted in urban parks and community gardens have shown decreased density and diversity of arbuscular mycorrhizal fungi in high-density urban environments, especially in areas with compacted soils or high content of anthropogenic materials (Niu *et al*., 2025; Guo *et al*., 2025). This reduction has direct implications for urban plant health and the soil's ability to sustain efficient nutrient cycles, increasing the vulnerability of urban soils to environmental stresses such as drought, pollution, and invasion by exotic species.

Soil invertebrates, including earthworms, collembolans, and mites, face significant pressures due to compaction, habitat loss, and chemical contamination (Pouyat *et al*., 2009). For example, earthworm density and diversity decrease in densely built urban areas, while in fragmented green spaces, communities are impoverished and less structured (McNaughton *et al*., 2025). These organisms perform key functions in aggregate formation, soil mixing, and organic matter decomposition. Their decline therefore compromises soil physical structure, nutrient distribution, and the capacity to support diverse vegetation (Prabhakar, 2023).

Fragmentation of urban green spaces further amplifies negative effects on soil biodiversity. Isolated green areas create microenvironments with reduced biological connectivity, limiting the dispersal of microorganisms and invertebrates and reducing functional heterogeneity in soils (McDonnell & Hahs, 2015). In highly urbanized contexts, this fragmentation leads to simpler pedobiological communities with lower resilience to anthropogenic and climatic stresses (Ramirez *et al*., 2014; Pouyat *et al*., 2010).

Sustainable Urban Soil Management

Recent studies suggest that the implementation of sustainable management practices can reduce the negative effects of urbanization. These measures include the use of organic amendments (e.g., compost, digestate), the protection and connectivity of green areas, reduction of soil compaction, and planting of native plant species (Malone *et al*., 2023). The aim is to promote richer and functionally diverse biological communities, thereby enhancing ecological processes and the resilience of urban soils, as biological alterations can simplify microbial functions and compromise organic matter decomposition, nutrient mineralization, and the stability of biogeochemical cycles (Fiorentino *et al*., 2025).

Soil organic matter (SOM) plays a crucial role in maintaining soil ecosystem functions, influencing physical fertility (soil aggregation, aeration, structure), chemical fertility (pH buffering capacity, nutrient storage and release), and biological fertility (supporting microbial activity and soil organisms) (Figure 3).

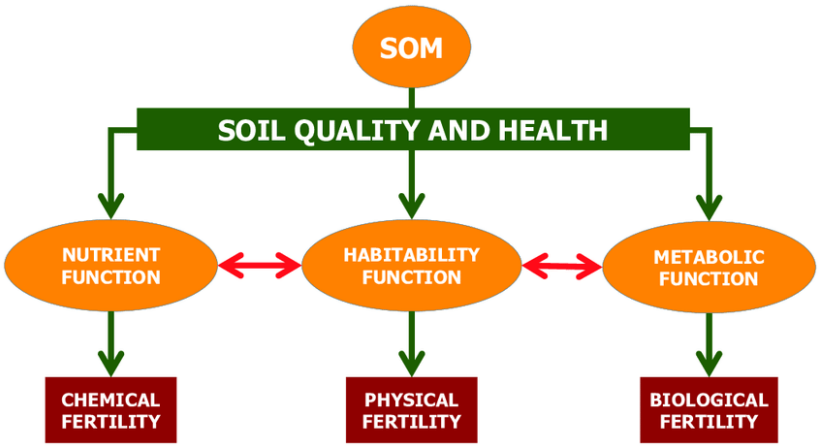


Figure 3. *Conceptual representation of the functional pathways through which soil organic matter (SOM) contributes to soil quality and health. SOM regulates nutrient, habitability, and metabolic functions, whose reciprocal interactions support chemical, physical, and biological fertility. Source: Libutti et al. (2021).*

A significant portion of SOM consists of soil organic carbon (SOC), whose presence is essential not only for soil quality but also for mitigating global climate change through atmospheric carbon dioxide (CO_2) sequestration.

In urban contexts, soil transformations, such as sealing, compaction, removal or alteration of surface layers, and green space management, have profound impacts on SOM/SOC content and stability. Available evidence indicates that urban soil responses are highly heterogeneous, depending on land use, modification history, soil depth, and management practices (Fiorentino *et al*., 2025). For

instance, studies in metropolitan areas have shown that soil in green spaces, parks, gardens, and vegetated areas can contain SOC stocks comparable to or even exceeding those of analogous agricultural or natural soils, particularly when environmental conditions and management practices favor organic matter accumulation. This phenomenon has been observed in several cities in the United States and Europe, suggesting that urban soils are not necessarily depleted in carbon (Pouyat *et al*., 2006; Guo *et al*., 2024a; Fiorentino *et al*., 2025).

However, not all urban areas exhibit this potential: impervious surfaces (pavements, buildings, roads) typically show considerable losses of SOC and nutrients, particularly in the surface horizons. In many cases, these losses result from topsoil removal, compaction, reduced organic inputs, and limited vegetation cover (Lu *et al*., 2020). In "sealed" soils, carbon and nutrient storage capacities are severely compromised (O'Riordan *et al*., 2021).

A critical issue highlighted in the literature is the spatial and management-related variability of SOC in urban soils. SOC content is strongly influenced by multiple factors, including land-use type (parks, gardens, recreational areas, streets), built density, historical land use, sampling depth, presence or absence of vegetation cover, maintenance frequency and type, as well as climatic and microclimatic conditions (Fiorentino *et al*., 2025).

Given this complex scenario, a promising approach to restore or increase SOM/SOC stocks in urban soils is the application of organic amendments, such as compost, biochar, and biosolids, combined with sustainable soil and green space management practices. Recent studies and meta-analyses indicate that such amendments can significantly increase SOM content and improve the physical and chemical properties of urban soils, including bulk density, water retention capacity, structure, and aggregate stability. Compost and biochar are among the most effective materials for enhancing SOM, whereas biosolids, while providing nutrient benefits, exhibit a more modest effect on organic matter accumulation (Malone *et al*., 2023).

The loss of SOM in urban soils not only affects carbon sequestration capacity but also has direct impacts on the structure and functionality of plant communities. Urban green spaces characterized by high heterogeneity of trees, shrubs, and herbaceous species provide a wide range of ecosystem services in a sustainable manner (Grilo *et al*., 2020; Chen *et al*., 2020b). Key benefits include mitigation of the urban heat island effect (Wang *et al*., 2021a), reduction of airborne pathogens and filtration of atmospheric pollutants (Bonilla-Bedoya *et al*., 2021), carbon sequestration, and regulation of stormwater runoff (Wang *et al*., 2021a).

Despite these benefits, one of the main objectives of urban biodiversity conservation is to understand how urbanization processes affect biodiversity by altering species composition and interspecific interactions (Ventura *et al*., 2024). Recent studies indicate that in some urban contexts, plant diversity

can increase, especially when favorable environmental conditions, such as soil, microclimate, pre-existing vegetation, and targeted management practices coexist (Boukita *et al*., 2024; Zhu *et al*., 2024). However, this increase is not uniform: the quality and connectivity of green spaces, along with species selection, largely determine the final species richness and floristic composition (Kacprzak *et al*., 2024; Biella *et al*., 2025).

Urban afforestation efforts and the use of native or historically present species can further enhance local biodiversity and ecosystem resilience (Magliocco *et al*., 2025; Kacprzak *et al*., 2024). Conversely, certain dynamics associated with urban development, such as industrial expansion, policy choices, and governance practices, can reduce plant diversity (Vakhlamova *et al*., 2014). It is therefore essential that urban planning and green space management policies are based on robust scientific evidence to maximize benefits for both biodiversity and ecosystem services (Jensen *et al*., 2025).

The effects of urbanization on vegetation can be distinguished between direct and indirect impacts (Zhao *et al*., 2016; Zhang *et al*., 2022a). Direct impacts, such as the replacement of natural surfaces with impervious areas, reducing vegetation cover and limit plant growth (Sandel *et al*., 2013). Indirect effects mainly arise from urban management practices and higher temperatures in cities compared to surrounding natural areas, further influencing vegetation development and composition (Wang *et al*., 2019c).

De Barros *et al*. (2022) analyzed over 170 studies on the subject, highlighting that the main urban drivers are land-use change and the invasion of non-native species. These processes often lead to reduced species richness, loss of native species, habitat homogenization, and dominance of generalist or invasive species, resulting in simplified and less functional plant assemblages. Accurately assessing the indirect effects of urbanization on vegetation growth is complex.

Satellite remote sensing is currently one of the most used tools to monitor dynamics such as vegetation development, productivity, and phenology, using spectral indices such as the Normalized Difference Vegetation Index (NDVI) (Zhang *et al*., 2022a). This perspective is strategic as it links urbanization to the loss or alteration of soil structure and function, opening new opportunities for urban regeneration and carbon sequestration.

In the context of urban soil management and urban carbon farming, urban soil is no longer considered merely an infrastructural support but a fundamental environmental resource for climate mitigation, quality of life, resilience, and microbial and edaphic biodiversity (Rumpel *et al*., 2023). In cities, plants face higher levels of pollutants, elevated temperatures, and increased CO_2 and nitrogen deposition compared to rural counterparts (Lovett *et al*., 2000).

Recent studies demonstrate that active green space management, through the addition of organic matter, use of native species, reduction of compaction, and increased connectivity between green areas, can mitigate the negative effects of urbanization on vegetation (Edmondson *et al*., 2014; Niemelä, 2014). Such interventions promote more resilient, diverse, and functionally rich plant communities capable of delivering ecosystem services and withstanding environmental changes associated with urbanization.

In this context, urban green infrastructure, such as parks, gardens, street trees, permeable flower beds, and green roofs, plays a crucial role in mitigating soil degradation. They help restore soil functionality, reduce the urban heat island effect, enhance carbon sequestration, decrease surface runoff, improve air quality, and support biodiversity. Recent studies show that ecologically managed green spaces have soils with better structure, higher organic matter content, and greater microbial diversity compared to degraded urban soils (Edmondson *et al*., 2014; Pouyat *et al*., 2010).

Urbanization and climate change: synergistic impacts

Urbanization and climate change are two major global processes of the twenty-first century whose dynamics are deeply interconnected. Urban expansion contributes substantially to greenhouse gas (GHG) emissions through increased energy consumption, transportation, infrastructure development, and the transformation of soils and vegetation cover. At the same time, climate change, manifested through rising temperatures, altered precipitation regimes and extreme weather events, places growing pressure on urban systems, affecting soils, biodiversity, urban microclimates, and overall environmental quality (Sharma, 2025). Understanding these interactions is essential for developing effective mitigation and adaptation strategies and for guiding the transition toward more resilient and sustainable cities. The schematic representation illustrated in Figure 4 summarizes the main drivers and potential outcomes of these interactions on urban vegetation dynamics.

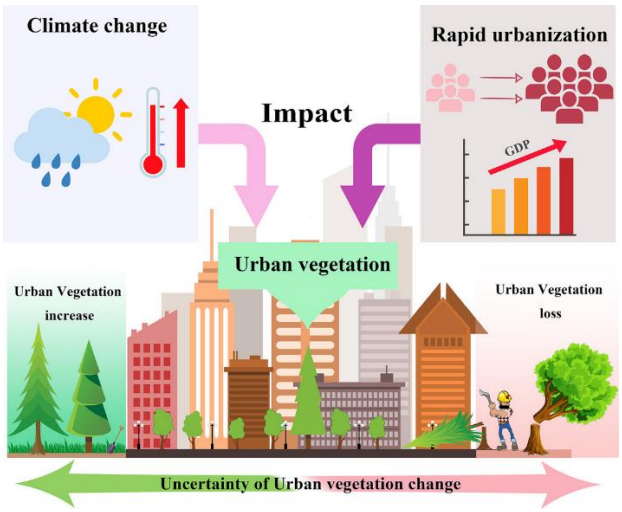


Figure 4. *Schematic representation of the synergistic effects of climate change and rapid urbanization on urban ecosystems and vegetation dynamics. The interaction between these global drivers influences urban environmental conditions, shaping patterns of vegetation gain and loss across cities. These contrasting processes generate heterogeneous responses and substantial uncertainty in the magnitude and direction of urban vegetation change. Source: Zhang et al. (2023).*

Urbanization profoundly alters biogeochemical cycles. The conversion of natural or agricultural land into built-up areas leads to a loss of vegetation and soil organic matter, thereby reducing the capacity of urban ecosystems to sequester carbon. In addition, the physical transformations characteristic of urban soils, including compaction, sealing, textural modifications, and reduced microbial diversity, directly influence GHG emissions, a research field experiencing rapid growth (Tobiloba *et al*., 2025). The interaction between urbanization and climate change generates synergistic effects that substantially amplify the degradation of urban soils. In densely built environments, the Urban Heat Island (UHI) effect leads to significant increases in surface and soil temperatures. This thermal intensification accelerates microbial respiration, resulting in more rapid losses of SOC and destabilizing carbon pools in urban soils. A case study conducted in the Moscow megacity showed that the UHI effect increased soil respiration by 5–10% on average, and up to 25% in the most affected zones, producing additional CO_2 emissions of approximately 0.2 Mg C ha^{-1} yr^{-1} in the top 10 cm of soil compared with non-urban reference areas (Vasenev *et al*., 2021).

At the same time, the widespread presence of impervious surfaces, roads, pavements, parking areas and buildings, drastically reduces soil infiltration capacity. Under increasingly intense precipitation events, a hallmark of climate change, this results in higher surface runoff, greater hydrological risk, loss of fertile soil, and deeper impairment of pedological functions (Lu *et al*., 2020).

When degraded soils interact with climatic stressors, the consequences for urban vegetation become particularly severe. Elevated temperatures, reduced water availability, nutrient depletion and lower soil structural stability constrain plant growth, diminish urban biodiversity, and weaken the ability of urban ecosystems to withstand extreme events. Furthermore, soil degradation promotes increased emissions of several GHG, including CO_2 and N_2O, with potential implications for global climate dynamics (Luo *et al*., 2012).

Collectively, these dynamics highlight that urban soils cannot be viewed as static or marginal components of the urban system; rather, they represent a critical element in regulating urban–climate interactions and maintaining ecological functionality.

To counteract these synergistic impacts, integrated urban planning and soil management strategies are urgently needed. Sustainable soil management practices, such as reducing sealing and compaction, promoting permeable substrates and restoring soil organic matter, can substantially improve the ecological functioning of urban soils. Experimental studies on rehabilitated urban soils amended with compost and subjected to deep tillage demonstrate increases in soil carbon stocks, improvements in soil structure, higher microbial biomass, and enhanced water infiltration capacity. These outcomes contribute simultaneously to reducing surface runoff and increasing the potential for urban carbon sequestration (Malone *et al*., 2023).

Alongside soil-focused interventions, the expansion and effective management of green and blue infrastructure, parks, ecological corridors, street trees, green roofs, and permeable pavements, are key components of urban climate adaptation. Such systems help cool cities, regulate stormwater, enhance carbon uptake, and strengthen overall resilience. Recent studies show that increasing vegetation cover and soil permeability can mitigate UHI intensity and reduce risks associated with extreme rainfall events (Del Serrone *et al*., 2022; Kara *et al*., 2025).

Soil Properties and Carbon Sequestration in Urban Environments

Carbon Pools in Urban Soils: SOC, SIC, and Anthropogenic Impacts

The carbon pool in urban soils includes all forms of organic (SOC) and inorganic (SIC) carbon found in the surface and sub-surface soil horizons under strong anthropogenic influence. In this chapter, the term “pool” refers to the totality of carbon forms present in urban soils, while “stock” denotes the total carbon stored per unit area or volume. Carbon fluxes are considered in relation to the processes that regulate their redistribution and stability within the soil profile. It is important to emphasize that,

in urban soils, the distinction between pools, stocks, and fluxes is often less clear than in natural soils, due to the interplay between pedogenic processes and anthropogenic inputs.

SOC constitutes the most significant component for maintaining ecosystem functions (Figure 5) and plays a key role in soil carbon cycling and CO_2 exchange processes. SOC includes both relatively fast-cycling fractions (labile carbon, dissolved organic matter, and particulate organic matter) and fractions characterized by longer residence times, such as mineral-associated organic carbon (MAOC) and pyrogenic carbon, or black carbon, which is particularly abundant in urban environments due to combustion and vehicle traffic. Recent studies indicate that in urban areas, the proportion of MAOC may be lower than in natural settings, due to compaction, structural degradation, and limited formation of stable aggregates.

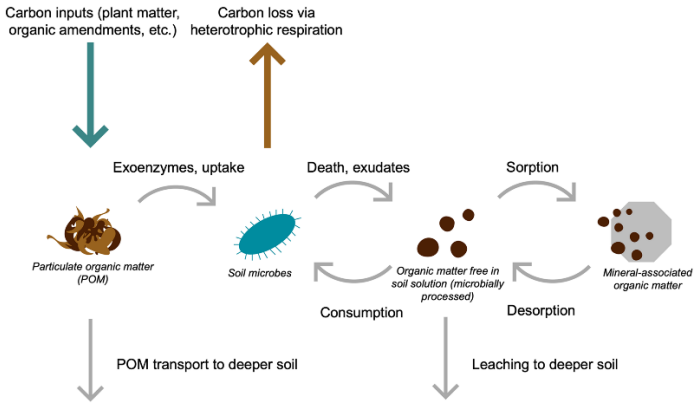


Figure 5. *Conceptual diagram of soil organic carbon (SOC) dynamics, illustrating the transformation of plant-derived inputs into particulate organic matter, dissolved organic matter, and mineral-associated organic matter. Microbial decomposition, exoenzyme activity, sorption–desorption processes, and vertical transport regulate the balance between carbon stabilization and carbon loss through heterotrophic respiration. Source: Dynarski et al. (2020).*

At the same time, black carbon and other anthropogenic inputs can increase the recalcitrant carbon fraction, but they do not always contribute to ecosystem services in the same way as biologically active SOC (Tobiloba *et al*., 2025; Zhao *et al*., 2025). This suggests that higher apparent carbon stability in urban soils does not necessarily correspond to enhanced soil ecosystem functions.

The complexity of SOC is further enhanced by the high spatial heterogeneity of urban soils, which reflects the coexistence of carbon sources of both biogenic origin (plant residues, microbial biomass) and anthropogenic origin (commercial substrates, fill materials, organic waste, and carbonaceous particulates) (Guo *et al*., 2024b). This heterogeneity limits the extrapolation of site-level results to broader urban or regional scales. A global meta-analysis shows that natural soils generally accumulate

higher SOC stocks than urban green spaces and heavily anthropized areas, with greater spatial variability in natural settings compared to urban ones, where anthropogenic impacts dominate storage dynamics (Chien & Krumins, 2022; Chaysaz *et al*., 2019) (Figure 6).

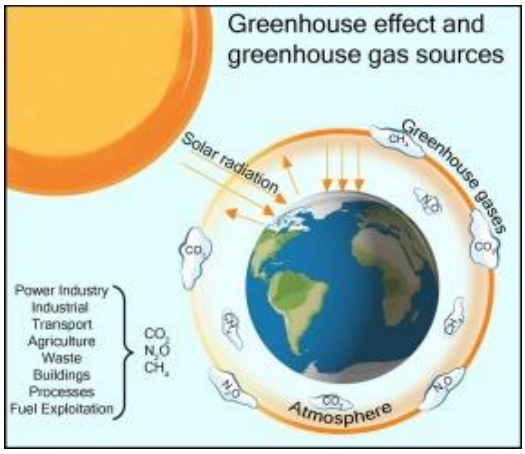


Figure 6. *Illustration of the greenhouse effect and the primary human-driven sources of greenhouse gases, including energy production, industry, transport, agriculture, and waste, which collectively intensify atmospheric CO_2, CH_4, and N_2O concentrations and drive global climate change. Source: Filonchyk et al. (2024).*

Urban expansion influences SOC stocks at multiple spatial and temporal scales, often leading to heterogeneous changes compared to natural environmental gradients (Chien & Krumins, 2022; Guo *et al*., 2024b). Global studies along urban–rural gradients confirm that urbanization significantly modifies SOC stocks, with impacts varying according to the degree of soil transformation, climatic conditions, and vegetation cover (Xu *et al*., 2024). Typical anthropogenic activities in urban areas produce a range of effects, from relatively modest modifications, as observed in parks and green spaces, to intense disturbances associated with the construction of infrastructure such as buildings and road networks (Wu *et al*., 2024a). Urban expansion frequently involves the conversion of highly productive ecosystems, including forests and agricultural lands, leading to the systematic removal of surface horizons rich in organic matter and a potential substantial reduction of ecosystem-level carbon reserves (Wu *et al*., 2024a).

In addition to SOC, urban soils host a significant fraction of inorganic carbon, whose importance has long been underestimated in terrestrial carbon budgets. SIC represents the mineral-derived fraction of carbon and is generally considered a pool characterized by greater stability compared to SOC (Jin *et al*., 2014). Unlike SOC, SIC is associated with geochemical processes linked to the weathering of rock materials and the formation of carbonates (Monger *et al*., 2015). SIC turnover times are

significantly longer than those of SOC, with estimates suggesting persistence up to 70–400 times greater (Bughio *et al*., 2016), conferring a potentially important role in long-term carbon storage over centennial to millennial timescales. However, in urban contexts, this stability can be partially altered by the presence of highly reactive anthropogenic materials and modified hydrological conditions.

Although SOC represents the main carbon pool in surface soils (<1 m) at the global scale (Zhang *et al*., 2020), the contribution of SIC becomes particularly significant in arid and semi-arid environments, where the SIC/SOC ratio can range from 2 to 17 (Ferdush & Paul, 2021). This predominance is largely attributable to limited carbonate leaching and resolubilization under low precipitation regimes, which favor carbonate accumulation in the soil profile. Additionally, reduced primary productivity and lower organic matter inputs from vegetation in these environments constrain SOC formation and replenishment, further increasing the relative importance of the inorganic carbon pool. In urban soil, SIC may be important for several reasons. Firstly, many urban areas consist of heavily disturbed or reworked soils, often classified as Technosols, in which anthropogenic materials (cement, mortars, concrete, construction aggregates) incorporate mineral carbonates that contribute to the soil inorganic carbon pool (Abbruzzini *et al*., 2015). In these contexts, it is often challenging to distinguish pedogenic SIC from that directly associated with construction materials, with significant implications for interpreting carbon budgets. These materials, originating from construction activities, the reuse of building waste, and excavation, not only alter the physical structure of urban soils but also act as a source of alkaline earth cations that can promote the formation of pedogenic carbonates when combined with bicarbonate derived from the interaction between soil CO_2 and water (Greinert, 2015). Moreover, global studies indicate that urban soils can exhibit substantial accumulations of inorganic carbon alongside SOC and black carbon, with spatial variations linked to urbanization history, the presence of deep cultural layers, and specific land uses; for instance, industrial areas and paved surfaces may display higher SIC fractions compared to urban green spaces (Xu *et al*., 2013). In urban soil profiles, the distribution of SIC is influenced both by natural factors, such as the dissolution–precipitation equilibrium of carbonates, and by anthropogenic processes, including the addition of fill materials, infrastructure construction, and alterations of hydrological regimes due to impervious surfaces and drainage. This can result in inorganic carbon accumulation patterns that differ from those observed in natural or agricultural soils, with vertical and horizontal variability accentuated by the presence of mixed horizons, fill layers, and incorporated anthropogenic materials (Hernández *et al*., 2021).

Such vertical and horizontal variability necessitates a multiscale analysis of carbon pools, from the soil profile to the urban system. In this context, SIC dynamics must be interpreted across multiple spatial scales, from the pedological profile to the urban site, and ultimately in terms of the overall

contribution of urban areas to regional and global carbon budgets. Finally, although SIC is often considered less dynamic than SOC in short-term cycles, its inclusion in urban carbon budgets is essential for a comprehensive assessment of carbon sequestration and storage capacity, particularly given that in anthropogenic soils the total carbon stocks (SOC + SIC + black carbon) can be comparable to or exceed those observed in reference natural soils (Vasenev *et al*., 2018; Schifman *et al*., 2018). Moreover, beyond its role as a long-term carbon reservoir, SIC can actively influence soil chemical buffering processes. The partial dissolution of carbonates releases alkaline species, including hydroxyl ions, which contribute to increasing soil pH and counteracting potential acidification processes. This buffering capacity is particularly relevant in urban soils, where acidifying inputs derived from atmospheric deposition, construction materials weathering, or organic matter decomposition may alter soil chemical stability. It is, however, important to distinguish between the theoretical potential for carbon sequestration and the actual capacity of urban soils to function as carbon sinks, which strongly depends on land-use type, disturbance intensity, and management practices.

SIC occurs predominantly in the form of calcite ($CaCO_3$) (Sanderman, 2012), although in some cases a non-negligible fraction of dolomite ($CaMg(CO_3)_2$) has been documented (Prokof'eva *et al*., 2021). In recent years, scientific interest in SIC and its contribution to the global carbon budget has increased significantly (Leogrande *et al*., 2021), overcoming the traditional underestimation of this fraction, historically considered less dynamic than SOC in the context of climate change mitigation.

The vertical distribution of SIC in soil profiles is strongly controlled by carbonate dissolution, transport, and re-precipitation processes, regulated by the chemical equilibrium between calcite and carbonic acid ($CaCO_3(s) + H_2CO_3(aq) \rightleftharpoons Ca^{2+} + 2HCO_3^-$) (Wang *et al*., 2010). Depending on climatic conditions, these processes can lead either to the downward mobilization of dissolved inorganic carbon or to the accumulation of carbonates within soil horizons. In this regard, Monger (2014) distinguished "flushing" regimes, typical of humid climates, in which dissolved carbonate is transported to groundwater, from "non-flushing" regimes, more common in arid environments, which promote the accumulation of solid carbonates within the soil profile.

At the global scale, the flux of carbon sequestered as bicarbonate to aquifers is estimated at approximately 0.2–0.36 Pg C yr^{-1}, with residence times on the order of hundreds to thousands of years (Sanderman, 2012). The SIC pool can be further subdivided into lithogenic carbonate (LC) and pedogenic carbonate (PC). LC originates directly from the soil's parent material, whereas PC forms in situ through processes of carbonate dissolution and re-precipitation, or via the solvation of CO_2 in the soil water film followed by precipitation with Ca^{2+} and Mg^{2+} ions (Monger, 2014; Leogrande *et al*., 2015).

In urban soil, these processes can be amplified or altered by the presence of alkaline anthropogenic materials and modified hydrological conditions. The formation of pedogenic carbonates can significantly affect soil physical properties, including porosity, water content, and gas diffusion (Zamanian *et al*., 2016). PC dynamics are closely linked to carbon exchanges between the soil and the atmosphere and, consequently, to global climate processes (Golubtsov *et al*., 2019). Atmospheric CO_2 enters the terrestrial ecosystem primarily through photosynthesis and root respiration, indirectly contributing to PC formation (Ferdush & Paul, 2021).

Several factors can promote the accumulation of pedogenic carbonates, including the input of aeolian dust, fertilizer application, irrigation, wet deposition, and weathering of the parent rock material (Dietrich *et al*., 2017; Kim *et al*., 2020). For net accumulation of SIC as pedogenic carbonate to occur, the alkaline earth cations involved in precipitation must originate from non-carbonate sources; otherwise, the carbon sequestered in the soil is offset by the release of CO_2 into the atmosphere (Carmi *et al*., 2019). For this reason, a distinction has been proposed between pedo-atmogenic pedogenic carbonates and pedo-lithogenic carbonates (Monger *et al*., 2015; Leogrande *et al*., 2015).

Intensive exploitation of natural resources, landscape transformation, and increased emissions of CO_2, CH_4, and other greenhouse gases have contributed significantly to global climate change processes (Chaysaz *et al*., 2019). Urban expansion influences SOC stocks at multiple spatial and temporal scales, often generating heterogeneous responses compared to natural environmental gradients (Chien & Krumins, 2022; Guo *et al*., 2024b).

Urban ecosystems may also contribute to carbon storage through vegetation growth, organic inputs, waste management, and atmospheric deposition processes (Richter *et al*., 2021; Pregitzer *et al*., 2022), although their capacity to do so varies widely depending on urbanization intensity and management practices. However, their capacity to store carbon is highly variable and strongly dependent on the degree of urbanization, soil sealing, and management practices. Global studies indicate that SOC stocks are generally lower in highly urbanized areas compared to peri-urban or natural soils, although site-specific management may partially mitigate these differences (Xu *et al*., 2024). Moreover, urban-specific phenomena such as soil sealing and compaction can reduce microbial activity and slow organic matter decomposition, in some cases helping to limit carbon loss (Vasenev & Kuzyakov, 2018; Ding *et al*., 2022). Given the complexity of carbon pools in urban soils, both organic and inorganic carbon dynamics, along with their stabilization and transformation processes, are essential to understand carbon cycling in urban environments.

Dynamics of Carbon Mineralization and Stability in Urban Soils: The Role of Microorganisms and Soil Structure

Soil organic carbon (SOC) mineralization in urban soils represents a central process in the terrestrial carbon cycle, linking carbon turnover in urban ecosystems with CO_2 emissions to the atmosphere.

Soil organic matter mineralization is a fundamental biological process in which decomposer microorganisms transform complex organic compounds into simpler mineral forms, such as carbon dioxide (CO_2) in the case of carbon, and ammonium (NH_4^+) in the case of nitrogen. The subsequent oxidation of ammonium to nitrate (NO_3^-) is not directly linked to organic matter decomposition but occurs through nitrification, a distinct microbially mediated process carried out by specialized chemoautotrophic microorganisms. This transformation represents a key step in the nutrient cycle, as it makes nutrients available to plants and influences greenhouse gas emissions from the pedosphere, reflecting the balance between carbon inputs, transformation, and release in soils (Gan *et al*., 2020).

Within the carbon cycle, mineralization is closely linked to the concept of organic carbon stability, which refers to the soil's capacity to protect carbon from microbial decomposition through physical, chemical, and biological mechanisms (Six *et al*., 2002; Lehmann & Kleber, 2015). In this context, the term *recalcitrant fraction* has traditionally been used to describe organic compounds characterized by inherent chemical resistance to microbial breakdown, such as lignin-rich materials or complex aromatic structures. However, increasing evidence suggests that carbon persistence in soils is not solely determined by molecular recalcitrance, but rather by ecosystem properties and stabilization mechanisms, including organo-mineral associations, spatial inaccessibility within aggregates, and interactions with mineral surfaces (Schmidt *et al*., 2011; Cotrufo *et al*., 2013). Therefore, the persistence of organic carbon in soils is now understood as an emergent property resulting from the interplay between substrate characteristics and environmental protection mechanisms. The complex nature of the soil microenvironment implies that even minor alterations in biological activities and physicochemical properties can have significant effects on carbon mineralization and sequestration (Dong *et al*., 2022).

In urban environments, mineralization dynamics are particularly complex due to multiple anthropogenic pressures that alter the soil's physicochemical and biological properties. Urbanization modifies both the quantity and quality of organic matter inputs through factors such as the addition of plant residues, compost, and other organic amendments associated with green space management, which can alter carbon and nutrient pools compared with non-urban soils (Pouyat *et al*., 2010). Additionally, urban-specific microclimatic conditions, including elevated soil temperatures resulting from the urban heat island effect, and management practices such as irrigation and fertilization, can

influence microbial activity and thereby affect carbon and nitrogen mineralization rates (Wang *et al*., 2022b). However, the effects of temperature on biological soil in urban areas are not uniform. While moderate warming in vegetated urban soils may enhance microbial activity and soil respiration, exposed urban soils can experience extreme surface temperatures under direct solar radiation, frequently exceeding 50–60 °C in bare patches during the summer. Such extreme thermal stress, combined with high evaporation rates, leads to rapid destruction, a decrease in microbial biomass, and inactivation of key soil enzymes, ultimately constraining organic matter decomposition and nutrient cycling (Qu *et al*., 2023). These conditions can create thermal and moisture constraints that override the stimulatory effects of moderate warming, particularly in soils lacking vegetative cover. Therefore, urban soil mineralization dynamics reflect a balance between enhanced microbial activity under moderate heat island conditions and microbial inhibition under extreme surface heating and moisture deficit. This balance is further modulated by other urban soil characteristics such as compaction, heterogeneity in organic inputs, and spatial variability in management practices, highlighting the need to consider both microclimatic extremes and land-use context when interpreting C and N cycling in urban ecosystems. These changes may lead to enhanced organic matter decomposition and increased CO_2 efflux from urban soils from urban soils to the atmosphere. At the same time, they can increase the availability of mineral nutrients for vegetation in urban green spaces (Fan *et al*., 2025).

Most predictive models of the carbon cycle forecast a decline in soil carbon stocks due to increased microbial activity and mineralization under warmer conditions (Haaf *et al*., 2021). However, recent evidence suggests that soil microorganisms, by regulating the physical and chemical microenvironment, can modulate the response of carbon mineralization to rising temperatures, contributing to the maintenance of a dynamic equilibrium of soil organic carbon and introducing substantial uncertainty into climate model projections, particularly in highly anthropized contexts (Na *et al*., 2022). Specifically, it has been shown that a significant portion of mineralized carbon can be reincorporated into relatively stable microbial residues, according to the Microbial Efficiency–Matrix Stabilization (MEMS) framework, thereby contributing to the formation of microbial-derived carbon that can be stabilized in soils (Cotrufo *et al*., 2013).

Studies conducted in specific urban contexts confirm this variability. For example, analyses of urban soils in Pisa showed that the potential for carbon mineralization, measured as CO_2 evolution during laboratory incubations, can be significantly higher in anthropized soils compared to a reference rural soil, suggesting greater variability in microbial activity and organic matter decomposition in urban settings (Saviozzi *et al*., 2014). However, it is important to distinguish between the potential for carbon mineralization, commonly estimated through laboratory incubations, and the actual CO_2

fluxes occurring under field conditions. In urban soil, physical factors such as compaction, reduced porosity, limited oxygen diffusion, and the presence of impervious surfaces can constrain the expression of microbial potential, resulting in a decoupling between mineralization capacity and in situ soil respiration (Vasenev & Kuzyakov, 2018).

Soil aggregates, fundamental units of soil structure, provide habitats and activity sites for microorganisms, driving material exchange and energy flow in terrestrial ecosystems (Liu *et al*., 2021). Approximately 90% of organic carbon in the surface layer of terrestrial ecosystems is contained within soil aggregates, highlighting the close relationship between aggregate formation and carbon sequestration/mineralization (Kan *et al*., 2022; Huang *et al*., 2021). Aggregate fragmentation leads to organic matter decomposition, whereas an optimal aggregate composition can promote carbon sequestration (Liu *et al*., 2018; Han *et al*., 2021). In urban soils, aggregate stability can be strongly influenced by compaction, physical fragmentation, and management practices associated with urban green spaces. While compaction can limit pore space and restrict microbial habitat, physical fragmentation and urban green space management practices (e.g., incorporation of organic amendments) can break down aggregates and increase the accessibility of organic carbon to microorganisms, thereby enhancing mineralization rates (Trammell *et al*., 2017).

Soil microorganisms play a dual role in the carbon balance, acting both as a source of CO_2 through heterotrophic decomposition and as a sequestration mechanism via the conversion of organic carbon into microbial residues that can be stabilized within soil aggregates. The net effect of these processes on carbon loss or retention strongly depends on the soil microenvironment, particularly oxygen availability and aggregate structure (Xu *et al*., 2024).

The rhizosphere, located approximately 1–3 mm from the root surface, is a hotspot of biological activity due to root exudates and litter inputs (Na *et al*., 2022). Organic matter in the rhizosphere undergoes faster decomposition and mineralization compared to bare soil, stimulated by the high levels of fresh nutrients that promote microbial activity (Dong *et al*., 2022).

At the same time, studies on nitrogen mineralization in urban green spaces in China have shown that the intensity of urbanization can increase the potential for organic nitrogen mineralization, partly through enhanced microbial biomass and labile nitrogen fractions sensitive to environmental changes (Fan *et al*., 2025).

In urban soils, CO_2 produced by SOC mineralization does not necessarily represent a net carbon loss but can fuel geochemical processes of inorganic carbon formation and transformation, promoting the formation of pedogenic carbonates within SIC in the presence of alkaline materials and elevated pH (Monger *et al*., 2015; Zamanian *et al*., 2016). Therefore, organic carbon mineralization constitutes a key linkage between SOC and SIC dynamics in urban systems (Monger *et al*., 2015; Zamanian *et al*.,

2016). Understanding mineralization in urban soils is thus crucial for assessing their capacity to regulate carbon storage, nutrient cycling, and gas fluxes at the city scale, particularly in the context of urban green management strategies and emerging practices of urban soil regeneration and fertilization.

Biodiversity in Urban Ecosystems

Ecological Role of Plant Biodiversity

The dynamics of carbon mineralization and stability in urban soils highlight how soil biogeochemical processes result from complex interactions among microorganisms, soil structure, and vegetation, underscoring the need to consider the role of the plant component and its diversity for an integrated understanding of ecosystem processes.

Plant biodiversity, defined as the variety of species, genes, functional traits, and plant communities present in terrestrial and aquatic ecosystems, represents one of the main drivers of ecosystem functioning. It encompasses the number and distribution of individuals and species, intra- and interspecific genetic diversity, and multiple levels of ecological organization (populations, communities, ecosystems, and biomes), whose interactions across different spatial and temporal scales frame ecosystems as complex adaptive systems (Levin, 2011).

Across these multiple levels of organization and interaction, plant biodiversity supports key ecosystem processes and the provision of essential ecosystem services. These include regulation of the hydrological cycle, carbon sequestration, soil protection and stability, support of trophic networks, and the production of biological resources.

Empirical studies indicate that highly diverse plant communities exhibit greater multifunctionality, resistance, and adaptive capacity to environmental disturbances, including climate change and anthropogenic pressures (Balvanera *et al*., 2014; Isbell *et al*., 2018).

Plant biodiversity also contributes to habitat structuring by creating ecological niches and maintaining complex networks involving animals, fungi, and microorganisms. The reduction of plant biodiversity can disrupt these networks, with negative consequences for ecosystem stability and biogeochemical cycles. In agroecosystems, the simplification of plant diversity resulting from intensive management practices reduces system resilience, whereas higher diversity enhances nutrient recycling, microclimate regulation, and reduces dependence on external inputs (Yan *et al*., 2023).

The relationship between biodiversity and ecosystem functioning is underpinned by several key mechanisms that determine productivity, stability, and resilience (Figure 7). One of the main

mechanisms is the complementarity effect, whereby species with different functional traits exploit resources in a spatially or temporally differentiated manner, thereby increasing overall community efficiency. Long-term studies on plant communities have shown that overall productivity is more stable when different species dominate at different times, ensuring efficient resource use and greater system resilience (Cardinale *et al*., 2012; Allan *et al*., 2011).

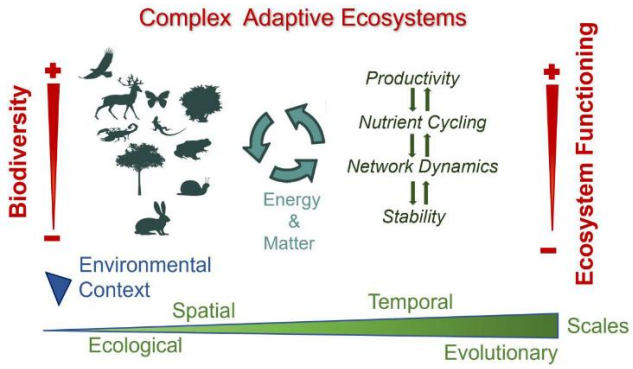


Figure 7. *Conceptual framework illustrates how biodiversity influences key ecosystem processes, including productivity, nutrient cycling, network dynamics, and stability, through interactions among organisms and the flow of energy and matter. The diagram highlights the role of environmental context and the integration of ecological and evolutionary scales in shaping ecosystem functioning. Source: Correia et al. (2023).*

Another important mechanism is the selection or dominance effect, which reflects the disproportionate contribution of highly productive or functionally efficient species that tend to prevail in more diverse communities. The relative importance of these mechanisms depends on environmental context, analytical scale, and the functional composition of plant communities (Turnbull *et al*., 2013).

Functional redundancy represents an additional mechanism of stability: when multiple species perform the same ecological function, the loss of individual species has a reduced impact on ecosystem functioning, acting as an 'ecological insurance' (Flynn *et al*., 2011; Bricca *et al*., 2021). Interactions between plants and soil microorganisms, such as mycorrhizal fungi, can further amplify the positive effects of biodiversity by enhancing productivity, resource-use efficiency, stability, and resilience of plant communities (Wahab *et al*., 2023).

Ecosystem functioning refers to the flows of energy, matter, and information within ecosystems, encompassing fundamental processes such as primary productivity, nutrient cycling, and the dynamics of ecological networks. From these processes emerge stability and resilience, which sustain ecosystem complexity across broader scales (Hagstrom *et al*., 2017). In this context, ecosystems can be regarded as complex adaptive systems (CAS), characterized by interconnected components,

nonlinear dynamics, and the capacity for self-organization in response to environmental change (Levin *et al*., 1998). Biodiversity and ecosystem functioning are therefore not static entities, but dynamic and emergent processes arising from local interactions among organisms, species' adaptive strategies, and combinations of functional traits (Levin *et al*., 2005).

The effects of plant biodiversity strongly depend on the spatial and temporal scales considered. At local scales and over short time intervals, ecosystem functioning may be dominated by a few highly productive species. At broader scales and over longer time periods, the effects of functional diversity, ecological redundancy, and species-specific responses to disturbances become more pronounced (Isbell *et al*., 2018).

Plant biodiversity is multidimensional: in addition to taxonomic diversity, functional diversity (the variety of ecological, morphological, and physiological traits) and phylogenetic diversity (the evolutionary relationships among species) are essential for understanding ecosystem functioning (Díaz *et al*., 2007; Flynn *et al*., 2011). Functional diversity often predicts ecosystem multifunctionality better than species richness alone, while functional redundancy reduces system vulnerability to the loss of individual species.

Despite consensus on the positive role of biodiversity, BEF literature presents certain limitations. Many experiments are conducted in simplified systems and over short temporal scales, making it difficult to distinguish the direct effects of biodiversity from those mediated by environmental factors (Cardinale *et al*., 2012; Turnbull *et al*., 2016). Moreover, the biodiversity–functioning relationship depends on the environmental context, the scale of analysis, and the type of ecosystem function considered. In complex natural ecosystems, dominant abiotic factors, such as climate, can modulate or obscure biodiversity effects (Jing *et al*., 2015; Valencia *et al*., 2018).

Plant biodiversity is not merely a structural attribute, but a dynamic process that governs ecosystem productivity, stability, resilience, and multifunctionality. Understanding the mechanisms linking biodiversity and ecosystem functioning is crucial for developing effective conservation strategies, preventing biodiversity loss and excessive ecosystem simplification, and ensuring ecological sustainability and human well-being at a global scale.

Mitigation of Urban Heat Island through Urban Vegetation

One of the most well-documented benefits of urban vegetation is its capacity to mitigate the Urban Heat Island (UHI) effect, a phenomenon in which densely built-up areas exhibit significantly higher temperatures compared to surrounding rural zones (Figure 8). This is due to the prevalence of heat-absorbing surfaces, reduced evapotranspiration, and heat emissions from anthropogenic activities

such as traffic and the use of heating, ventilation, and air-conditioning systems (Irfeey *et al*., 2023; Van der Meulen *et al*., 2022).

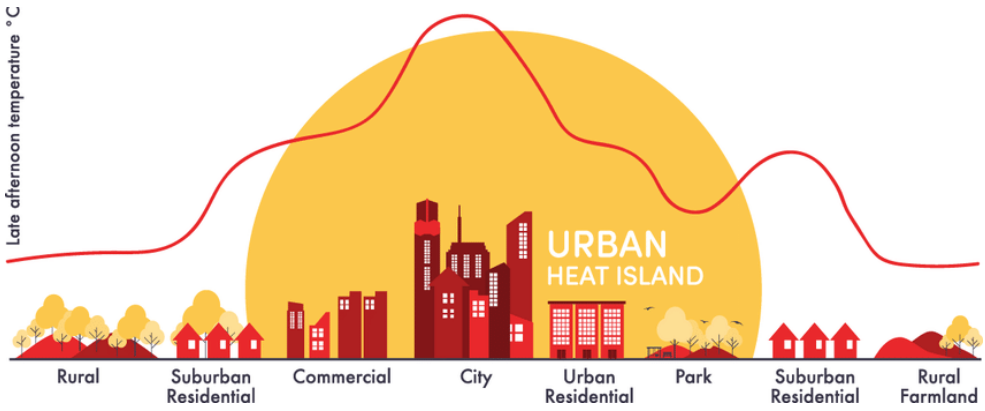


Figure 8. *Representation of the Urban Heat Island (UHI) effect, highlighting the temperature gradient from rural and vegetated areas to highly urbanized zones, were reduced vegetation cover and extensive built surfaces lead to significantly elevated surface and air temperatures. Source: Fuladlu et al. (2018).*

In addition to increasing thermal discomfort for urban populations, the UHI can enhance pollutant circulation, facilitating the transport of contaminated air from rural areas to cities and exacerbating air quality issues and energy costs (Van der Meulen *et al*., 2022). Urban afforestation and increased vegetation cover represent effective strategies to counteract these effects (Zhao *et al*., 2023). Remote sensing analyses have shown a widespread increase in urban vegetation, attributable to planting campaigns and public green initiatives, which contribute to lowering surface temperatures (Chen *et al*., 2019b; Piao *et al*., 2020). However, the magnitude of cooling depends on local factors, including climate, city size, and the spatial configuration of vegetation (Yang *et al*., 2022; Wang *et al*., 2022c). A recent global analysis of over 700 megacities highlighted that in approximately 22% of cities with annual precipitation below 1000 mm, vegetation may have a reduced cooling effect or even contribute to slight surface warming, particularly in areas with lawns or vegetation characterized by low albedo and limited evapotranspiration capacity. In these contexts, trees maintain a more stable cooling effect due to the use of deep soil moisture, indicating that vegetation effectiveness strongly depends on local climate and the types of plant species used (Lin *et al*., 2023).

In United States cities, the cooling effect resulting from urban afforestation ranges from 0.04 to 0.57 °C, whereas in large African cities it can reach values between 0.11 and 1.26 °C (Wang *et al*., 2020; Cheng *et al*., 2022). The main mechanisms through which urban vegetation reduces temperatures include shading, evapotranspiration, and convective heat exchange (Speak *et al*., 2020;

Paschalis *et al*., 2021; Li *et al*., 2023a). Shading decreases heat accumulation in urban materials such as asphalt and concrete, with surface temperature reductions of up to 11–25 °C compared to unshaded surfaces (Moncada-Morales *et al*., 2025), while evapotranspiration absorbs latent heat from the surrounding environment, enhancing the cooling effect.

Empirical studies and systematic reviews confirm that urban green areas exhibit lower temperatures than built-up or unvegetated surfaces, with average reductions ranging from 1 °C to over 2 °C, depending on the type, cover, and scale of vegetation interventions (Knight *et al*., 2021). The spatial configuration and type of vegetation significantly modulate thermal benefits: urban parks and connected green corridors can mitigate temperatures at the city scale, whereas smaller interventions, such as street trees and gardens, create cooler microclimates at the neighborhood level. However, the effectiveness of these mechanisms is influenced by water resource management and the physiological characteristics of plant species. Recent studies have shown that during heatwaves, lawns and trees respond differently: while lawns provide rapid cooling but deplete surface water more quickly, trees ensure more stable cooling over time by utilizing deep soil moisture (Fang *et al*., 2025). This suggests that the design of urban green interventions should consider not only the amount of vegetation, but also species selection, spatial distribution, and local water context, integrating sustainable resource management strategies.

Cooling effects have direct environmental and societal implications: they reduce thermal stress on the population, lower energy demand for air conditioning, and can help decrease mortality during extreme heat events (Li *et al*., 2023). Therefore, UHI assessments should consider not only vegetation cover, but the entire urban context, in order to design more effective, resilient, and sustainable public green interventions.

Urban Vegetation in Water Regulation and Soil Protection

Urban vegetation plays a fundamental role in soil water regulation and protection against erosion, providing a dynamic interface between the natural hydrological cycle and a highly anthropized environment. Plant roots improve soil structure by increasing porosity and promoting water infiltration and retention, thereby reducing the energy of surface runoff and its erosive potential (Xiao *et al*., 2024).

This effect is particularly important in urban contexts characterized by high imperviousness, where asphalted and concrete surfaces rapidly increase the volume and velocity of rainfall, overloading drainage networks and contributing to the risk of flooding and erosive events. Root systems not only create porous spaces that facilitate the downward movement of water through the soil profile, but also

directly influence soil hydraulic properties through processes of root exudation, penetration, water uptake, and root decay, affecting water retention and macropore formation in urban soils (Xiao *et al*., 2024).

The ability of plants to promote macropore formation is particularly effective in counteracting the effects of urban compaction, which would otherwise reduce hydraulic conductivity and infiltration capacity, increasing erosive forces and surface runoff. In degraded urban systems, the presence of deep roots and structurally complex plant communities can enhance pore connectivity and accelerate the detention and retention of rainfall in the soil (Corduan & Kühn, 2024).

The introduction of vegetation in impervious contexts, such as green roofs, rain gardens, or sustainable drainage systems, represents a nature-based approach to restore hydrological conditions closer to those of natural ecosystems, slowing runoff peaks and promoting local infiltration (Sgobbo, 2018). Soil protection from erosion is another key ecosystem service provided by urban vegetation. Herbaceous and tree cover reduce the kinetic energy of raindrops and surface water velocity, limiting particle detachment and the loss of fertile material.

Numerous studies show that vegetation acts as a natural "buffer strip", slowing the flow of runoff and retaining sediments and nutrients. In particular, the establishment of vegetated strips along slopes and watercourses can significantly reduce surface runoff and sediment production, as well as intercept nutrients such as nitrogen and phosphorus transported by runoff, through the combined effects of physical filtration, deposition, and vegetation-induced infiltration (Zhang *et al*., 2022b). However, these benefits are not without limitations and constraints. In the presence of highly impervious or compacted soils, infiltration capacity may remain severely limited even in the presence of vegetation, as roots struggle to penetrate hostile layers or those saturated with anthropogenic debris. Under such conditions, the positive effect of vegetation on infiltration may be constrained and require physical soil rehabilitation interventions (e.g., decompaction techniques or the use of organic amendments such as biochar or compost) to restore more favorable hydraulic conditions (Chowdhury *et al*., 2024).

Furthermore, vegetation-induced water regulation is influenced by plant management: species with very shallow root systems may provide lower hydrological benefits compared to species with deep and structurally complex roots (Functional urban groundcover) (Nur Hannah Ismail *et al*., 2023). The maintenance of green areas, the selection of native species with high water retention capacity, and the design of green infrastructure are therefore critical elements to maximize positive hydrological effects and minimize risks such as water competition in drier areas or overconsumption during drought periods.

The Role of Urban Vegetation in Carbon Sequestration

Urban vegetation contributes significantly to the global carbon cycle by acting as a CO_2 sink through the accumulation of aboveground and belowground biomass and the storage of carbon in soils associated with urban ecosystems (Figure 9). Recent studies demonstrate that vegetation community structure, tree cover, plant density, and a range of functional traits directly influence the carbon sequestration potential in urban areas.

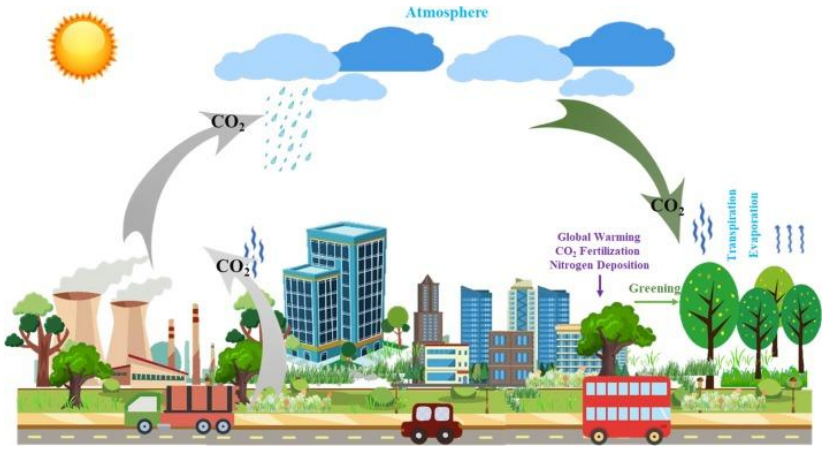


Figure 9. *Conceptual diagram illustrating carbon fluxes in urban environments, highlighting major CO_2 emission sources and the role of urban vegetation as a carbon sink. Vegetation absorbs atmospheric CO_2 through photosynthesis and contributes to greening, transpiration, and evaporation, while atmospheric processes such as global warming, CO_2 fertilization, and nitrogen deposition influence carbon dynamics within urban ecosystems. Source: Zhuang et al. (2022).*

In an analysis of 106 plant communities within an urban park in Zhengzhou, plant density and canopy cover were found to be strongly correlated with carbon stocks in both soil and biomass, highlighting how structural regulation of urban vegetation can maximize the capacity to absorb atmospheric CO_2 (Zhang *et al*., 2024a). Several international-scale studies highlight the quantitative relevance of urban vegetation as a component of the urban carbon budget. For example, in the United States, urban forests are estimated to store approximately 643 million tonnes of carbon and to sequester about 25.6 million tonnes annually, underscoring the substantial cumulative contribution that urban green areas can achieve within cities (Nowak *et al*., 2013).

Similarly, investigations of street trees in Beijing indicate that urban trees can contribute to carbon storage, albeit with lower carbon storage densities than surrounding natural forests due to urban

environmental conditions (e.g., elevated temperatures and nitrogen deposition), illustrating the complexity of carbon dynamics in anthropogenic environments (Tang *et al*., 2016).

The use of advanced technologies such as multispectral remote sensing and LiDAR to monitor the dynamics of vegetation cover and subsequently estimate the carbon sequestration potential of urban green infrastructure has helped overcome traditional methodological limitations. These approaches improve the spatial accuracy of carbon storage assessments and demonstrate that both species distribution and vegetation structure strongly influence the overall effectiveness of urban green infrastructure in sequestering carbon (Chang *et al*., 2025). Further evidence indicates that sequestration potential is highly dependent on species selection, photosynthetic efficiency, leaf area, and specific functional traits, suggesting that the use of species with high biomass accumulation capacity, based on photosynthetic rates, leaf area, and canopy architecture, can substantially enhance the contribution of urban vegetation to climate change mitigation (Jin *et al*., 2023).

Urban reserve forests, protected or regenerated forested areas within urban contexts, exhibit carbon densities comparable to those of natural tropical forests, with estimated carbon stocks ranging from 799 to 867 Mg CO_2 ha^{-1}. This highlights the importance of considering not only conventional public green spaces but also urban forest reserves within integrated climate change mitigation strategies (Malunguja *et al*., 2025).

Despite the documented benefits, literature highlights significant limitations and uncertainties. Many urban carbon assessments rely on allometric equations developed for natural forests, which may not be transferable to typical urban conditions, where vegetation is exposed to environmental stress, resource competition, compacted soils, and intensive anthropogenic management. These factors can substantially bias estimates of carbon storage and sequestration, underscoring the need to develop species- and context-specific allometric models for urban environments (Xie *et al*., 2025).

The net effectiveness of urban carbon sequestration is also influenced by emissions associated with green space maintenance (e.g., irrigation, pruning, and the use of fossil-fuel-powered machinery), which are often underestimated or omitted from overall carbon budgets. Failure to account for these components may lead to an overestimation of the net mitigation potential of urban vegetation (Zhang *et al*., 2024a). Recent studies further indicate that additional modulators, such as microbial biodiversity, soil amendment practices (e.g., biochar or compost), and soil management technologies, are critical for maximizing carbon stability in urban soils. However, these factors remain poorly integrated into urban sequestration models and represent an open and promising area of research (Fiorentino *et al*., 2025).

Effects of Urban Vegetation on Biodiversity Patterns and Ecosystem Functioning

Urban vegetation plays a central role in shaping biodiversity patterns and ecosystem functioning within cities, influencing ecological, social, and regulatory processes (Figure 10). Recent scientific literature highlights that urban green infrastructure should not be considered merely as a collection of isolated services, but rather as a network of interconnected ecological functions capable of generating both synergies and trade-offs among ecosystem services (Kowarik *et al*., 2023).

The ability of urban vegetation to simultaneously provide carbon sequestration, water regulation, microclimate mitigation, and wildlife habitat strongly depends on the structural and ecological characteristics of green spaces, such as size, connectivity, naturalness, and habitat heterogeneity (Belaire *et al*., 2022).

Figure 10. *Conceptual representation of the diversity of urban green spaces and their associated biota, illustrating how parks, historical landscapes, forests, grasslands, and water bodies collectively contribute to biodiversity and ecosystem functioning within cities. These interconnected green infrastructures support ecological processes, provide habitat for wildlife, and enhance the ecological, social, and regulatory functions of urban environments. Source: Gentili et al. (2024).*

At the species and community levels, urban vegetation influences biodiversity through habitat availability, structural complexity, and spatial connectivity. Continuous and structurally heterogeneous green spaces, including trees, shrubs, lawns, riparian zones, and small water bodies support higher species richness and abundance, hosting both generalist and specialist taxa (Jato-Espino *et al*., 2023). In contrast, isolated or heavily modified patches are more vulnerable to edge effects, environmental stress, and species loss.

The use of native species is particularly important: native plants sustain greater urban fauna abundance and diversity and provide a broader range of ecosystem services compared to non-native species, which often dominate urban plantings but offer less diversified services (Tartaglia & Aronson, 2024). The structural and functional diversity of urban vegetation further influences species interactions and local trophic networks, promoting ecological resilience and reducing the risk of functional simplification.

Studies indicate that riparian groves and mixed plantations along waterways simultaneously enhance habitat quality and the provision of ecosystem services such as carbon sequestration and microclimate regulation (Belaire *et al*., 2022). Urban vegetation drives key ecosystem functions by mediating nutrient cycles, hydrological processes, and microclimatic conditions. The effectiveness of these functions depends on species' composition, patch connectivity, and soil quality.

Trade-offs among ecosystem services are common: intensively managed parks may optimize cultural or regulatory services while providing limited habitat, whereas semi-natural areas can support biodiversity and multiple regulatory functions, albeit offering fewer recreational opportunities. Recognizing these trade-offs is essential for planning interventions that simultaneously maximize ecological and social benefits.

The distribution of ecosystem services and biodiversity is not uniform across cities. Socioeconomically disadvantaged neighborhoods tend to have fewer and lower-quality green spaces, limiting access to ecosystem services and exacerbating environmental inequalities (Zúñiga González *et al*., 2025). This phenomenon, known as the "luxury effect", highlights the importance of inclusive planning that integrates ecological and social objectives (Aznarez *et al*., 2023).

Despite emerging evidence, significant knowledge gaps remain. Research is concentrated in North America, Europe, and China, while other regions are underrepresented. Moreover, many studies are short-term or do not consider the specific contributions of species to ecosystem functioning, limiting our understanding of urban functional biodiversity.

Urban vegetation profoundly influences biodiversity patterns and ecosystem functioning, modulating the provision of multiple ecosystem services. An integrated approach that considers ecological, structural, and social aspects is essential to enhance urban biodiversity, optimize ecosystem functions, and ensure equitable distribution of benefits. Strategic planning and management, focusing on ecological connectivity, native species, functional diversity, and long-term monitoring, can transform urban green infrastructure into resilient, multifunctional ecological networks capable of supporting both biodiversity and human well-being in future cities.

Strategies for Biodiversity Conservation in Urban Social–Ecological Systems

Despite the growing scientific evidence on the positive effects of urban vegetation on biodiversity and ecosystem functioning, translating this knowledge into operational conservation strategies remains a significant challenge. In urban settings, biodiversity conservation cannot rely solely on traditional approaches focused on the protection of individual habitats or species but requires integrated planning tools capable of operating within complex and highly dynamic social–ecological systems (McDonnell & Hahs, 2015; Aronson *et al*., 2017).

The first critical issue concerns the gap between urban planning and conservation objectives. In many contexts, urban policies continue to prioritize quantitative indicators (e.g., per capita green space) at the expense of ecological quality, functionality, and connectivity of green spaces. This approach risks producing fragmented and biologically simplified green infrastructure, providing limited benefits for biodiversity (Belaire *et al*., 2022). However, more effective conservation strategies require the integration of biodiversity into urban planning instruments, such as zoning plans, green space strategies, and urban climate policies, overcoming the traditional separation between ecological and urban planning.

A second strategic axis concerns the multi-level and adaptive governance of urban biodiversity. The literature emphasizes that conservation in cities strongly depends on coordination among local authorities, planners, green space managers, and resident communities (Del Serrone *et al*., 2022). Adaptive management approaches, based on long-term monitoring and the continuous updating of management practices, are particularly relevant in urban environments subject to rapid climatic, social, and infrastructural changes (Ren *et al*., 2023). However, the lack of standardized data on urban biodiversity and its functional contribution still represents a significant limitation to the effectiveness of these strategies.

Another key aspect is the need to integrate biodiversity conservation with other urban objectives, such as climate mitigation, water management, public health, and environmental justice. While the multifunctionality of green infrastructure provides significant opportunities for synergy, it also entails potential trade-offs. For example, interventions primarily aimed at recreational use or urban cooling may reduce habitat quality for sensitive species, whereas overly intensive green space management can compromise soil ecological processes and trophic networks (Ken *et al*., 2020b; Bonilla-Bedoya *et al*., 2021). Conservation strategies must therefore recognize and manage these trade-offs, avoiding standardized solutions and favoring context-specific approaches.

The social dimension represents an additional critical element. As discussed in the previous section, urban biodiversity and access to ecosystem services are unevenly distributed across cities. Conservation strategies that fail to consider socio-spatial inequalities risk reinforcing the luxury effect and limiting the long-term effectiveness of environmental policies (Aznarez *et al*., 2023; Zúñiga González *et al*., 2025). In this regard, participatory tools, citizen science programs, and inclusive planning policies can contribute not only to the collection of ecological data but also to building social consensus around conservation objectives.

Finally, literature highlights significant knowledge gaps that limit the applicability of urban conservation strategies. Many studies focus on species richness metrics, neglecting functional biodiversity and soil–vegetation–microbiota interactions, which are fundamental for ecosystem stability. Moreover, most evidence comes from cities in the Global North, reducing the transferability of findings to other climatic and socio-economic contexts (McDonald *et al*., 2020). Addressing these gaps is essential to develop truly effective and generalizable conservation strategies.

In summary, biodiversity conservation in urban contexts requires a paradigm shift: from the mere implementation of green spaces to the planning of integrated social–ecological systems, grounded in scientific evidence, adaptive governance, and attention to both social and ecological dimensions of the city. Only through this approach can urban biodiversity persistence and long-term maintenance of ecosystem functions be ensured.

Integrated Management of Urban Soils and Green Spaces

Types of Urban Soil Management

Urban soils are characterized by high heterogeneity and profound alterations due to anthropogenic activities. To better understand their management and ecological potential, it is useful to distinguish between residual and anthropogenic soils, and to examine their classification within the Technosols system.

Residual soils represent portions of natural soil still present in parks, green areas, or lightly disturbed peri-urban zones. They retain much of the original pedogenetic processes, while still being affected by indirect urbanization impacts, such as increased surface temperatures, atmospheric pollutant deposition, or hydrological alterations (Burghardt, 2025).

Anthropogenic soils, on the other hand, are those whose profiles have been created de novo or are dominated by human-derived materials, often lacking continuity with pre-existing natural soils. In the international World Reference Base for Soil Resources (WRB) system, many of these soils fall

under the category of Technosols, defined as soils whose properties are governed by the presence of artifacts or human-constructed materials (Rigillo, 2022).Within urban contexts, Technosols can be distinguished into several types: i) Urbic Technosols: residential or densely built urban areas with a high presence of anthropogenic materials and construction debris; ii) Spolic Technosols: soils associated with sediments contaminated by industrial activities or waste deposits; iii) Ekranic (sealed) Technosols: soils subjected to permanent sealing, such as roads, plazas, and other paved surfaces (Rigillo, 2022).

This distinction has direct implications for urban soil management and regeneration. Residual soils can be conserved, restored, or enhanced through targeted interventions aimed at increasing organic matter and biodiversity, whereas artificial Technosols require specific management and monitoring strategies, particularly in cases of chemical contamination or sealing, to restore or maintain ecosystem functions. Urban soil management aims to improve or restore properties that allow soils to perform ecological functions and provide ecosystem services in highly anthropized contexts. Management approaches can be classified into several categories, often integrated: physical management, chemical management, and biological/ecological management (Figure 11).

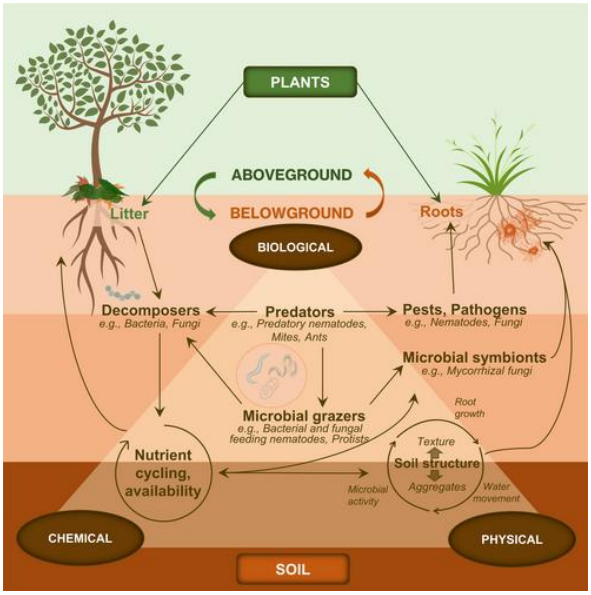


Figure 11. *Conceptual diagram illustrating the integrated physical, chemical, and biological components of the plant–soil system. The figure highlights how root processes, soil organisms, nutrient cycling, and soil structural properties interact to regulate soil functioning and plant growth. These interconnected domains form the basis for physical, chemical, and biological management approaches aimed at sustaining soil health and ecosystem performance. Source: Raupp et al. (2024).*

Integrated Management of Urban Soils: Physical, Chemical, and Ecological Approaches

Urban soils represent fundamental components of city ecosystems, providing essential services such as water regulation, nutrient cycling, carbon sequestration, and habitat support, yet urbanization often impairs these functions through compaction, surface sealing, chemical imbalances, and reduced biodiversity. Effective management of these soils requires integrated strategies that address physical, chemical, and ecological aspects simultaneously, aiming to restore soil functionality and resilience (Pouyat et al., 2010; Morel et al., 2015; Vasenev & Kuzyakov, 2018).

Physical interventions are central to this approach, targeting structural regeneration to enhance water infiltration, reduce compaction, and improve porosity. In highly impervious urban areas, limited infiltration increases flood risk and compromises eco-hydrological services essential for environmental resilience (Chowdhury et al., 2024). Techniques such as soil decompaction and aeration, often implemented with specialized mechanical equipment, break compacted layers to improve gas exchange and water movement, and when combined with organic amendments, enhance soil structure and infiltration capacity (Olson et al., 2013). Removing impervious pavements through depaving and desilting restores natural permeability, supports hydrological and biological functions, reconnects urban microhabitats, and fosters soil biodiversity (Maienza et al., 2021). On a broader scale, interventions like permeable surfaces, infiltration trenches, retention basins, and vegetated channels improve stormwater infiltration, groundwater recharge, and the overall resilience of urban soils (García & Santamarta, 2022).

Chemical management complements these structural interventions by rebalancing soil composition to restore fertility, correct pH imbalances, and reduce the presence of contaminants. Urban soil often accumulates heavy metals, hydrocarbons, and other pollutants from traffic, industry, and atmospheric deposition, disrupting natural biogeochemical cycles and impairing soil functions (Lovett et al., 2000; Marcotullio et al., 2008; Trammell et al., 2011; Burghardt, 2025). Organic amendments such as compost, stabilized manure, and biochar increase organic matter, stimulate microbial communities, improve nutrient retention, and reduce pollutant mobility, while slow-release fertilizers provide a gradual nutrient supply that minimizes leaching and accumulation risks (Edmondson et al., 2014; Schifman et al., 2018; Paz-Ferreiro et al., 2018; Breure et al., 2018; Vasenev & Kuzyakov, 2018). In more severely contaminated soils, techniques such as phytoextraction and chemical stabilization mitigate pollutant bioavailability, addressing a key limitation to ecosystem functionality in urban and peri-urban areas (Chaoyang & Tongbin, 2001; Morel et al., 2015).

Ecological and biological management further strengthens soil resilience by enhancing biodiversity, microbial activity, and biological interactions, which are crucial for maintaining ecosystem functions

in urban contexts. Soil is recognized as a living component of cities, regulating biogeochemical cycles, supporting vegetation, and contributing to human well-being (Kowarik, 2023; Burghardt, 2025). Nature-Based Solutions such as green roofs, rain gardens, bioswales, and infiltration trenches simultaneously influence physical properties, chemical stability, and microbial biodiversity, enhancing multifunctionality and ecosystem services. Empirical studies indicate that soils treated with these interventions show up to 30–50% increases in microbial activity and improved water retention compared to unmanaged soils, confirming the effectiveness of integrated approaches in heavily anthropized environments (Guo et al., 2024a; Rumpel et al., 2023; Fiorentino et al., 2024). Promoting functionally diverse microbial communities through organic matter addition and careful vegetation management further stabilizes urban soils and supports their fertility and resilience (Edmondson et al., 2014; Breure et al., 2018; Neina, 2019). Hybrid systems like urban agriculture and community gardens exemplify this integration, combining food production with ecological soil management while reinforcing human-nature connections and monitoring soil quality, provided contamination risks are carefully assessed (Pouyat et al., 2010; Kicińska et al., 2022).

A critical element of managing urban soils effectively is integrating pedological knowledge into urban planning. Despite advances in soil science, planning policies often underestimate soil's role and ecosystem services, lacking adequate indicators to monitor health and guide interventions (Morel et al., 2015; Burghardt, 2025; Lehmann & Stahr, 2007). Combining soil analyses, decision support systems, and green infrastructure allows for targeted, adaptive interventions that optimize soil multifunctionality, mitigate the risk of ineffective measures, and strengthen ecosystem services in urban environments (Breure et al., 2018; Vasenev & Kuzyakov, 2018). Nonetheless, knowledge gaps remain, particularly regarding deep soil layers and the complex interactions between pedological properties, biodiversity, human health, and ecosystem services. Addressing these gaps is essential to align scientific understanding with sustainable urban planning goals and to ensure resilient, multifunctional urban soils capable of supporting future cities (Pouyat et al., 2020; Kowarik, 2023).

Agronomic Management of Urban Green Areas

Agronomic management of urban green areas represents a central element for ensuring ecological functionality, soil health, and the overall resilience of urban ecosystems. It integrates cultivation practices and technical interventions aimed at maintaining parks, gardens, flower beds, and green spaces in optimal conditions, with the goal of promoting biodiversity, stabilizing soils, and enhancing carbon sequestration (Konijnendijk *et al*., 2021; Pouyat *et al*., 2010).

In recent years, the planning of urban green areas has seen the introduction of innovative guidelines, such as the so-called 3-30-300 rule (Figure 12), proposed by Konijnendijk *et al*. (2021). This guideline recommends that every citizen should be able to see at least three trees from their home or workplace, live in neighborhoods with at least 30% tree canopy cover, and have access to a public green space within 300 meters. Recent studies suggest that adopting these criteria not only improves the accessibility and usability of green spaces but also contributes to integrating ecological, social, and human well-being considerations into urban park management, thereby strengthening the multifunctionality and resilience of urban vegetation and soils.

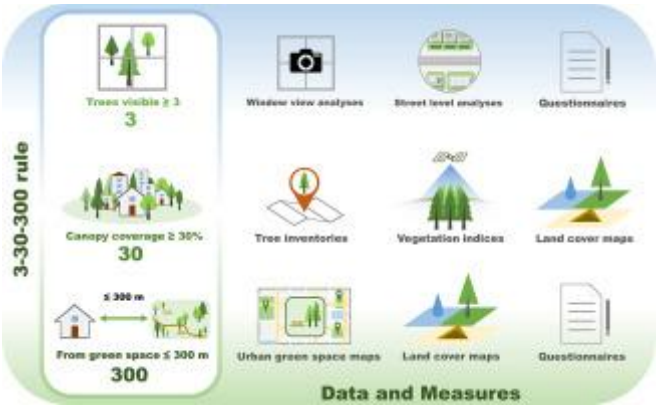


Figure 12. *Illustration of the 3-30-300 rule, summarizing the three core criteria for urban green-space planning, visibility of at least three trees, a minimum of 30% neighborhood tree-canopy cover, and access to a public greenspace within 300 meters—together with the main data sources used to assess these indicators. Source: Browning et al. (2024).*

Maintenance practices form the foundation of agronomic management. Irrigation, calibrated according to the soil's water-holding characteristics and the specific needs of plants, is essential to reduce water stress, stimulate soil biological activity, and promote healthy vegetation growth. The adoption of efficient systems, such as drip or micro-irrigation, has been shown to reduce water consumption by up to 30–40% compared to traditional methods, while simultaneously decreasing surface compaction and runoff (Berland *et al*., 2013).

Pruning and mowing, when carried out in a targeted manner, help maintain the vertical stratification of vegetation and control the spread of invasive species, contributing to the complexity of urban habitats (Tartaglia & Aronson, 2024). However, poorly calibrated interventions can have negative effects, reducing the availability of resources for urban wildlife, altering nutrient cycles, and limiting the capacity of plants to store carbon (Nowak *et al*., 2013).

Species selection is another critical element. It should be based on soil type, local microclimate, and plant tolerance to environmental stresses such as drought, salinity, and air pollution, as well as their ability to withstand extreme climatic events (Kowarik, 2023; Aznar *et al*., 2023). The integration of native species is effective in promoting urban biodiversity, as it supports local trophic networks and facilitates colonization by insects, birds, and soil microorganisms. Moreover, species with deep or highly branched root systems contribute to improving soil structure, increasing water retention, and promoting infiltration (Xiao *et al*., 2024; Nur Hannah Ismail *et al*., 2023). In areas subject to high environmental stress, such as neighborhoods with extensive impervious surfaces or elevated temperatures, the selection of resilient species becomes crucial to maintain ecosystem functionality and prevent the loss of essential ecosystem services, including water regulation and carbon sequestration (Zhang *et al*., 2024a).

Soil fertility and structure can be enhanced through targeted techniques. The addition of compost and biochar increases organic matter, stimulates microbial activity, and promotes stable carbon sequestration (Fiorentino *et al*., 2025; Chowdhury *et al*., 2024). Experimental studies indicate that the combined application of compost and biochar can increase soil water retention by up to 20–25% and boost microbial biomass by up to 30%, improving the resilience of compacted soils typical of urban environments (Paz-Ferreiro *et al*., 2018; Chowdhury *et al*., 2024). Mulching with organic materials reduces evaporation and limits surface erosion, maintaining more stable temperatures and creating favorable microhabitats for insects and microorganisms.

The inoculation of arbuscular mycorrhizae and other symbiotic fungi further enhances nutrient uptake by plants and strengthens the soil's capacity to store stable carbon (Wahab *et al*., 2023; Cotrufo *et al*., 2013).

Recent agronomic management of urban parks has evolved toward more sustainable and evidence-based practices. Intensive chemical fertilization has been progressively replaced or complemented with mature compost, organic amendments, and stabilized manure, which supply nutrients more evenly, improve soil structure, and increase water retention capacity (Edmondson *et al*., 2014; Malone *et al*., 2023; Breure *et al*., 2018). Periodic nutrient monitoring allows fertilizers to be applied according to the actual needs of plants, reducing the risk of nitrogen and phosphorus accumulation and limiting leaching into urban water bodies (Fan *et al*., 2025; Valencia *et al*., 2018).

Some urban administrations have also implemented digital park management systems, with detailed mapping of green areas and periodic soil analysis, thereby optimizing nutrient supply and minimizing environmental impact (Zhang *et al*., 2024a; Chen *et al*., 2019b). In urban parks with high foot traffic, organic mulches and localized fertilization are used to reduce erosion, protect plant cover, and supply nutrients more efficiently (Nur Hannah Ismail *et al*., 2023; Wahab *et al*., 2023).

In degraded or contaminated soils, modern practices combine organic fertilization with bioremediation or inoculation of mycorrhizal fungi and beneficial microorganisms, increasing nutrient availability, enhancing microbial biodiversity, and strengthening the ecological resilience of parks (Cotrufo *et al*., 2013; Wahab *et al*., 2023).

Challenges remain in urban agronomic management. First, the availability of financial resources and technical expertise can limit the widespread adoption of practices such as biochar application, digital monitoring, or targeted nutrient management. Moreover, high urban densities and widespread impermeabilization restrict the space available for green areas and the potential to optimize plant cover. In historically contaminated soils, organic fertilization and bioremediation practices reduce contaminant bioavailability but do not eliminate the risks associated with residual heavy metals or hydrocarbons. Finally, the integrated management of soil, vegetation, microorganisms, and nutrients requires interdisciplinary approaches, which are not always fully implemented within urban administrations (Pouyat *et al*., 2020; Kowarik, 2023; Breure *et al*., 2018).

Organic amendments

Benefits of Using Organic Amendments in Urban Areas

Traditionally, the use of organic amendments has primarily aimed at improving soil fertility and promoting plant productivity. However, in recent years, scientific interest in these materials has expanded, recognizing their potential contribution to climate change mitigation strategies (Figure 13). From a climate perspective, organic amendments contribute both to reducing the flow of organic waste destined for disposal and to increasing soil organic carbon stocks, thereby supporting carbon sequestration (Scharlemann *et al*., 2014).

Figure 13. *Schematic representation of the urban green waste management cycle and its contribution to soil improvement. Grass clippings and pruning residues are converted into organic soil amendments, enhancing nutrient availability (N, P, K, Ca, Mg, S), stimulating microbial activity, and increasing soil carbon stocks. Urban green area management, together with tree photosynthesis, promotes atmospheric CO_2 reduction and contributes to climate change mitigation. Source: created by the author with assistance from AI.*

The integration of organic amendments into urban soils can therefore simultaneously enhance soil health and increase carbon storage (Rastogi *et al*., 2023). Despite this potential, the contribution of urban soils to achieving climate targets at local, national, and global scales remains poorly quantified. It is therefore necessary to develop robust assessment frameworks capable of estimating the impact of materials such as compost and biochar not only on carbon sequestration but also on the ecosystem functions of the soil.

Emerging urban sustainability policies increasingly recognize the strategic role of organic amendments, although this growing attention must be accompanied by a critical assessment of potential environmental risks (Brose *et al*., 2014; Urra *et al*., 2019). One of the main challenges associated with the use of organic amendments in urban settings concerns the potential presence of undesirable components or contaminants. Heavy metals, persistent organic pollutants, and emerging contaminants have frequently been detected in materials such as compost, biosolids, livestock effluents, and sewage sludge, posing a potential threat to soil quality and human health (Mohapatra *et al*., 2016; Park *et al*., 2011; Petrie *et al*., 2014). In this context, agronomists and land managers are called upon to select materials that maximize agronomic benefits while minimizing ecological and health risks. Numerous experimental studies show that the application of compost in urban soils can significantly improve soil hydraulic properties, increasing infiltration capacity, water retention, aggregate stability, and total porosity. These positive effects largely depend on the molecular composition of the compost, which varies according to the source materials and the operational

conditions of the composting process (Kranz *et al*., 2020). In particular, the release of humic substances plays a key role in enhancing soil properties, due to their ability to regulate pH, act as redox agents, complex metals, promote nutrient mobilization, and stimulate plant growth (Wu *et al*., 2021). Furthermore, the use of compost in urban soils can promote the immobilization of potentially toxic elements, reduce their bioavailability and limit their migration toward groundwater (Palansooriya *et al*., 2020). Alongside compost, biochar has attracted growing interest as an amendment for degraded urban soils. It is a carbon-rich material produced through the pyrolysis of agroforestry biomass, characterized by high chemical stability and a wide range of functions. Initially proposed as a tool for carbon sequestration, biochar has since been associated with improvements in soil structure, nutrient dynamics, and microbial activity. Moreover, it can serve as support for beneficial microorganisms, immobilize organic and inorganic contaminants, and contribute to reducing greenhouse gas emissions (Bolan *et al*., 2022). Additional benefits include the enhancement of mycorrhizal symbioses, with positive effects on plant resilience and nutrient uptake (Agegnehu *et al*., 2017). Considering these characteristics, biochar appears particularly promising for the functional recovery of degraded urban soils. Recent evidence also suggests that the combined application of biochar and compost can produce synergistic effects, further enhancing soil fertility and plant productivity.

This approach aligns with the principles of the circular economy, as it allows the valorization of organic by-products from mechanical-biological waste treatment processes, such as compost and anaerobic digestates, to improve the quality of urban soils (Lord & Sakrabani, 2019). For these benefits to be fully realized, however, it is necessary to adopt an integrated approach based on careful characterization of the materials, long-term ecotoxicological assessments, and site-specific application protocols. Incorporating these amendments during soil preparation is crucial to optimizing carbon sequestration, enhancing the functionality of urban soils, and reducing risks associated with environmental contamination.

Carbon Storage and Nutrient Availability in Urban Soils Following Organic Amendment Application

Urban soils, when managed appropriately, possess significant carbon storage potential and can even enhance existing carbon stocks when amended with organic materials such as compost or biochar (Awad *et al*., 2017). However, the effectiveness of these amendments is highly context-dependent: soil physicochemical properties, the quality and type of amendment applied, and local environmental conditions substantially influence the resulting effects. A recent meta-analysis by Malone *et al*. (2023)

highlights that the use of organic amendments can increase the organic matter content of urban soils by an average of 3.6%, with biochar showing a higher increase (6.5%) compared to compost (3.1%). On the other hand, these mean values mask considerable variability across studies, underscoring the need for further site-specific research and standardized methodologies.

Several case studies confirm the benefits of managing urban soils with organic amendments. For example, De Lucia *et al*. (2013) reported that the application of sewage sludge-derived compost on urban soils can increase water retention capacity by up to 278% at the highest application rates, while also improving infiltration rates. In this context, the growth of native shrub species along urban hedgerows suggests that compost use can enhance the functionality of green infrastructure and support local biodiversity. However, the use of sewage sludge-derived compost raises significant concerns regarding contaminant accumulation, particularly heavy metals and organic pollutants, which are often insufficiently considered or monitored in available studies.

Furthermore, the long-term sustainability of these amendments remains uncertain, especially under the multiple environmental stresses typical of urban contexts, such as atmospheric pollution, soil compaction, or extreme climatic events. Another limitation of the current literature concerns the generalizability of results: most studies focus on specific types of urban soils or conditions of amendment application, neglecting the diversity of real urban contexts. Moreover, many works primarily evaluate the physicochemical effects on soils, without thoroughly analyzing the ecological implications, potential risks, or trade-offs associated with the use of organic amendments.

These aspects highlight a significant gap in current research: to optimize the benefits of organic amendments in urban soils, it is necessary to develop a multidisciplinary assessment framework that integrates chemical, physical, and ecological aspects, while also considering risks and long-term sustainability. Only in this way can the efficiency of agronomic practices be maximized and the resilience of urban soils and ecosystems supported (De Lucia *et al*., 2013; Awad *et al*., 2017; Malone *et al*., 2023).

Urbanization profoundly alters soil properties, often reducing their capacity to support healthy plant growth. Typical physical disturbances associated with urban environments lead to decreased water infiltration and water-holding capacity, while also disrupting natural nutrient cycles and depleting organic carbon stocks. These processes increase soil vulnerability to surface crusting and erosion, further exacerbating degradation (McDonnell *et al*., 1997; Lorenz & Lal, 2009; Haase, 2009; Chen *et al*., 2013; Chen *et al*., 2014). Among the most common strategies for restoring degraded urban soils are mechanical tillage and the addition of organic amendments, such as compost or biochar. However, the effectiveness of these interventions is highly dependent on site-specific characteristics and application methods (Sax *et al*., 2017; Beaudet *et al*., 2018). For example, a study by Somerville *et*

al. (2018) on three degraded urban plots examined the application of compost derived from urban green waste, with or without mechanical tillage to depths of 25 and 50 cm. The plant species used, *Corymbia maculata* H., chosen for its urban tolerance, exhibited heterogeneous growth responses: while the combination of compost and tillage improved certain soil physical properties, such as bulk density and porosity, plant growth at one site was negatively affected, likely due to temporary nitrogen immobilization or nutrient imbalances induced by the interaction between tillage and amendment. The study highlights that mechanical interventions combined with organic amendments can have unintended consequences, particularly when nutrient cycling processes are disrupted, and underscores the lack of long-term data to assess the persistence of these effects.

Similarly, Manrique-Veja *et al*. (2023) examined the influence of compost on soil properties and growth parameters of five native species (*Retrophyllum rospigliosii* (Pilg.) C.N.Page, *Inga edulis* Mart., *Citharexylum montanum* Moldenke, *Caesalpinia spinosa* Molina, and *Citharexylum sulcatum* Moldenke) cultivated in 60 L containers with amended substrate. The study reported improvements in soil electrical conductivity, cation exchange capacity, organic carbon content, and base saturation, accompanied by increases in plant height, stem diameter, leaf production, and chlorophyll content. Despite these promising results, the controlled nursery conditions limit the extrapolation of the data to real urban soils, which are characterized by high heterogeneity and multiple environmental stresses. Additionally, long-term effects and the potential accumulation of contaminants from compost, an crucial aspect in urban applications, were not assessed.

The application of organic amendments in urban soils is often promoted for their potential to enhance carbon storage; however, empirical data on carbon fluxes in urban contexts remain limited and sometimes contradictory (Bernal *et al*., 2006). While inputs of organic matter such as compost and biochar can increase soil organic carbon content, their effects on the carbon cycle are complex and do not always result in net sequestration. In particular, the addition of labile organic matter can stimulate microbial activity and accelerate the mineralization of pre-existing soil carbon, a phenomenon known as the priming effect, which may lead to a net increase in CO_2 emissions rather than enhanced carbon retention (Clark *et al*., 2007; Liu *et al*., 2006).

Studies such as those by Beesley (2012, 2014) have shown that the application of compost derived from urban green waste can increase dissolved organic carbon (DOC) concentrations in soil pore water, thereby stimulating microbial respiration (Luo & Zhou, 2006). In measurements conducted both in the field, across five peri-urban sites, and in laboratory incubations, Beesley observed that compost addition increases overall soil respiration rates, indicative of enhanced heterotrophic and autotrophic microbial activity. However, the temperature sensitivity of soil respiration decreases, suggesting a stabilizing effect of compost on CO_2 emissions under warming scenarios. These findings

highlight the complex relationship between organic amendments and carbon fluxes: while organic matter inputs may increase carbon loss through microbial respiration, they can also help modulate soil responses to temperature changes.

Ghosh *et al*. (2015) conducted a study in a tropical urban area of Singapore, evaluating the impact of biochar and compost, applied individually or in combination, on a clay-loam surface soil and on the growth of two tree species (*Samanea saman* (Jacq.) Merr. And *Suregada multiflora* (A.Juss.) Baill.). The results showed positive effects on nutrient availability and plant growth when the two amendments were applied together. However, the study did not provide a long-term perspective nor insight into the microbial or physics chemical mechanisms underlying these effects. In more temperate contexts, Somerville *et al*. (2020) conducted a trial at two urban sites in Melbourne, characterized by different soil textures (sandy-loam and sandy-clay), comparing six treatments including a control, mechanical tillage, compost, biochar, and two biochar–compost combination doses, while monitoring soil physical properties and the growth of *Corymbia maculata* (Hook.) K.D. Hill & L.A.S. Johnson. Biochar improved soil aggregation and water retention, particularly in sandy soils with low organic matter, but the combined benefits relative to compost alone were largely limited to macroaggregate formation. The study also highlights economic and practical limitations associated with biochar use in urban contexts, due to the high production costs, especially at small scales (Kumar *et al*., 2020).

Controlled experiments, such as that by Japakumar *et al*. (2021), have shown that the combined application of biochar and compost increases plant height, leaf number, chlorophyll content, and soil organic carbon, confirming the potential of organic amendments to enhance fertility and urban plant productivity. However, these experiments were conducted in pots with artificial substrates, limiting the replicability of the results in complex urban soils subject to variable environmental stresses.

Generally, the literature indicates that biochar and compost can improve soil fertility, structure, and water retention, particularly in sandy soils or under drought conditions. However, a critical analysis shows that compost alone often provides comparable benefits at significantly lower costs. The production costs and market price of biochar (Haider *et al*., 2022) raise further questions about its widespread use. Therefore, a thorough preliminary assessment of urban soils is essential to tailor amendment strategies (Eldridge *et al*., 2018). Future studies should focus on long-term trials across diverse urban contexts, include microbial and biochemical analyses, and evaluate cost–benefit ratios, to guide sustainable urban soil management and maximize the ecosystem services provided by green spaces.

Organic Amendments and Microbial Function in Urban Soils

The application of organic amendments represents a promising strategy to stimulate microbial activity, increase microbial biomass, and improve soil biochemical properties. Both classical and recent studies have demonstrated significant increases in microbial biomass and enzymatic activity in soils amended with organic matter compared to soils receiving inorganic fertilizers or left unamended (Bastida *et al*., 2008; Biederman *et al*., 2008). Organic amendments supply carbon substrates and essential nutrients that promote microbial growth and proliferation, thereby enhancing key soil functions related to carbon, nitrogen, and phosphorus cycling (Figure 14). This evidence is further supported by recent meta-analyses showing a positive relationship between microbial diversity, functional capacity, and soil fertility following large-scale applications of organic amendments (Liu *et al*., 2023; Shu *et al*., 2022).

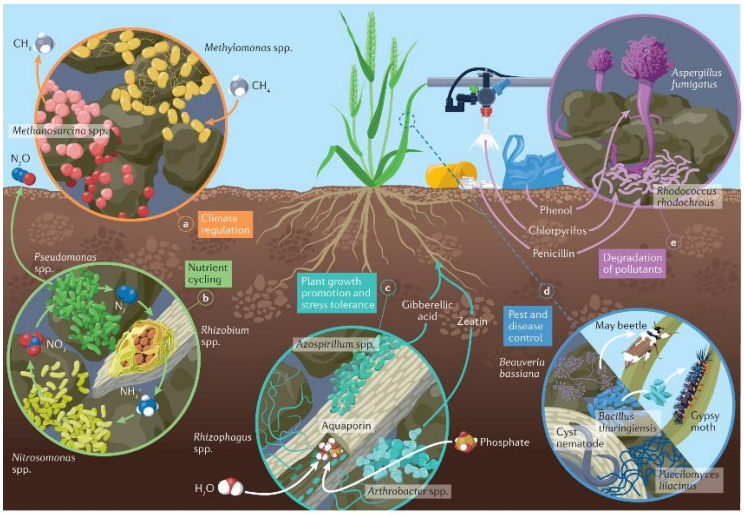


Figure 14. *Functional roles of soil microorganisms in regulating climate processes, nutrient cycling, plant growth promotion, pest and disease suppression, and pollutant degradation. These microbially mediated pathways constitute the biochemical foundation through which organic amendments enhance microbial activity, increase microbial biomass, and improve soil functional properties. Source: Hartmann & Six (2023).*

Biochar, owing to its highly porous structure and large specific surface area, creates favorable microhabitats that protect microorganisms from environmental stresses such as desiccation and predation, thereby promoting biofilm formation and the colonization of taxa capable of metabolizing recalcitrant carbon and contributing to the stabilization of soil organic matter (Palansooriya *et al*., 2019). These structural properties can also enhance water retention and influence key soil variables such as pH and cation exchange capacity, which in turn shape the composition and activity of soil

microbial communities. This has been demonstrated in studies showing that biochar and compost applications can significantly alter microbial assemblages in soils associated with urban trees (Shiu *et al*., 2022). However, the effects of biochar on soil microbial communities are not uniform. While biochar can increase microbial diversity and promote copiotrophic bacteria under certain conditions, its application alone generally induces more moderate changes than those observed with organic compost, particularly during the first years of the amendment application. Direct comparisons between biochar and compost have shown that compost more strongly alters microbial community structure and enhances enzymatic activity and nitrogen-induced respiration. This suggests that the presence of readily degradable substrates in compost stimulates higher microbial turnover than biochar, whose effects are more closely associated with carbon stabilization processes and physical interactions with the soil matrix (Azeem *et al*., 2020).

Studies conducted in urban soils and under conditions of anthropogenic degradation further confirm these trends. For instance, Azeem *et al*. (2020) reported that the application of compost, either alone or in combination with biochar, increases both enzymatic activity and microbial diversity during turfgrass establishment, with effects intensified at higher amendment rates that modify soil pH and nutrient availability (Gomez *et al*., 2014). However, excessive biochar application can reduce bacterial abundance, indicating that a "one-size-fits-all" approach is not universally applicable to urban soils, where environmental conditions and soil physicochemical properties vary widely (Wang *et al*., 2015).

The relationship between amendment rate and microbial response is also supported by global meta-analyses, which show that the effects of organic amendments on microbial biomass are stronger in soils with low initial carbon and nitrogen contents, underscoring the importance of pre-existing pedological conditions in modulating biological responses (Liu *et al*., 2023). The co-application of biochar and compost is often more effective than single treatments in supporting key microbial functions, as compost supplies readily available labile carbon and nutrients, while biochar provides physical and chemical stability to the incorporated organic matter. This synergistic effect simultaneously enhances soil fertility and microbial quality, supporting processes such as carbon and nutrient mineralization and increasing the activity of enzymes including β-glucosidase, dehydrogenase, and phosphatase, which are fundamental to biogeochemical cycles.

Studies using compost–biochar mixtures have reported significant shifts in microbial pools, with increases in bacterial taxa potentially beneficial for soil functioning (Shiu *et al*., 2022). The literature reviewed by Carlson *et al*. (2015), for example, indicates that different amendments derived from urban waste, including biosolids and plant residues, can induce short-term increases in fungal biomass and enzymatic activity. However, after three years, microbial indicators tend to converge across

treatments, highlighting that immediate benefits do not necessarily persist over time in the absence of further interventions and underscoring the importance of multi-year studies to understand the stability and persistence of microbial responses.

These dynamics are consistent with broader evidence showing that microbial community responses to organic amendments vary widely across pedoclimatic contexts, pH conditions, moisture regimes, and initial soil nutrient availability (Garcia *et al*., 2024). Ndour *et al*. (2025) demonstrated that different compost types influence not only the composition of microbial communities in remediated urban brownfield soils, but also the structure of bacterial–fungal interaction networks and overall soil multifunctionality. Specifically, compost application increased metabolic richness and the capacity to degrade a broad range of organic compounds, thereby enhancing soil functional performance in nutrient cycling processes and carbon sequestration. These shifts in microbial structure and diversity are generally accompanied by increases in both alpha diversity and overall community composition, as confirmed by large-scale meta-analyses reporting significant increases in diversity indices such as Shannon diversity and microbial taxonomic richness in response to organic amendments compared with mineral fertilizers (Shu *et al*., 2022). Under urban conditions, studies on compost derived from municipal waste mixed with pruning residues and garden waste have shown enhanced microbial diversity and community complexity, with a greater representation of bacterial groups associated with the mineralization of organic compounds and improved metabolic efficiency (Chiarelli *et al*., 2025).

In summary, the scientific literature confirms that organic amendments, namely compost, biosolids, and biochar, applied individually or in combination, exert a substantial influence on urban soil microbial communities, affecting microbial biomass, diversity, and functional activity. However, the magnitude and persistence of these effects are strongly dependent on amendment type, application rate, site-specific conditions, and treatment duration. The paucity of long-term studies and large-scale multi-omics approaches represents a significant knowledge gap, highlighting the need for future research that integrates multi-year monitoring with detailed analyses of microbial networks and their functional roles, to develop truly effective and adaptable strategies for the sustainable management of urban soils under ecological and anthropogenically heterogeneous conditions.

Soil remediation strategies in urban environments using organic amendments

In urban contexts, soils are often subject to degradation processes caused by compaction, contamination, and structural alterations resulting from human activities. To counteract these effects, the use of organic amendments, such as compost and biochar, has been proposed as a sustainable

strategy for soil remediation and restoration, capable not only of improving soil fertility and structure but also of enhancing the ecological resilience of urban ecosystems.

Several experimental studies have documented the effectiveness of compost in rehabilitating urban soils. For example, Sax *et al*. (2017) conducted a long-term intervention at the Cornell University campus, combining physical soil fracturing with the incorporation of 33% by volume compost derived from food waste, plant residues, manure, and animal bedding followed by annual mulching. After 12 years, treated soils showed a 51% reduction in bulk density, increased water retention capacity, and a threefold increase in root penetration depth compared to untreated soils. Additionally, biochemical soil indicators, such as active carbon and potentially mineralizable nitrogen, increased, correlating with greater tree growth and overall improved plant performance. Despite these promising results, the replicability of such intensive interventions may be limited by economic and logistical constraints, including compost availability and the use of specialized equipment.

Other studies have compared different types of compost. Heyman *et al*. (2019) evaluated compost derived from manure, green residues, and food waste, assessing soil quality and the growth of *Phaseolus vulgaris* L. using a nutrient leaching bioassay. All compost types improved soil quality and plant growth, with the best performance observed in manure-based compost. However, the study did not investigate potential long-term negative effects, such as nutrient imbalances or contaminant accumulation.

The use of biochar as an urban soil amendment has been studied in various contexts of acute contamination and biological degradation. Škrabalová *et al*. (2025) applied biochar at 5% to an urban soil contaminated by tire fires, characterized by high phytotoxicity and reduced biological activity. Germination tests, plant growth assessments, and microbial respiration measurements showed that biochar significantly reduced phytotoxicity, increased seed germination rates, and decreased plant growth inhibition. At the same time, microbial respiration increased, indicating a recovery of soil biological functions. These results confirm the potential of biochar as a sustainable strategy for the remediation of urban soils degraded by acute contamination events.

Reviews and meta-analyses have confirmed the effectiveness of both amendments. Bolan *et al*. (2014) reported that compost improves soil fertility and biological activity, while biochar reduces contaminant mobility; their combination produces synergistic effects, enhancing water retention, soil structure, and the resilience of degraded ecosystems. Zhou *et al*. (2023), through a meta-analysis of over 40 studies, showed that the combined application of biochar and compost increases plant biomass, soil organic carbon content, and reduces the bioavailability of heavy metals, proving more effective than the use of each amendment separately.

The effectiveness of organic amendments is also contingent upon the type of contaminant present. Karer *et al*. (2015) reported that the impact of biochar, compost, and inorganic amendments varies depending on the specific heavy metal, with some combinations capable of immobilizing metals, whereas in other cases they may inadvertently enhance metal mobility. Similar studies have confirmed that compost and biochar can reduce the bioaccessibility of lead and arsenic; however, their efficacy remains highly contaminant-specific (Paltseva *et al*., 2020; Kargar *et al*., 2015). Numerous experiments on industrially or artificially contaminated soils further corroborate the synergistic role of compost and biochar. Beesley *et al*. (2010) demonstrated that the compost–biochar combination simultaneously enhances the chemical and biological quality of the soil, increasing organic carbon and microbial activity while reducing the bioavailability of heavy metals (Cd, Pb, Zn). Studies on soils contaminated with copper (Cárdenas-Aguiar *et al*., 2017) and with antimony and zinc (Garau *et al*., 2024) highlighted that biochar decreases the mobile fraction of metals and, when combined with compost, maximizes biological functionality and supports plant growth, promoting effective phytoremediation strategies. Mazzucco-Miritana *et al*. (2025) showed that the combined application of biochar, bioaugmentation, and phytoremediation can remove up to 90% of hydrocarbons while enhancing plant tolerance in contaminated soils.

Finally, Wang *et al*. (2025) demonstrated that the application of biochar (4–8%) and compost (7.5%) to urban soils intended for ornamental plantings enhances soil moisture, available nutrients, and functional microbial communities, optimizing the chemical, physical, and biological quality of the soil. Additionally, this treatment promoted genes associated with carbon fixation, highlighting the potential of compost–biochar blends to enhance the carbon sink function in urban environments. Generally, recent literature confirms that compost and biochar, applied individually or in combination, represent effective strategies for the remediation and rehabilitation of degraded or contaminated urban soils. Compost enhances fertility and stimulates biological activity, whereas biochar reduces contaminant mobility and stabilizes soil structure. Their combined application offers synergistic benefits, increasing water retention, stable carbon content, and microbial functionality. However, effectiveness is contingent upon the type of contaminant, amendment dosage, and soil characteristics, underscoring the importance of site-specific and tailored interventions. These strategies constitute a promising and sustainable approach for the ecological restoration of urban soils, with positive implications for plant productivity and the resilience of urban ecosystems.

Micronized Amendments in Soils: Principles, Properties, and Application Perspectives

The application of organic amendments represents a key strategy for improving the quality of urban soils, which are often degraded, compacted, and depleted in organic matter. In recent years, alongside traditional amendments, increasing attention has been directed toward the use of micronized amendments, i.e., organic materials subjected to intensive particle-size reduction processes. Micronization may increase specific surface area and reactivity, potentially enhancing interactions with the soil matrix, which can be relevant in urban soil contexts, where edaphic conditions are frequently extreme and highly heterogeneous. Micronization is a particle-size reduction technology that enables the production of particles in the micrometer range without substantially altering the surface structure of the material. Compared to conventional grinding techniques, micronization allows for more controlled particle-size reduction and may reduce thermal or mechanical stress on the processed materials. The process typically involves the use of high-pressure air or mechanical impact to break down particles, ensuring uniform size distribution while preserving the material's chemical and physical characteristics. Compared to classical grinding, which relies on mechanical shear and compression, micronization offers finer control over particle size and reduces the risk of heat-induced degradation. This technology has been applied in several specialized sectors, including the pharmaceutical industry over the past decades, such as the pharmaceutical industry, where particle-size reduction is critical for enhancing the bioavailability and efficacy of active compounds (Rasenack *et al*., 2004; Joshi, 2011). Interest in this technology has also been explored in environmental and agronomic contexts, particularly as a means to enhance the quality and efficiency of organic amendments. Fine particle-size reduction markedly increases the specific surface area of the material, enhances its reactivity, and facilitates interactions which may influence nutrient availability, water dynamics, and microbial colonization processes. (Ding *et al*., 2016; Palansooriya *et al*., 2019). An additional potential implication of finely divided amendments in urban soils is their improved applicability under vegetated conditions. Conventional bulk organic amendments require incorporation during soil preparation, limiting their use to pre-vegetation stages and constraining temporal nutrient management. In contrast, micronized amendments, owing to their reduced particle size and increased surface area, can be applied via fertigation or precision liquid injection systems, potentially allowing more uniform distribution, more targeted nutrient release, and reduced mechanical disturbance to established vegetation. This approach enables continuous modulation of soil physicochemical properties, nutrient bioavailability, and microbial colonization dynamics throughout the growing season.

Micronized Biochar: Strategies to Maximize Agronomic Efficiency

Biochar is a carbonaceous material produced through the pyrolysis of biomass and has been extensively studied for its ability to improve the physical, chemical, and biological quality of soils (Figure 15). Its properties are strongly influenced by several factors, including pyrolysis temperature, feedstock type, and process conditions (Lehmann & Joseph, 2015).

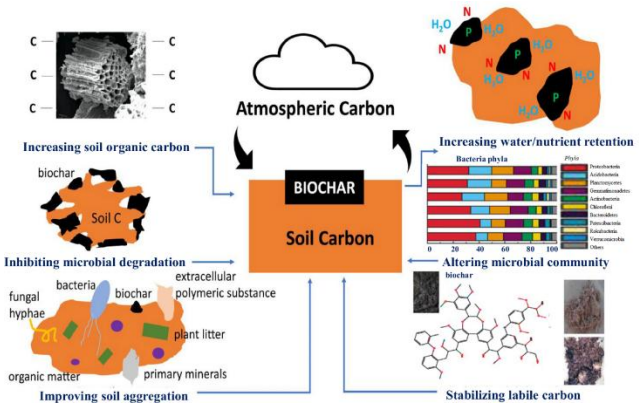


Figure 15. *Functional mechanisms through which biochar enhance soil physical, chemical, and biological properties, including increased soil organic carbon, improved aggregation, greater water and nutrient retention, altered microbial community structure, reduced microbial degradation, and stabilization of labile carbon. These processes underpin the growing interest in biochar as a soil amendment derived from biomass pyrolysis. Source: Biswal & Balasubramanian (2025).*

One particularly relevant aspect, widely documented in scientific literature, concerns the influence of particle size on biochar performance in soils. Although studies explicitly focusing on micronized biochar are still limited, numerous investigations have demonstrated that reducing particle size increases specific surface area, accessible porosity, and material reactivity (Tomczyk *et al*., 2020; Zhang *et al*., 2025).

These findings support the relevance of particle-size reduction effects on biochar behavior in soils: micronization does not introduce a fundamentally new principle, but rather amplifies an already well-established mechanism, namely the increase in specific surface area as a key driver for enhancing the agronomic effectiveness of biochar.

From a physical perspective, several studies have shown that finely sized biochar promotes the formation of stable soil aggregates, increases porosity, and enhances water infiltration (Herath *et al*., 2013; Zhang *et al*., 2024b). These effects are particularly relevant in urban soils, which are frequently characterized by compaction and poor structural development. Micronization, by further reducing

particle size, therefore represents a strategy to maximize these benefits, enhancing the effectiveness of biochar in improving the physical quality of urban soils.

Soil chemical properties may be influenced by particle size reduction. Biochar with finer particles exhibits a higher cation exchange capacity per mass unit, improved pH buffering capacity, and a greater ability to retain nutrients, thereby reducing nutrient leaching losses (Yuan *et al*., 2011; Ding *et al*., 2016). By increasing the reactive surface area, finer particle sizes may enhance these effects, making biochar more efficient in sustaining soil chemical fertility.

Finally, regarding carbon sequestration, the stability of pyrogenic carbon is primarily determined by the chemical structure of the material rather than particle size. However, finer particles may enhance interactions with the soil mineral matrix, increasing the likelihood of organo-mineral associations and improving the physical protection of carbon within aggregates (Cotrufo *et al*., 2013).

Micronization of Vermicompost: Enhancing Soil Fertility and Biological Function

Vermicompost is an organic amendment produced through the biological decomposition of organic matter mediated by earthworms (Figure 16). It is widely recognized for its richness in readily available nutrients, hormone-like compounds, enzymes, and beneficial microorganisms (Edwards *et al*., 2010; Arancon & Edwards, 2011). Although scientific literature does not explicitly address micronized vermicompost, numerous studies have investigated the effects of fine particle size and fractionation on its agronomic efficacy.

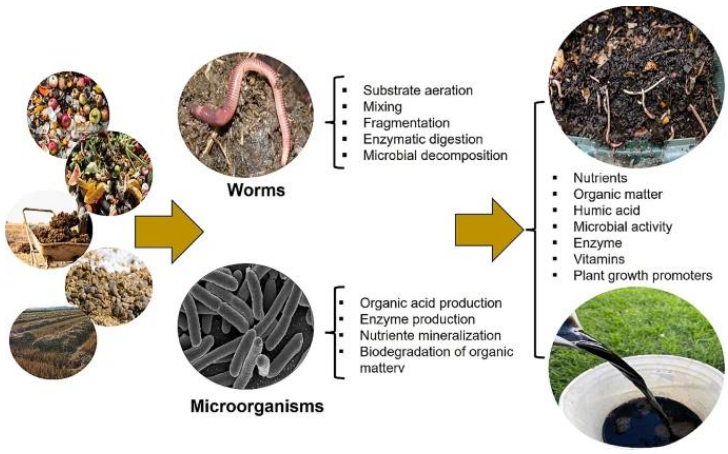


Figure 16. *Overview of the vermicomposting process, showing how earthworms and microorganisms transform organic waste into nutrient-rich compost and liquid fertilizer through aeration, fragmentation, enzymatic activity, and microbial mineralization. Source: Cruz et al. (2024).*

Reducing the particle size of vermicompost increases the contact surface with the soil and accelerates the mineralization of organic matter, thereby making nutrients more rapidly available to plants. Studies comparing vermicompost fractions of different fineness have shown that smaller particles release nutrients more uniformly and in a timelier manner (Saha *et al*., 2012). Micronization, by further reducing particle size to even finer scales, therefore represents a logical extension of these findings, with the potential to further enhance nutrient bioavailability.

From a physical perspective, finely fractionated vermicompost improves soil structure, enhances aggregate stability, and increases water-holding capacity (Castellini *et al*., 2024). These effects are particularly relevant in urban soils, were compaction and low organic matter content limit soil functionality. Micronization, by increasing the ability of the material to penetrate soil micropores, may further enhance these effects, enhance porosity and reduce bulk density.

Soil chemical properties are also influenced by the particle size of vermicompost. Finer fractions exhibit higher cation exchange capacity and faster nutrient availability, thereby enhancing soil chemical fertility (Atiyeh *et al*., 2000). Micronization, by further increasing the reactive surface area, has the potential to amplify these effects, making vermicompost more effective in supporting plant growth under urban soil conditions.

The biological component of the soil responds particularly positively to finely fractionated vermicompost. The increased specific surface area enhances microbial activity and stimulates the rhizosphere through the provision of bioactive compounds and beneficial microorganisms (Domínguez *et al*., 2019). Micronization, by further increasing the contact surface, can intensify these processes, improving plant vitality and resilience to water and thermal stresses.

Finally, although vermicompost is not primarily intended as a long-term carbon sequestration amendment, its finely fractionated form can contribute to the stabilization of organic matter through the formation of stable aggregates and the production of microbial necromass carbon (Aira *et al*., 2010). These processes, already documented in the literature on fine particle size, provide the scientific rationale for employing micronization as a technique to enhance urban soil quality.

Regulatory Framework for Soil Amendments: European and Italian Legislation

In recent years, scientific and policy interest in the use of organic amendments in both agricultural and urban soils has increased significantly. This trend is closely linked to growing attention to environmental sustainability, circular management of organic waste, and the strategic role of soils in climate change mitigation. The increasing use of compost, digestates, biochar, and other amendments

has necessitated the development of a comprehensive and progressively harmonized regulatory framework aimed at ensuring material quality, environmental safety, and human health protection.

At the European level, the primary reference for soil amendments is Regulation (EU) 2019/1009 of the European Parliament and Council, concerning making available on the market of EU fertilizing products. Fully applicable since July 2022, this regulation replaced the previous Regulation (EC) No. 2003/2003, substantially expanding the scope of EU legislation (European Commission, 2019).

Regulation (EU) 2019/1009 establishes a harmonized classification of EU fertilizing products, including fertilizers, soil amendments, growing media, and plant biostimulants. Soil amendments are defined as materials intended to improve the physical, chemical, or biological properties of soils, independently of their nutrient content, formally recognizing their functional role in enhancing soil quality rather than directly supplying plant nutrition.

One of the most innovative aspects of this regulation is the introduction of harmonized contaminant limits, particularly for heavy metals such as cadmium, lead, mercury, and nickel, to prevent hazardous accumulation in soil and reduce risks to food chains and public health (Bolan & Kirkham, 2023). The regulation also aligns with EU circular economy policies, promoting the recovery and valorization of organic waste as a soil resource, in line with the EU Circular Economy Action Plan (European Commission, 2020).

A closely related regulatory aspect concerns by-products of animal origin, governed by Regulation (EC) No. 1069/2009 and its implementing rules (Regulation (EU) 142/2011). Implementing Regulation (EU) 2023/1605 clarifies the so-called “end point” in the production chain, after which materials derived from animal by-products are no longer subject to sanitary restrictions, allowing their safe transformation into amendments (Collivignarelli *et al*., 2019).

In Italy, soil amendments are primarily regulated by Legislative Decree 29 April 2010, No. 75, which serves as the national reference text. The decree defines amendments as materials to be applied in situ to maintain or improve the physical, chemical, and biological characteristics of soils, explicitly acknowledging their multifunctional role in soil quality enhancement.

Legislative Decree 75/2010 specifies the categories of allowed amendments, minimum chemical-physical requirements, contaminant limits, labeling requirements, and registration obligations with the national Manufacturers Register. Attention is given to material traceability and the transparency of information provided to end-users, which is especially relevant in urban contexts where direct human exposure to amended soils is more likely. The decree has been periodically updated to include new materials and adjust quality standards, reflecting progressive alignment with EU regulations while integrating provisions on waste management (Legislative Decree 152/2006) for materials derived from the composting of municipal organic waste.

Currently, the regulation of soil amendments in Italy operates on a dual-level system. Products compliant with Regulation (EU) 2019/1009 can enter the European market as EU fertilizing products, benefiting from free circulation, while Legislative Decree 75/2010 governs materials marketed exclusively at the national level. This coexistence provides flexibility to operators but requires careful assessment of material compliance, particularly for organic amendments intended for urban use. Recent studies indicate that differences between EU and national frameworks can influence usage strategies and perceived risks associated with amendments (Cucina *et al*., 2021).

The European and Italian regulatory frameworks establish clear requirements for contaminant limits, traceability, chemical-physical characteristics, and product quality, which are essential for safe use in highly anthropized urban environments. However, scientific literature emphasizes that current regulations mainly focus on product safety and quality, while long-term effects on carbon stabilization, microbial biodiversity, and soil ecosystem services are still poorly addressed, especially in urban soils (Rastogi *et al*., 2022).

In conclusion, the regulation of soil amendments in Europe and Italy has evolved toward harmonized criteria for product quality, safety, and sustainability, with Regulation (EU) 2019/1009 and Legislative Decree 75/2010 representing the core regulatory pillars. While ensuring safety and compliance, the complexity of urban systems and the increasing recognition of soils as ecological infrastructure highlight the need for further scientific and regulatory development. Integrating long-term assessments of amendment effects on soil carbon, biodiversity, and ecosystem functions will be crucial to support sustainable management practices.

Digital Technologies for Monitoring Organic Amendments in Urban Systems

Digital agriculture is transforming the way cropping systems are observed, analyzed, and managed. The integration of in situ sensors, IoT platforms, proximal sensing techniques, and remote sensing, combined with predictive models based on machine learning, enables the collection of high-resolution spatial and temporal data on soil and plant conditions (Wolfert *et al*., 2017; Liakos *et al*., 2018). Sensors measuring soil moisture, temperature, electrical conductivity, matric potential, and CO_2 facilitate real-time monitoring of water dynamics, organic matter mineralization, and microbial activity (Viscarra Rossel *et al*., 2017). In urban environments, where spatial variability is high and edaphic conditions are often extreme, these tools provide a critical advantage for understanding and managing soil responses to improvement interventions.

The integration of organic amendments with digital technologies is gradually emerging in scientific literature. Although studies specifically addressing urban soils remain limited, there is research

utilizing sensors to monitor the effects of biochar, compost, and vermicompost on soil properties. Several studies have employed sensors to assess the impact of organic amendments, albeit primarily in non-urban contexts. For instance, Abel *et al*. (2013) investigated the effect of biochar on soil water retention using continuous measurements of moisture and matric potential, reporting a significant increase in water-holding capacity. Similarly, Basso *et al*. (2013) monitored water dynamics in sandy soils amended with biochar, highlighting improvements in water availability and greater temporal stability of soil moisture.

Other studies have employed electrical conductivity (EC) sensors to monitor nutrient availability in soils treated with compost and vermicompost. Arancon *et al*. (2006) demonstrated that vermicompost application increases soil electrical conductivity, measurable via EC sensors, reflecting enhanced availability of readily assimilable nutrients. In urban contexts, Rivier *et al*. (2022) utilized moisture and EC sensors to assess the effects of compost and vermicompost on soil structure and hydraulic properties, revealing significant improvements in water-holding capacity and chemical fertility. Regarding the mineralization of organic matter and microbial activity, several studies have employed soil CO_2 sensors to monitor microbial respiration following amendment application. Jones *et al*. (2012) observed that biochar alters soil CO_2 fluxes, indicating changes in decomposition and carbon stabilization processes. Similarly, Case *et al*. (2014) confirmed that biochar can reduce CO_2 emissions, with effects measurable through soil respiration sensors.

In urban contexts, the use of IoT technologies is playing an increasingly important role in the intelligent management of soils and green spaces. Sensor network–based monitoring systems enable continuous collection of data on soil moisture, temperature, electrical conductivity, and other key parameters, which can be integrated into digital platforms to support site-specific decision-making. Samarpita and Satpathy (2025), in a study on IoT-enabled soil monitoring within "smart" agricultural systems, demonstrated how such technologies can transform sustainability dynamics across urban and rural contexts, highlighting the potential of sensors to optimize resource use, reduce water losses, and enhance the resilience of managed ecosystems. Although Satpathy's (2025) work does not focus exclusively on urban soils, the conceptual framework proposed is fully transferable to urban green spaces and community gardens, where high spatial variability and water limitations make data-driven management particularly valuable.

In this context, the integration of organic amendments with IoT-based sensing represents a promising approach: amendments enhance soil structure, water retention, and fertility, while sensors enable real-time monitoring of system responses, allowing for the dynamic calibration of irrigation, nutrient inputs, and adaptive management strategies in urban green areas.

Remote sensing is becoming an increasingly valuable tool for assessing vegetation responses to soil management interventions, including in urban contexts. Although studies directly applying proximal sensing to biochar-amended soils are still lacking, the literature demonstrates that multispectral indices obtained from drones or handheld sensors can detect variations in plant water availability and physiological status (Zhang *et al*., 2022a). Remote sensing allows the integration of point-based in situ sensor data with broader spatial information, enhancing the understanding of vegetation responses to soil conditions. The combined use of multispectral data, analytical models, and vegetation vigor maps enables the identification of water stress gradients, growth differences, and variations in nutrient distribution, providing a spatially continuous representation of the effects of soil management practices.

In this context, micronized amendments represent an emerging frontier. Although the specific literature remains limited, established knowledge on the effects of fine particle size in biochar, compost, and stabilized organic fractions suggests that finer materials can elicit faster and more pronounced responses in soil water and nutrient dynamics. The increased specific surface area and higher reactivity of micronized amendments make them particularly suitable for monitoring with digital sensors, which can detect subtle variations in water availability, electrical conductivity, and microbial respiration. This paves the way for experimental studies that integrate micronized amendments with advanced sensor technologies to achieve a more detailed understanding of urban soil regeneration processes.

Furthermore, the integration of data from in situ sensors, drones, and satellites can be enhanced through machine learning algorithms, which model the complex relationships between soil parameters and amendment responses. These predictive models enable the optimization of irrigation, fertilization, and urban soil improvement interventions, promoting a more adaptive and resilient management of urban soils.

Overall, the convergence of organic amendments and digital agriculture offers a unique opportunity to develop adaptive management frameworks for urban soils. Amendments enhance the physical, chemical, and biological quality of the soil, while digital sensors allow real-time monitoring of these improvements, enabling optimized interventions and increasing the resilience of urban ecosystems. The integration of these two dimensions, agronomic and technological, represents one of the most promising directions for research and sustainable management of urban green spaces, forming the conceptual foundation of the present doctoral work. Future perspectives include the development of integrated digital urban monitoring frameworks, the use of citizen science and open data to increase observation density, and the combination of sensors, drones, satellites, and machine learning for more accurate predictive assessments. Furthermore, experiments with micronized amendments coupled

with advanced sensing technologies provide an opportunity to gain a more detailed understanding of urban soil regeneration processes.

Challenges and Research Gaps: Scientific Limitations and the Need for Integrated Studies on the Use of Organic Amendments in Urban Soils

The increasing focus on urban sustainability and ecological restoration has highlighted the crucial role of urban soils, both as carbon reservoirs and biodiversity hotspots, as well as key components of the resilience of anthropized ecosystems. Despite the rapid growth of literature on the use of organic amendments in these contexts, a critical analysis reveals that a fully coherent and integrated methodological framework is still limited. Compost, digestates, biosolids, and biochar are increasingly proposed as tools to improve soil quality, enhance biodiversity, and increase carbon sequestration in urban environments; however, the available studies suffer from several structural limitations: they are often fragmented, conducted under unrepresentative conditions, of short duration, scarcely comparable, and rarely able to convincingly link observed effects to clear and generalizable mechanistic processes. In other words, the enthusiasm surrounding organic amendments in urban soils is not yet supported by a sufficiently solid empirical basis, particularly considering the complexity of urban soils described in the introduction: anthropized, engineered, compacted, contaminated soils characterized by strong vertical and horizontal heterogeneity, altered climatic conditions (e.g., UHI), and continuous management pressures.

A primary and perhaps most evident limitation concerns the lack of truly integrated studies that simultaneously link, within the same experimental design, the physical, chemical, and biological properties of the soil, microbial and plant communities (herbaceous, shrub and tree crops), and associated ecosystem services. Most studies on organic amendments in urban soils focus on only one or two aspects at a time: some measure solely physical parameters (bulk density, porosity, field capacity, infiltration), others assess only chemical indicators (organic C, total N, CEC, pH), while still others are limited to evaluating the response of a model plant species in terms of growth or biomass. Even rarer are studies that systematically include microbial biodiversity (taxonomic diversity, community structure, enzymatic functions) and greenhouse gas fluxes (CO_2, N_2O, CH_4) in amended urban soils. Consequently, the ecosystem dimension is often neglected, namely how the application of amendments in urban soils simultaneously influences soil structure, functionality, biodiversity, and carbon sequestration potential. From a critical perspective, this suggests that many conclusions reported in the literature are based on partial evidence, rendering inferences regarding

the “overall benefits” of amendments often more extrapolative than demonstrably supported by empirical data.

A second major limitation is the lack of experimental data collected under real urban conditions, with all the complexities that such environments entail. Many studies on organic amendments are conducted in pots, greenhouses, or laboratory microcosms: sterilized soils or artificial mixtures are often used, plants are grown under control conditions, amendments are applied at high and homogeneous doses, and variables such as compaction, contamination, and fluctuations in water and temperature are largely eliminated or minimized. While these studies provide valuable insights into general trends, their applicability to real urban soils, often compacted, artificially stratified, contaminated with heavy metals or microplastics, and subject to recurrent mechanical disturbances such as trampling, traffic, or maintenance, is limited. In this context, translating results obtained from simplified experimental systems to urban soil conditions require caution and further investigation.

Closely linked to this issue, the temporal dimension represents an additional structural limitation of existing literature. Most studies on organic amendments are limited to a few months, and in some cases one to two years, rarely extending beyond this timeframe. However, the processes relevant to carbon sequestration and the stabilization of organic matter are, by definition, slow: formation of stable aggregates, organo-mineral associations, accumulation of microbial necromass carbon, transformations of pedogenic carbonates, and the development of microbial communities toward more complex and functionally redundant states. Short-term studies may detect increases in soil carbon content that simply reflect the carbon added with the amendment or temporary increases in microbial biomass; however, they are limited in their ability to distinguish between carbon effectively stabilized in persistent forms and rapidly mineralizable carbon that will return to the atmosphere over short timescales. From a critical perspective, this limitation may lead to an overestimation of the climate mitigation potential attributed to amendments in urban environments and an underestimation of possible trade-offs, such as increased N_2O emissions in nitrogen-rich soils with altered hydrological dynamics.

Another significant gap concerns the spatial scale and representativeness of study sites. Many investigations focus on single locations, often with limited area, and lack geographical replication or coverage along urban–periurban gradients. Urban soils are highly heterogeneous: they may include residual, technogenic, imported, sealed, or partially sealed soils, each with markedly different histories of use and disturbance. Applying the same interpretative frameworks or management recommendations to parks, street planters, abandoned industrial sites, and urban gardens is methodologically questionable, yet this is commonly observed in much of the existing literature. Furthermore, the geographical coverage of studies is often restricted to a few countries in North

America, Western Europe, and, to some extent, China; Mediterranean, tropical, arid, and Southern Hemisphere contexts remain relatively underrepresented.

A particularly challenging issue, especially in urban environments, concerns the management and assessment of contaminants. Compost, digestates, biosolids, and stabilized sludge may contain heavy metals, organic micropollutants, pharmaceutical residues, microplastics, and other emerging substances. While the risks and limitations of these materials are well-documented in agricultural studies, their consideration in urban contexts is still limited and fragmented. Many studies focus primarily on the "positive" effects of organic amendments, such as improvements in physical and chemical soil properties or enhanced plant growth, yet provide limited systematic evaluation of potential risks, including bioaccumulation, leaching, and direct human exposure (e.g., in parks, playgrounds, and urban gardens). The extensive use of organic amendments in urban settings should be critically evaluated in terms of potential environmental and health impacts without a clear and rigorous assessment of potential impacts on human health and urban ecosystem integrity.

A further and particularly relevant limitation, almost entirely absent from the current body of literature, concerns the use of micronized organic amendments, an emerging category that is attracting increasing interest but remains largely unsupported by a solid scientific foundation. Unlike conventional amendments, for which a broad and diversified literature exists, studies explicitly dedicated to micronization are still limited and fragmented, and often restricted to controlled laboratory conditions, with no evaluation in real soils, let alone in urban environments. Particle-size reduction can substantially affect surface area, reactivity, porosity, nutrient-release kinetics, and the physical–chemical interactions between amendments and soil; however, systematic studies are still lacking that compare micronized and non-micronized forms of the same material, nor that assess the effects of micronization on soil physical, chemical, and biological properties within a unified experimental framework. In urban soils, characterized by compaction, vertical heterogeneity, contamination, and altered hydrological regimes, the absence of studies on micronized amendments represents an even more critical gap. It is plausible that finer particles interact differently with technogenic substrates, compacted horizons, or contaminants, yet such hypotheses remain entirely untested. Similarly, the biological implications of micronization, such as potential shifts in microbial diversity, functional guilds, or trophic network stability, are still unknown, and no studies have examined how micronized materials influence vegetation dynamics or ecosystem resilience in urban settings.

Further limitations concern the constrained applicability of precision agriculture technologies, including IoT-based monitoring, proximal sensing, remote sensing, and data-driven decision-support systems, in urban environments. Although these tools are increasingly promoted as promising

solutions for improving resource efficiency and supporting adaptive management, their actual implementation in urban soils remains extremely limited, and the available evidence is insufficient to support robust or generalizable conclusions.

Most precision agriculture research has been developed in rural or peri-urban contexts, where soils are relatively homogeneous, management practices are standardized, and spatial scales allow for the deployment of sensor networks, automated irrigation systems, and high-resolution remote sensing. In contrast, urban soils present structural constraints that challenge the assumptions underlying precision agriculture: extreme spatial heterogeneity, discontinuous soil volumes, compaction, contamination, and the presence of artificial layers and technogenic materials. These conditions reduce the reliability of sensor-based measurements and complicate the interpretation of spatial patterns derived from proximal or remote sensing.

Furthermore, the spatial scale of urban green areas is often too small, fragmented, or irregular to justify the deployment of technologies originally designed for agricultural fields. Tree pits, roadside planters, pocket parks, and highly disturbed soils do not provide the continuity required for geostatistical analyses, variable-rate applications, or spatially explicit modelling. As a result, many of the core principles of precision agriculture, such as within-field variability mapping, zone delineation, or site-specific management, become difficult to apply or lose operational meaning in urban settings.

Another critical limitation concerns data integration and interpretability. Urban environments generate complex microclimatic conditions (e.g., heat islands, shading patterns, altered hydrology) that influence sensor readings and vegetation indices in ways that are not yet fully understood. The lack of calibration datasets specific to urban soils and vegetation further limits the accuracy of models used to estimate soil moisture, nutrient availability, or plant stress. Consequently, the risk of misinterpretation is high, and the potential for erroneous management decisions cannot be overlooked.

From a practical perspective, maintenance, accessibility, and vulnerability of sensors represent additional challenges. Urban green areas are subject to vandalism, theft, accidental damage, and frequent disturbances due to maintenance operations. Power supply, connectivity, and long-term data continuity, often taken for granted in rural precision agriculture, become problematic in fragmented urban landscapes.

Finally, the absence of integrated studies that combine precision agriculture tools with soil amendments, vegetation dynamics, and ecosystem service assessments in urban contexts represents a major research gap. While these technologies hold significant potential for improving the monitoring and management of urban soils, their current use is supported by a very limited empirical

foundation, and their applicability to the complexity of urban ecosystems remains largely untested. This gap is particularly relevant considering that the present thesis incorporates original data collected in urban environments using MPM100 and TDR sensors, and thermal imaging demonstrating both the potential and the practical challenges of applying precision agriculture tools to highly heterogeneous and anthropized soils.

The biological component of urban soils is often treated in a reductive or superficial manner in studies on organic amendments. On one hand, several studies report increases in microbial biomass or enzymatic activity following amendment application, yet they rarely investigate community structure, functional diversity, or the stability of microbial trophic networks. Regarding plant biodiversity, the literature is frequently limited to the responses of individual species or simple growth parameters, without addressing floristic composition, functional diversity, community resilience, or trade-offs between productivity, stability, and resistance to invasive exotic species. This gap is particularly striking considering that one of the primary arguments for using organic amendments in urban environments is their potential to support more diverse, structurally complex, and resilient vegetation.

From a methodological perspective, application rates, incorporation methods, timing, compost type and degree of maturation, material origin, soil moisture conditions, and subsequent management practices vary considerably across studies. Detailed descriptions of the materials used, such as physical and chemical properties, contaminant content, and carbon fractions, are often lacking, which hampers reproducibility and comparability of results. In many cases, appropriate controls are absent (e.g., treatments with only mechanical disturbance, or comparisons among different amendments at the same carbon dose), and statistical analyses are limited by low replication and incomplete experimental designs. Frequently, results are often interpreted in a positive framework, with broad conclusions about “ecosystem benefits” drawn from restricted datasets, limited to few parameters and a single urban context.

In conclusion, the current literature indicates that the use of organic amendments in urban soils is still characterized by incomplete knowledge and significant experimental and methodological gaps. These limitations limit a fully robust assessment of the real effects of such interventions on soil functionality, biodiversity, and carbon dynamics. It is precisely within these gaps that the need arises for more rigorous and integrated studies, such as the one developed in this thesis, aimed at providing a more realistic and robust understanding of the role of organic amendments in the ecological regeneration of urban soils.

Aims of the thesis

The increasing urbanization of recent decades has profoundly transformed urban soils, with significant implications for their ecological functioning, biodiversity, and capacity for carbon sequestration. In this context, the sustainable management of urban soils represents a critical challenge for contemporary cities, which must reconcile environmental, social, and climate-related demands. Scientific research has demonstrated that the application of organic amendments can substantially contribute to improving soil quality, promoting the regeneration of spontaneous vegetation, and enhancing soil organic carbon stocks; however, the majority of existing studies have focused on conventional materials and agricultural settings, leaving urban soil.

The micronization of organic amendments, such as vermicompost and biochar, has recently attracted attention, although it remains relatively underexplored in agronomic and urban soil contexts. Reducing particle size to the micrometer scale increases the specific surface area of the material, potentially influencing soil–amendment interactions, with possible effects on nutrient availability and vegetation response dynamics. Despite these promising attributes, the scientific literature still provides limited evidence assessing the effects of micronization under real-world conditions, particularly in urban environments characterized by strong heterogeneity, compaction, low fertility, and multiple interacting stressors.

In parallel, the advent of digital agriculture has made innovative tools available for the non-destructive monitoring of vegetation and soil. Sensors such as MPM100, NDVI, PRI, thermal cameras, and TDR (time domain reflectometry) enable the acquisition of detailed information on plant physiology, vigor, photosynthetic efficiency, canopy temperature, and soil water content. The integration of micronized amendments with digital monitoring represents an integrated experimental approach, capable of providing high temporal and spatial resolution datasets and of more accurately characterizing the response dynamics of urban systems.

The present thesis is positioned precisely within this space of innovation, with the aim of assessing the effects of commercial micronized organic amendments (vermicompost and biochar) in real urban soils, monitoring spontaneous vegetation responses through digital sensors, and analyzing the medium-term carbon sequestration potential. The experimental work was carried out at two urban sites with contrasting agronomic management, the campus of the University of Salerno (Fisciano) and a field site in the province of Avellino, to evaluate soil responses under different environmental and fertility conditions. These initial sites were relatively undisturbed, with no nearby trees or cemented surfaces. From the second year onwards, the study was extended to include two additional plots at the Salerno campus: one adjacent to cemented areas and subject to frequent trampling (Path),

and another under a tree canopy with Linden trees (Linden), representing more disturbed conditions than the original sites

The present thesis aims to address a series of fundamental research questions. The first concerns the response of urban soils to the application of micronized amendments compared to conventional materials and mineral fertilizers. The second investigates how micronized organic amendments affect nutrient availability, water retention, and soil physicochemical properties. The third question focuses on the effects of amendments on spontaneous vegetation physiology, assessed through leaf pigments, vigor indices, and photosynthetic parameters. The fourth examines the ability of digital sensors to sensitively and promptly detect differences among treatments.

Preliminary observations suggest several well-founded hypotheses. It is plausible that micronized amendments produce faster and more pronounced effects than non-micronized materials due to their increased specific surface area. The combination of vermicompost and biochar may generate positive synergies on vegetation physiology, as indicated by results obtained at the Fisciano and Avellino sites. Digital sensors appear capable of detecting treatment differences with greater sensitivity than traditional methods, particularly regarding NDVI, PRI, and leaf pigment measurements. Moreover, soils with lower initial fertility, such as the Avellino site, may exhibit more pronounced responses to amendments.

The experimental design implemented over the three-year period is particularly robust and comprehensive. It includes two real urban sites, additional plots with increased amendment rates, five initial treatments later reduced to four, bimonthly surveys, soil physicochemical analyses, digital vegetation monitoring, and statistical analyses based on Anova and Duncan's tests. This framework allows for an integrated assessment of the interactions between soil, vegetation, and environment, providing a comprehensive view of the effects of micronized amendments.

This thesis provides one of the first field-based assessments of micronized amendments in urban soils, integrates digital agriculture with urban soil management, delivers multi-year data under real-world conditions, and proposes an innovative conceptual model for urban soil regeneration. This research was carried out within the framework of the National Biodiversity Future Center (NBFC), funded by the Italian Piano Nazionale di Ripresa e Resilienza (PNRR) under Mission 4 "Education and Research", Component 2 "From Research to Business", Investment 1.4 "Strengthening research structures and the creation of national R&D champions on Key Enabling Technologies", supported by the European Union through the NextGenerationEU programme (Project code CN00000033). The NBFC represents the first Italian national research center fully dedicated to biodiversity. Its main objective is to advance scientific knowledge, monitoring systems, and innovative solutions for the conservation, restoration, and sustainable management of biodiversity in terrestrial, marine, and

urban ecosystems. The center operates through a multidisciplinary Hub & Spoke structure involving universities, research institutions, and stakeholders across Italy, with the aim of integrating ecological research, technological innovation, and policy-relevant knowledge to support biodiversity protection and sustainable development. The research presented in this doctoral thesis contributes to the activities of Spoke 5 – Urban Biodiversity, which focuses on understanding biodiversity patterns and ecological processes in urban environments and on developing strategies to enhance ecosystem resilience and ecosystem services within cities. Specifically, this work is part of Task 2.3, which addresses the ecological and biogeochemical functioning of urban soils, with particular emphasis on their role in carbon sequestration, soil ecological processes, and the enhancement of ecosystem functions through sustainable management practices and nature-based solutions. Within this framework, the study contributes to the broader objectives of the NBFC and the PNRR programme, aimed at strengthening national research capacity and developing scientific knowledge and innovative approaches to support biodiversity conservation and sustainable ecosystem management in Italy and the Mediterranean region.

Materials and Methods

Study Sites

Location and environmental context

Experimental activities were conducted in two urban green areas located in the Campania region (southern Italy), within the municipalities of Fisciano (FI), at the University of Salerno Campus, and Avellino (AV). Both sites represent urban ecosystems typical of the Mediterranean context and share similar climatic conditions; however, they differ substantially in terms of land-use history, management intensity, and vegetation structure. These differences make the two sites particularly suitable for evaluating the response of urban soils and spontaneous vegetation to the application of micronized organic amendments.

The FI site (40°46′10.49″ N, 14°47′25.07″ E; 251 m a.s.l.) is an artificially established urban green space, covering an area of approximately 130 × 48 m, and characterized by an intensive management regime. Historical imagery indicates that the area was converted from agricultural to recreational use between 1984 and 1998, involving the construction of buildings, sidewalks, and landscaped gardens. Current management practices include daily irrigation (20 minutes), biweekly mowing, and fertilization with urea (40 g m^{-2}) applied twice per year. The site is subject to regular trampling due to pedestrian traffic and recreational activities. This intensive management regime strongly influences floristic composition, favoring species tolerance of disturbance and mechanical stress (Baldi *et al*., 2025).

The AV site (40°54′22.71″ N, 14°48′19.73″ E; 358 m a.s.l.) is also an artificially established, unmanaged peri-urban green space, covering an area of approximately 160 × 114 m. Prior to urban development, which occurred around 2010, the area was predominantly occupied by orchards. Following land-use conversion, attempts were made to enrich the tree layer through the planting of *Quercus ilex* L. and *Tilia cordata* Mill.; however, these efforts were unsuccessful due to the absence of irrigation and fertilization. At present, vegetation relies exclusively on precipitation, and mowing is carried out only twice per year, in spring and summer. Trampling is minimal and limited to maintenance activities (Baldi *et al*., 2025). This low-intensity management regime has promoted the spontaneous establishment of a diverse herbaceous community, making the AV site an ideal model for investigating natural vegetation dynamics in urban environments. Over the three-year experimental period, agronomic management was characterized by two irrigation events per year, concentrated during the summer season.

Differences in management history, water availability, and anthropogenic pressure make the AV and FI sites complementary urban systems. AV represents a low-interference environment in which vegetation dynamics are driven primarily by natural seasonal filters. In contrast, FI constitutes a highly managed system, where anthropogenic practices tend to override spontaneous ecological processes. This complementarity provides a robust experimental framework for assessing the effects of micronized organic amendments on soil properties, vegetation physiology, and carbon sequestration potential under real-world urban conditions.

Experimental Design

The experimental design was structured to evaluate the effects of micronized organic amendments on spontaneous vegetation and soil properties in the two urban study sites. The experiment was conducted in two phases: the first phase, initiated in 2023 at the Fisciano and Avellino sites, and the second phase, initiated in 2024 at two new plots on the Fisciano (Path and Linden), where amendment doses were increased to amplify the effects observed during the initial phase. The two additional plots were specifically selected to represent more disturbed urban conditions: the Path plot is adjacent to cemented areas and subject to frequent trampling, while the Linden plot is located under the canopy of Linden trees, introducing shade and litter inputs.

Treatments

In 2023, five treatments were applied, each with three biological replicates, at the Fisciano and Avellino sites:

1. **Control (T1)** – no application.
2. **Mineral fertilizer (T2)** – *urea.*
3. **Micronized vermicompost (T3)** – *Humus Lombricò*.
4. **Micronized biochar (T4)** – *Black Fluid*.
5. **Combination (T5)** – 50% *Humus Lombricò* + 50% *Black Fluid*.

Based on the preliminary results from 2023, which showed sometimes modest physiological and agronomic effects, two new experimental areas were established at Fisciano in 2024 (Path and Linden). In this phase, the mineral fertilizer was removed, since these managed soils had previously been regularly fertilized with synthetic fertilizers prior to the start of the trial, and the doses of organic amendments were substantially increased. The treatments applied were:

1. **Control (T1)** – no application.
2. **Micronized vermicompost (T2)** – *Humus Lombricò.*
3. **Micronized biochar (T3)** – *Black Fluid*.
4. **Combination (T4)** – 50% *Humus Lombricò* + 50% *Black Fluid*.

Organic Amendments Used in the Study

The amendments used in this study, namely micronized vermicompost and micronized biochar, represent two types of organic materials with complementary properties.

Micronized Vermicompost (*Humus Lombricò*)

The *Humus Lombricò* vermicompost from the "Gallorosso" farm is a natural organic amendment obtained exclusively from aged bovine manure, processed through vermiculture into a stable and biologically active material. Indoor processing prevents exposure to sunlight and reduces the risk of contamination by weed seeds, ensuring a pathogen-free product that is safe even at high application rates, without harming plant roots.

This amendment contains organic matter that has been partially decomposed by earthworms and is rich in humic and fulvic acids, enzymes, amino acids, phytohormones, beneficial bacteria, and micronutrients. These components act synergistically to nourish plants, stimulate growth, and enhance resistance to pests, diseases, and environmental stress. Moreover, the organic matter in the vermicompost contributes to the formation and maintenance of soil humus, increasing the soil's capacity to retain carbon in a stable form, promoting temporary organic carbon sequestration, and facilitating the formation of stable aggregates that reduce oxidation and CO_2 loss over time.

Humus Lombricò promotes the gradual release of nutrients, improves soil structure, increases porosity and aeration, reduces root asphyxiation, and creates an optimal environment for seed germination and plant development. It is characterized by a balanced C/N ratio and low levels of heavy metals. More details are shown in Table 1. The product is registered in the Fertilizer Registry of the Ministry under authorization 0014388/15, is approved for use in organic agriculture, and falls under the category "Amendment – Manure-Derived Vermicompost" according to Legislative Decree 75/2010.

Table 1. *Chemical composition and heavy metal content of Humus Lombricò.*

Parameter	Value	Regulatory Limit (D.lgs. 75/2010)
Organic nitrogen (dry matter)	1.6%	-
Total nitrogen	1.7%	-
Organic carbon (dry matter)	20%	-
Total organic matter	40%	-
Extractable organic matter / total organic matter	19%	-
Humified organic matter / extractable organic matter	37%	-
Carbon/Nitrogen ratio (C/N)	12.5	-
pH	7.25	-
Total lead (Pb)	3.8 mg kg^{-1}	140 mg kg^{-1}
Total cadmium (Cd)	<0.1 mg kg^{-1}	1.5 mg kg^{-1}
Total nickel (Ni)	6.8 mg kg^{-1}	100 mg kg^{-1}
Total zinc (Zn)	89 mg kg^{-1}	500 mg kg^{-1}
Total copper (Cu)	11.3 mg kg^{-1}	230 mg kg^{-1}
Total mercury (Hg)	<0.1 mg kg^{-1}	1.5 mg kg^{-1}
Total hexavalent chromium (Cr VI)	<0.1 mg kg^{-1}	0.2 mg kg^{-1}

Micronized Biochar (*Black Fluid*)

Black Fluid biochar from Biodea is a carbonaceous amendment produced through controlled pyro-gasification of plant biomass. The process involves partial combustion in the absence of oxygen, followed by micronization and dispersion in solutions, with careful control of time and temperature to ensure low ash content and high organic carbon stability. These characteristics make biochar a highly stable form of carbon, resistant to microbial degradation, capable of sequestering up to 3 tons of

CO_2 per ton of applied product, storing stable organic carbon in the soil for hundreds of years, and enhancing the soil's capacity to function as a long-term carbon reservoir.

Black Fluid biochar improves the chemical, physical, and microbiological properties of soil by enhancing structural stability and porosity, promoting aeration, drainage, water retention, and resistance to compaction. Its application stimulates the development of beneficial microbial communities, facilitates the transformation of organic matter into humus, and increases nutrient availability. The porous structure of the biochar also contributes to the accumulation and protection of existing soil organic carbon, enhancing soil fertility, plant resilience to water and salinity stress, and mitigating the effects of pollutants.

Black Fluid exhibits high levels of stable carbon and low contaminant content, with a pH ranging from 7.5 to 9. It is classified as Class I according to Legislative Decree 75/2010, with a strong capacity to enhance the chemical, physical, and microbiological fertility of soils. Detailed chemical properties, as well as nutrient and heavy metal contents, are reported in Table 2.

Table 2. *Chemical Composition and Physical Properties of Black Fluid.*

Parameter	Value	Regulatory Limit (D.lgs. 75/2010)
pH	7.5 – 9	-
Total carbon	67 – 75%	-
Total nitrogen (N)	0.2 – 0.4%	-
Total phosphorus (P)	0.03 – 0.04%	-
Total sodium (Na)	280 – 310 mg kg^{-1}	-
Total potassium (K)	2950 – 3200 mg kg^{-1}	-
Total calcium (Ca)	9900 – 10650 mg kg^{-1}	-
Total magnesium (Mg)	800 – 980 mg kg^{-1}	-
Phytotoxicity test	Suitable	Must be suitable
Ash content	3 – 5%	≤ 7% (Class I requirement)
Electrical conductivity	1.10 mS cm^{-1}	-
Molar H/C ratio	0.2	≤ 0.7 (biochar stability requirement)

Plot layout

Plot Size at Fisciano (Unisa)

The experimental area at the Fisciano (Unisa) consisted of rectangular plots measuring 7.5 m × 1.8 m. Five treatments were applied: Control, Mineral Fertilizer, *Humus Lombricò*, *Black Fluid*, and a 50:50 mixture of the latter two, each with three biological replicates, for a total of 15 plots (Figure 17). The plots were permanently demarcated with boundary markers to ensure consistency in sampling and surveys. Vegetation was left to grow spontaneously to preserve the natural composition of the existing herbaceous species. Representative images of the field are presented in Figures 18a and 18b, showing different perspectives of the experimental area.

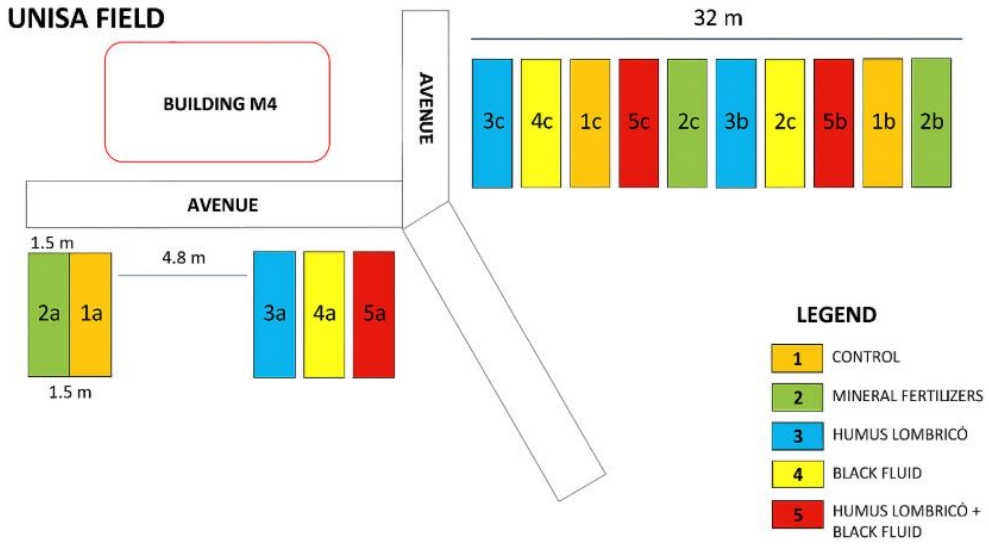


Figure 17. *Schematic layout of the experimental plots at the Fisciano (Unisa), showing the arrangement of treatments and replicates.*

a)

b)

Figure 18. *Field view of the experimental plots at Fisciano (UNISA), showing the spatial arrangement of treatments: (a) perspective 1; (b) perspective 2.*

Plot size at Avellino

The experimental site in Avellino consisted of plots measuring 5 m × 1.5 m, in accordance with the spatial constraints typical of urban green areas. The same five treatments applied at Fisciano were implemented, each with three biological replicates, for a total of 15 plots (Figure 19). The plots were permanently demarcated with boundary markers to ensure consistency in sampling and surveys. Vegetation was composed of spontaneous herbaceous species typical of roadside and peri-urban soils. Representative images of the field are presented in Figures 20a and 20b, showing different perspectives of the experimental area.

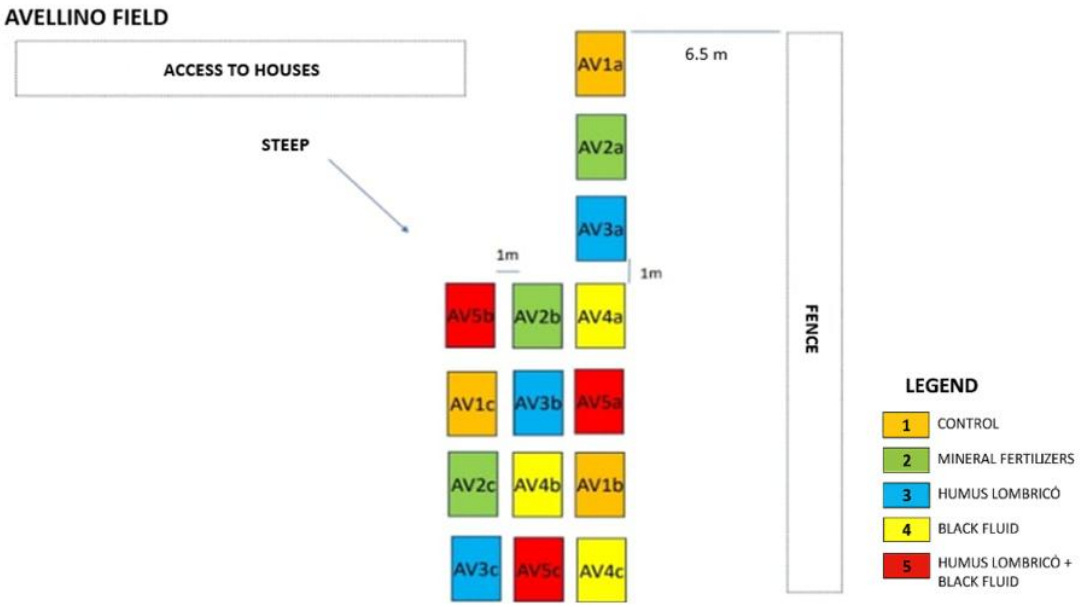


Figure 19. *Schematic layout of the experimental plots at the Avellino, showing the arrangement of treatments and replicates.*

a) b)

Figure 20. *Field view of the experimental plots at Avellino, showing the spatial arrangement of treatments: (a) perspective 1; (b) perspective 2.*

New Experimental Areas at Fisciano (Unisa)

In 2024, two new experimental areas were established at Fisciano (Unisa), specifically selected to represent more disturbed urban conditions: the Path plot, adjacent to cemented areas and subject to frequent trampling, and the Linden plot, located under the canopy of Linden trees, introducing shade and litter inputs.

- Path**:** plots measuring 3.5 m × 1.5 m
- Linden**:** plots measuring 3.5 m × 1.5 m

At these sites, four treatments were applied: Control, Humus Lombricò, Black Fluid, and a 50:50 mixture of the latter two, with increased amendment application rates compared to 2023 in order to amplify the effects observed during the initial phase. The mineral fertilizer treatment included in the 2023 experimental design was discontinued, as the soils had already received mineral fertilization in the past. Consequently, treatment labeling differs between the two experimental years, since in 2023 T2 corresponded to mineral fertilizer, whereas in 2024 T2 refers to micronized vermicompost. Each treatment was replicated three times, resulting in a total of 12 plots per site. The plots were permanently demarcated with boundary markers to ensure consistency in sampling and surveys. The experimental layout of the Path and Linden fields is shown in Figures 21a and 21b, respectively.

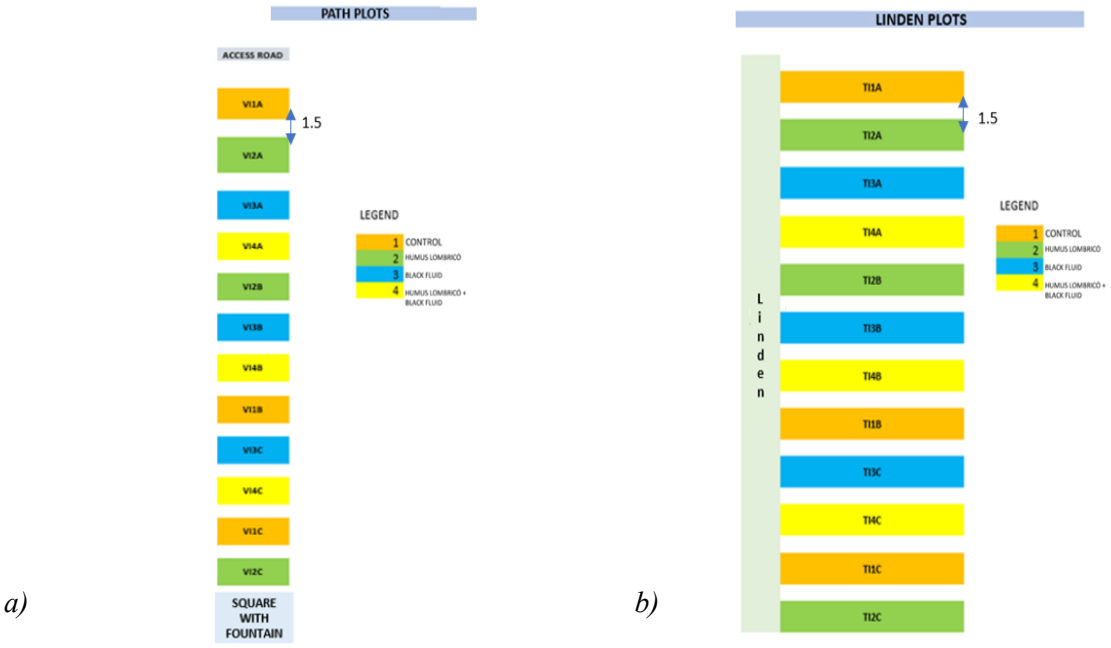


Figure 21. *Schematic layout of the experimental plots at the Fisciano (Unisa) fields established in 2024: (a) Path and (b) Linden, showing the arrangement of treatments and biological replicates.*

Representative photographs of the experimental fields at the Fisciano Path and Linden sites are shown in Figure 22 (a and b, respectively).

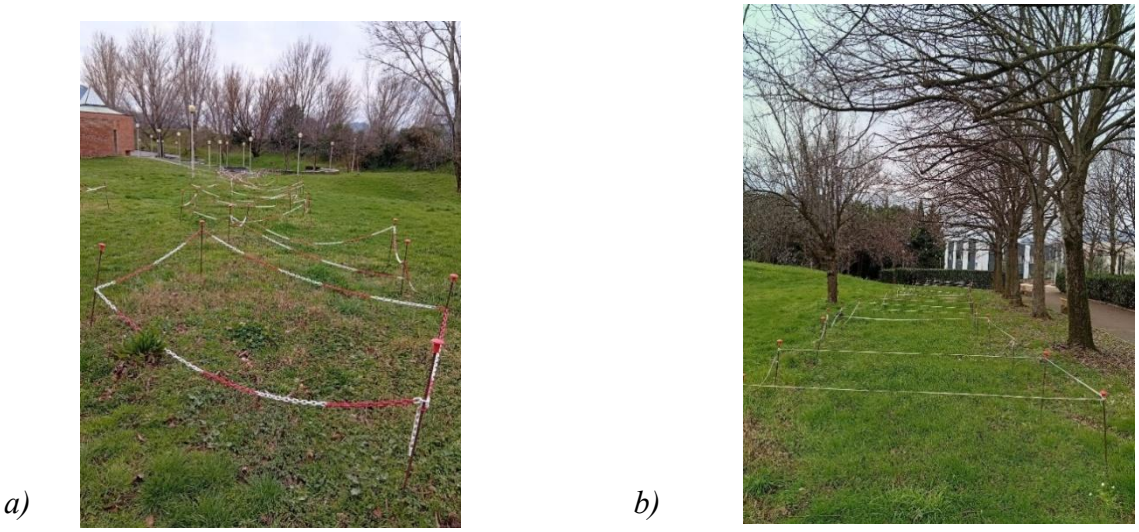


Figure 22. *Representative field photographs of the Fisciano Path (a) and Linden (b) experimental fields (2024), illustrating the plot layout and field conditions.*

Experimental Plot Randomization

At each site, treatments were assigned to plots using a completely randomized design. Randomization was performed separately within each block to minimize spatial bias and account for the high heterogeneity typical of urban soils. This approach ensures that the observed differences can be attributed to the applied treatments rather than to pre-existing soil variability.

Experimental Treatments with Organic Amendments and Mineral Fertilizer

Amendments were applied over three consecutive cycles in 2023, 2024, and 2025, following a standardized protocol across all experimental plots. The plots established in 2024 at the Fisciano site (Path and Linden) received treatments in 2024 and 2025. Applications were performed, once per year, during the summer period on soils with spontaneous vegetation.

The doses of both organic amendments and mineral fertilizer were expressed on an area basis (kg ha^{-1}). Doses of the organic amendments were determined based on the manufacturers' recommended application rates and were appropriately adjusted to the experimental conditions and plot sizes, to ensure compliance with technical guidelines and to allow proper comparability among treatments.

At the experimental sites in Fisciano and Avellino, *Humus Lombricò* was applied at a rate of 20 kg ha^{-1}, while *Black Fluid* was applied at 200 kg ha^{-1}. The mineral fertilizer (urea) was applied at a rate of 150 kg ha^{-1}, in accordance with fertilization practices typically adopted by the staff responsible for urban green maintenance within the university campus, to reproduce standard management conditions of urban green areas.

For the combined treatment, the amendments were applied in equal proportion (50%), corresponding to 10 kg ha^{-1} of *Humus Lombricò* and 100 kg ha^{-1} of *Black Fluid*.

At the experimental plots established in 2024 at the Fisciano site (Path and Linden), based on preliminary results, the doses were increased to 257 kg ha^{-1} for *Humus Lombricò* and 2143 kg ha^{-1} for *Black Fluid*. For the combined treatment, the amendments were applied in equal proportion (50%), corresponding to 128 kg ha^{-1} of *Humus Lombricò* and 1071 kg ha^{-1} of *Black Fluid*.

All treatments were applied through manual fertigation to ensure precision and uniformity.

Floristic Surveys and Functional Trait Assessment

The floristic characterization of the two areas was carried out by Baldi *et al*. (2025) through seasonal phytosociological surveys, following a standardized protocol that enabled the identification of species composition and the structural attributes of the herbaceous communities. At each site, 15 surveys were conducted per season, for a total of 120 sampling units over the course of one year. Each survey was performed within 50 × 50 cm quadrats, randomly positioned to ensure adequate representation of spatial variability.

Species present within each quadrat were initially identified in the field through expert taxonomic recognition, and their cover was estimated using the Braun–Blanquet method. Subsequently, all

individuals were collected in paper bags, counted, and transported to the laboratory for the determination of dry biomass, obtained by oven-drying at 75 °C.
Definitive taxonomic identification was performed in the laboratory using a Leica M165C stereomicroscope and the dichotomous keys of Pignatti *et al*. (2017), as reported in Baldi *et al*. (2025). Classification was further refined by assigning Raunkiær life forms, chorotypes, and Ellenberg indicator values for light, temperature, continentality, moisture, soil reaction, nutrients, and salinity. Using the applied methodology allowed not only the identification of the species present, but also the characterization of functional traits of the plant communities, providing a comprehensive assessment of the structural and functional biodiversity of the two sites.

Physical and Chemical Characterization of Experimental Soils

Chemical and physical analyses of soil samples were carried out at the AGRICHEMLAB laboratory (Building F, Fisciano Campus, University of Salerno), directed by Prof. Pierluigi Mazzei. All determinations were performed according to the official methods for soil chemical analysis (Italian Ministerial Decree of 13/09/1999 and subsequent amendments), with procedural modifications applied where necessary.

Urban Soil Sampling and Sample Preparation

Soil sampling activities were conducted at the experimental sites in Fisciano and Avellino during two successive sampling campaigns. An initial characterization of the soils at both sites was performed prior to the application of amendments. After amendment treatment, at the Fisciano site, soil samples were collected between December 2024 and January 2025 and in September 2025, while at the Avellino site sampling was carried out in March 2025 and in September 2025.
Soil samples were collected from the surface layer at a depth of 5–20 cm. Subsequently, the samples were transported to the laboratory, where they were air-dried, sieved through a 2 mm mesh, and stored in sterile containers until chemical and physical analyses were performed.
Two replicates per plot were performed for each analyte (the number of replicates increased in cases of high standard deviations or anomalous values). Soil respiration, on the other hand, was determined through three independent measurements per plot.

Particle Size Distribution and Soil Texture Classification According to the IUSS Method

Soil texture was determined following the official IUSS protocol, which employs the Andreasen pipette method. For each sample, 10 g of air-dried soil sieved at 2 mm were suspended in an aqueous solution containing 40 g L^{-1} sodium hexametaphosphate [$(NaPO_3)_6$] and 10 g L^{-1} sodium carbonate (Na_2CO_3) and agitated for 2 hours to achieve complete dispersion of the primary soil particles. The suspension was then wet-sieved through a 0.2 mm mesh to separate the coarse sand fraction, while the remaining fraction was allowed to settle for predetermined intervals. According to the IUSS protocol, the timing for the collection of the silt+clay and pure clay fractions was adjusted based on laboratory temperature, with the first aliquot collected after a few minutes and the second after approximately 15 hours of sedimentation.

The collected fractions were dried and, after correcting for the dispersing agents and applying the appropriate proportions, the relative percentages of coarse sand, fine sand, silt, and clay were calculated. These results were subsequently used to classify the soils according to the IUSS soil texture triangle. At least two replicates were performed for each sample to ensure accuracy and reproducibility.

Soil pH and Electrical Conductivity Analysis

Soil pH was determined on a soil–solution suspension prepared with 0.01 M $CaCl_2$, while electrical conductivity (EC) was measured on a soil–water suspension. For each sample, 5 g of soil were placed in a tube and combined with 25 mL of the extracting solution (0.01 M $CaCl_2$ for pH; ultrapure Milli-Q water for EC). The suspensions were agitated for 20 minutes at 220 rpm on a linear shaker (ARGOlab SKO-D XL; Figure 23a) and subsequently centrifuged for 10 minutes at 6,000 rpm to obtain a clarified supernatant.

The recovered supernatant was then analyzed using a combined pH and EC probe with a dual-channel HANNA HI5222 meter (Figure 23b). Electrical conductivity values (µS cm^{-1}) were corrected by subtracting the conductivity of the ultrapure water used and multiplying by 5 to account for the dilution factor.

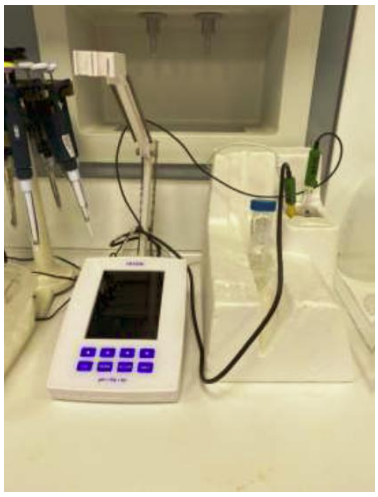
a) b) 

Figure 23. *Analysis of soil pH and electrical conductivity (EC): (a) linear shaker used for sample agitation; (b) digital pH and conductivity meter HI5222.*

Total Nitrogen Analysis Using the Kjeldahl Method

Total nitrogen content in the soil samples was determined using the Kjeldahl method, which involves digestion, distillation, and titration steps. For the digestion, 2 g of air-dried soil sieved at 2 mm were treated with concentrated sulfuric acid and a catalytic mixture composed of K_2SO_4, $CuSO_4$, and Se (Figure 24a). Digestion was carried out using a SpeedDigester K-425 (Figure 24b) until reaching an operational temperature of approximately 370 ± 20 °C for a total duration of about 60 minutes.

The digested material was subsequently subjected to steam distillation for 10 minutes using the EasyKjel module (Figure 24c). During this step, the digestate was treated with a strongly alkaline sodium hydroxide solution to neutralize the excess sulfuric acid and convert nitrogen into its ammoniacal form. The ammoniacal nitrogen was then transferred, via condensation, into an acid trap consisting of 200 mL of water and 10 mL of 1% H_3BO_3 (Figure 24b).

At the end of the distillation, methyl red and bromocresol indicators were added to the collection solution, which was then titrated with 0.1 M HCl. A color change from green to pink indicated the completion of the reaction. At least two replicates were performed for each sample.

Due to time constraints and resource availability, total nitrogen determination was carried out only on samples from the first sampling campaign (Fisicano: December 2024; Avellino: March 2025).

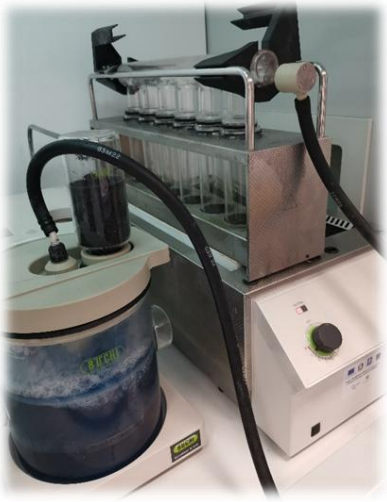
a) b)  c)

Figure 24. *Total nitrogen analysis: (a) addition of sulfuric acid to tubes containing soil samples; (b) SpeedDigester K-425 and Scrubber K-415 for trapping harmful gases released during digestion; (c) distillation apparatus.*

Total Carbonate Analysis Using the Dietrich–Frühling Method

Total carbonate content was determined using a gas-volumetric method with a Dietrich–Frühling calcimeter (Figure 25). For each sample, 1 g of air-dried soil saved at 2 mm was reacted with 5 mL of 1 M HCl. The CO_2 released from the dissolution of carbonates was conveyed, through a hermetically sealed system, into the headspace of the graduated column of the calcimeter containing water.

Carbon dioxide was quantified by measuring the lowering of the water meniscus within the graduated column. The measured volume (in mL) was standardized to conditions equivalent to 0 °C and 760 Torr (V_0) and subsequently used to calculate total carbonate content (g kg^{-1}) according to official methods. Laboratory temperature and pressure at the time of analysis were recorded and considered to ensure proper standardization.

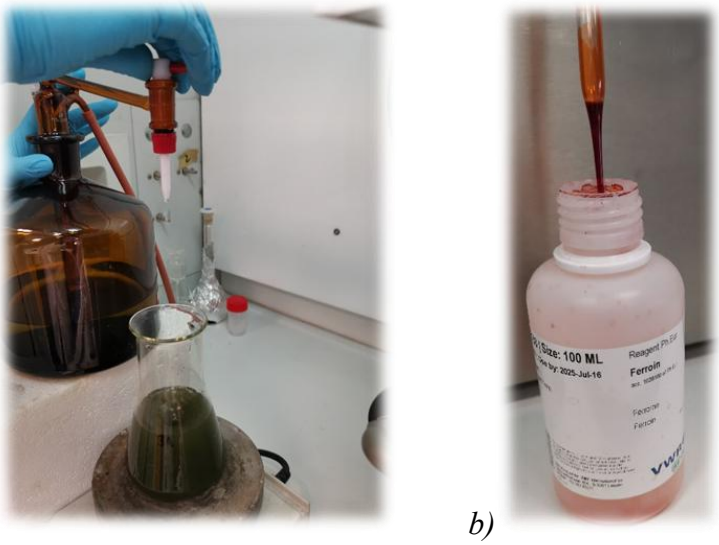
At least two replicates were performed for each sample.

Figure 25. *Analysis of total carbonates using a Dietrich–Frühling calcimeter.*

Total Carbon Analysis Using the Walkley–Black Method

Soil organic carbon was determined using the Walkley–Black wet oxidation method. For each sample, 1 g of soil was placed in a 500 mL flask, to which 10 mL of potassium dichromate was added under strongly acidic conditions, generated by adding 10 mL of concentrated H_2SO_4 (98%), to create an environment favorable for the oxidation of organic matter.

During the reaction, a watch glass was placed over the flask to slow the cooling of the suspension. After 30 minutes, the reaction was stopped by adding 200 mL of cold water. Organic carbon was quantified by redox titration, using 8 drops of Ferroin indicator (Figure 26a–b) to identify the endpoint. The color change from dark orange to olive green (intermediate stage) and finally to dark burgundy indicated that all residual Cr (VI) had been reduced to Cr (III) (E_0 = 1.06 V). Titration was carried out using a 0.5 M solution of ammonium iron (II) sulfate hexahydrate [$(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$]. At least two replicates were performed for each sample. Additionally, two reagent blanks were prepared for each analytical session, following the same procedure but without soil, to account for any contribution from the reagents.



a) b)

Figure 26. *Walkley–Black soil carbon analysis: (a) titration with 0.5 M $(NH_4)_2Fe(SO_4)_2 \cdot 6H_2O$ solution; (b) Ferroin indicator.*

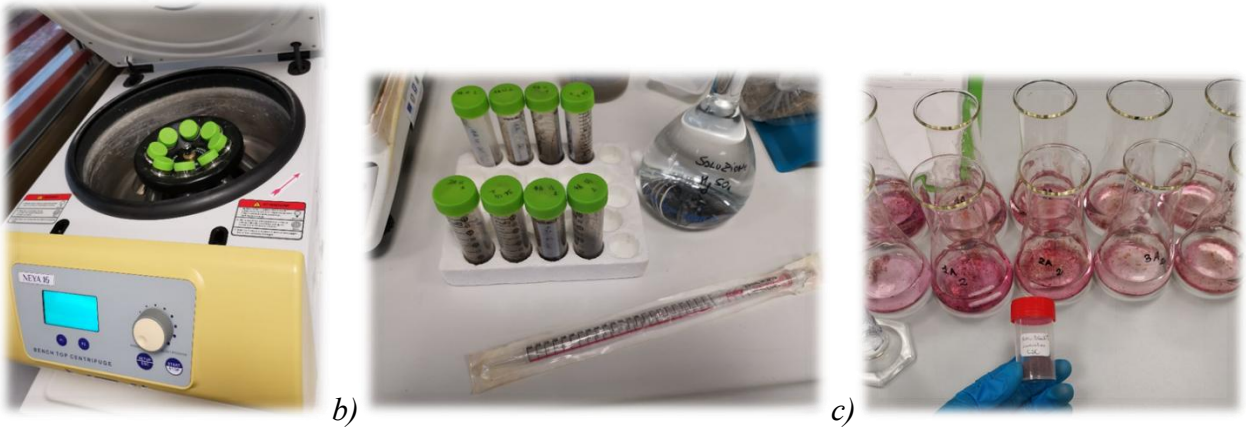
Cation Exchange Capacity Analysis Using the Ba^{2+}/Mg^{2+} Method

Cation exchange capacity (CEC) of the soil was determined using the Ba^{2+} saturation method, followed by Ba^{2+}/Mg^{2+} exchange and quantification of the excess Mg^{2+} via complexometric titration with EDTA.

Specifically, 2 g of air-dried soil sieved at 2 mm were placed in a 50 mL tube and treated with 25 mL of 0.41 M $BaCl_2 \cdot 2H_2O$ solution containing triethanolamine at pH 8.2. The suspension was agitated for 20 minutes at 120 rpm on a rocking plate, subsequently centrifuged for 5 minutes at 6000 rpm (Figure 27a). Then, the resulting supernatant was removed. The soil was again put in contact with the Barium solution, and the cycle was entirely repeated. The sample was then rinsed with water, the supernatant was removed, and the tube was reweighed.

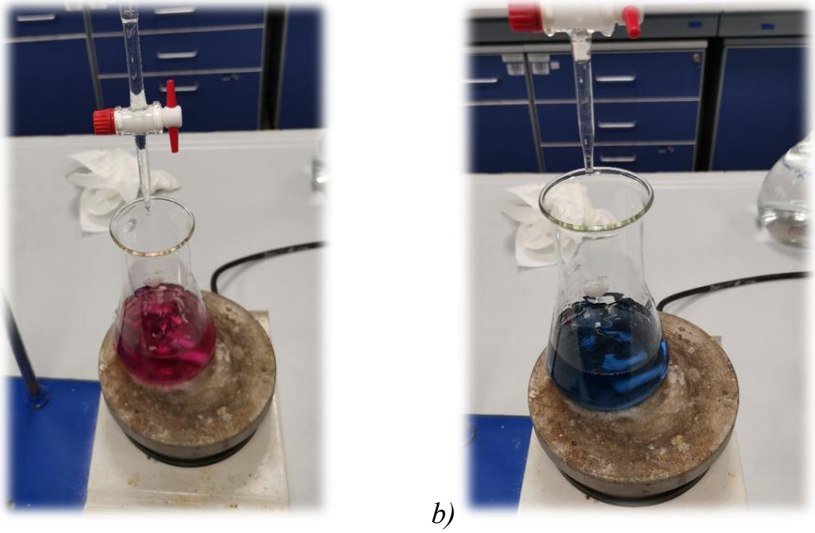
A 25 mL $MgSO_4$ solution was then added to the sample to perform the Ba^{2+}/Mg^{2+} exchange (Figure 27b). After agitation and centrifugation, 10 mL of the supernatant was collected and subjected to complexometric titration. The supernatant was added whit100 mL of water, 10 mL of ammonium buffer (pH 10), and a small amount of Eriochrome Black T indicator (mixed with NaCl (3:1, w/w)) (Figure 27c). Titration was conducted with 0.025 M sodium EDTA until the color changed from pink (Figure 28a) to blue (Figure 28b).

Reagent blanks were prepared prior to each analytical session. Cation exchange capacity was finally calculated in cmol(+) kg^{-1} according to official procedures.



a) *b)* *c)*

Figure 27. *Cation exchange capacity (CEC) analysis: (a) sample centrifugation; (b) addition of 25 mL $MgSO_4$ solution; (c) Eriochrome Black T indicator.*



a) *b)*

Figure 28. *Cation exchange capacity (CEC) analysis: (a) color change from pink; (b) to blue, indicating the end point of the titration.*

Available Phosphorus Analysis Using the Olsen Method

Available phosphorus (P-Olsen) was determined following the method of Olsen *et al*. (1954). For each sample, 2 g of soil sieved at 2 mm were suspended in 40 mL of 0.5 M $NaHCO_3$ solution, adjusted to pH 8.5 with NaOH. The suspension was agitated on a rocking plate for 30 minutes (100–120 oscillations) and subsequently centrifuged for 10 minutes at 6000 rpm using a NEYA 16 bench-top centrifuge. The supernatant was vacuum filtered through Whatman 41 filter paper.

Then, 5 mL of the extract were mixed with 5 mL of the Olsen reagent, which was prepared by combining 30 mL of ascorbic acid (1.75% w/v), 50 mL of 4 M H_2SO_4, 15 mL of ammonium molybdate (4% w/v), and 5 mL of potassium antimony tartrate (0.275% w/v), and diluted to 200 mL with water. The reaction, which produces a blue color, was allowed to develop in the dark for 16 hours. The flasks were then brought to a final volume of 25 mL with Milli-Q water, and absorbance was measured at 720 nm using a Spectronic 20 Genesys spectrophotometer (Figure 29a).

At least two blanks were prepared for each analytical session, consisting of 5 mL of extracting solution and 5 mL of Olsen reagent, treated identically to the samples. Absorbance values were converted to mg P L^{-1} by comparing the results whit a calibration curve constructed with standard K_2HPO_4 solutions at known concentrations (0.2, 0.4, 0.8, 1.2, 2.0 mg L^{-1}) (Figure 29b). Finally, results were converted to available soil phosphorus (mg P kg^{-1}) according to the official method and reported both as P and as P_2O_5 (by multiplying by 2.2914) (Figure 29c).

a) *b)* *c)*

Figure 29. *Available phosphorus (Olsen) analysis: (a) Spectronic 20 Genesys spectrophotometer (Spectronic Instruments); (b) standards in the concentration range 0.2–2.0 mg L^{-1} (0.2, 0.4, 0.8, 1.2, 2.0 mg L^{-1}); (c) soil extract samples during the reaction.*

Soil Respiration Measurement

Soil respiration was estimated by measuring the amount of carbon dioxide released from soil, in the time unit, by using the EGM-5 device (PP-Systems) equipped with an SRC-2 chamber (150 mm height × 100 mm diameter) and HydraProbe temperature and moisture sensors (Stevens) (Figure 30 a-c).

For each measurement, the respiration chamber was placed over the sampling point; air from the soil was drawn through the chamber for the duration of the measurement (typically 0.5–1.5 minutes) and

directed to an infrared gas analyzer (IRGA), which quantified CO_2 based on the IR absorption peak at 2350 cm^{-1}. Soil temperature and moisture were recorded simultaneously.

The instrument provided the respiration rate, expressed in g CO_2 m^{-2} h^{-1}. In all cases, respiration progressed linearly, and the final value was calculated using linear regression of the experimental data ($r^2 > 0.95$).

The measurements were standardized by conducting all the acquisitions in the range 11:30 and 14:30 under comparable weather conditions. Prior to measurement, the existing vegetation cover was reduced by mowing or cutting with scissors, 1-2 days before the measures, in order to assess heterotrophic soil respiration (Figure 31).

Figure 30. *Soil respiration analysis: (a) SRC-2 respiration chamber; (b) EGM-5 device; (c) soil temperature and moisture sensor.*

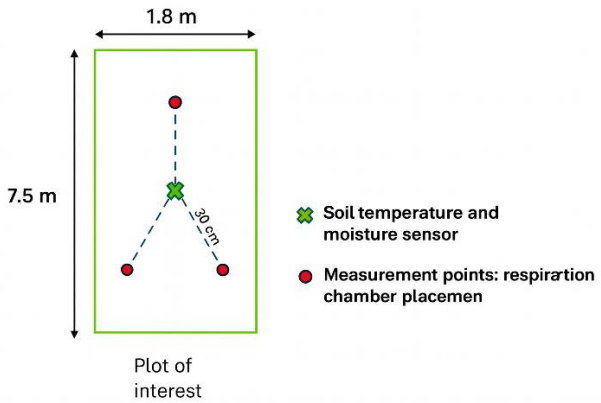


Figure 31. *Soil respiration analysis: schematic illustrating the layout used to position the temperature and moisture sensor and the respiration chambers for each plot (three measurements per plot).*

Monitoring of Physiological and Agronomic Parameters in the Experimental Plots

Physiological and agronomic surveys of the experimental plots were conducted on a bimonthly basis, starting from the application of the amendments, which was repeated annually for three consecutive years. For each application cycle, survey times are indicated as T_1 = 2 months, T_2 = 4 months, T_3 = 6 months, T_4 = 8 months, and T_5 = 10 months after amendment application. Surveys were performed using non-invasive, non-destructive digital instruments to systematically evaluate the effects of the treatments on vegetation dynamics. This frequency allowed regular monitoring of biomass, ground cover, and phenological indicators, ensuring that the collected data were representative and comparable over time. In cases of particularly dense or fast-growing vegetation, observations were conducted with special care to maintain accuracy and clarity, avoiding interference from excessive plant growth that could compromise the quality of the experimental measurements.

Plant Physiological Surveys

Multi-Pigment Meter (MPM-100) Analysis of Chlorophyll and Leaf Nitrogen in Urban Spontaneous Vegetation

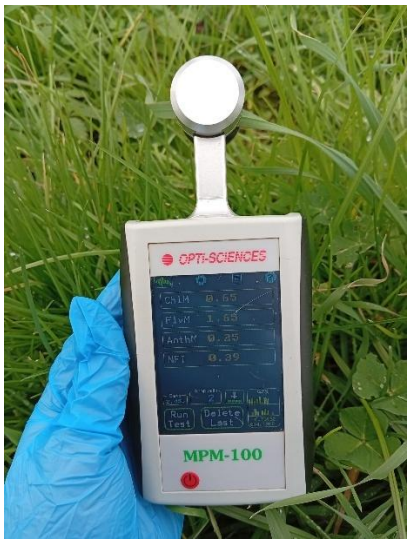
The Multi-Pigment Meter (MPM-100) (Opti-Sciences, USA) is a portable, non-destructive device designed to estimate chlorophyll content and leaf nitrogen status in plants (Figure 32a). Its operating principle is based on leaf transmittance and fluorescence, exploiting the strong light absorption by chlorophyll in the red (approximately 650–700 nm) and near-infrared (approximately 720–740 nm) regions. Fluorescence is used to estimate anthocyanin (AnthM) and flavonol (FlvM) content, while leaf transmittance in the far-red and near-infrared regions allows determination of chlorophyll content (ChlM). By measuring the fraction of light transmitted through the leaf at these wavelengths, the instrument calculates a chlorophyll index, which is linearly correlated with leaf nitrogen content (NFI index).

In this study, measurements were conducted on spontaneous vegetation in urban areas, characterized by heterogeneous herbaceous composition and irregular growth patterns. The MPM-100 sensor was positioned on fully expanded leaves, avoiding damaged or shaded tissue, without removing or altering the natural plant cover, thereby preserving the native soil and vegetation structure (Figure 32b). Light emitted by the device passes through the leaf lamina and is detected by photodiodes, allowing rapid, non-invasive estimation of chlorophyll, anthocyanin, and flavonol content.

Measurements were performed in the morning under stable light conditions to minimize the influence of ambient illumination on leaf transmittance and fluorescence signals.

Multiple readings per plant were taken on different leaves to account for intraplant variability and uneven chlorophyll distribution, and the averaged values were considered representative of each plot. The instrument, calibrated by the manufacturer against laboratory-determined chlorophyll concentrations, ensures high accuracy and reproducibility, even under field conditions with spontaneous vegetation.

The use of the MPM-100 enabled dynamic monitoring of the physiological status of herbaceous vegetation in response to micronized amendment treatments, providing information on leaf nitrogen content and photosynthetic status, without compromising the natural structure of the urban plant cover. The indices obtained from the MPM-100 (ChlM, AnthM, FlvM, and NFI) were interpreted as proxies for leaf chlorophyll content, nitrogen status, and stress-related pigment accumulation, allowing an integrated assessment of both the nutritional condition and physiological responses of spontaneous urban vegetation to the applied treatments.

a) 

b)

Figure 32. *Analysis of Chlorophyll and Leaf Nitrogen: (a) Multi-Pigment Meter (MPM-100); (b) MPM-100 sensor positioned on fully expanded leaves of spontaneous urban vegetation.*

Spectral Vegetation Indices: Normalized Difference Vegetation Index (NDVI) and Photochemical Reflectance Index (PRI) Assessment

To complement the physiological surveys of the experimental plots, monitoring was carried out using Decagon sensors to measure two spectral vegetation indices: the Normalized Difference Vegetation

Index (NDVI) and the Photochemical Reflectance Index (PRI). These indices provide synthetic information on plant vigor, health status, and physiological condition, allowing the effects of the treatments to be assessed in a non-invasive and continuous manner.

The Normalized Difference Vegetation Index (NDVI) is a multispectral index that expresses plant vegetative vigor through the measurement of reflectance in the near-infrared (NIR) and red (RED) spectral regions. NDVI is based on the contrasting optical behavior of healthy vegetation, which strongly absorbs red radiation due to chlorophyll pigments while reflecting a large fraction of near-infrared radiation because of leaf internal structure. The index was calculated according to the following equation:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}$$

where NIR represents reflectance in the near-infrared waveband (approximately 750–900 nm) and RED represents reflectance in the red waveband (approximately 630–680 nm), which is strongly absorbed by chlorophyll pigments. NDVI values typically range from −1 to +1: high values (close to +1) indicate healthy and dense vegetation, whereas low or negative values may reflect bare soil, water surfaces, or stressed vegetation.

The Photochemical Reflectance Index (PRI) is a narrow-band spectral index calculated from reflectance measurements in two wavebands characterized by small spectral differences, typically centered around 531 nm and 570 nm. The formula commonly adopted is:

$$\mathrm{PRI} = \frac{R_{531} - R_{570}}{R_{531} + R_{570}}$$

where R_{531} and R_{570} represent reflectance values at the corresponding wavelengths. PRI is sensitive to diurnal changes in photosynthetic efficiency and in the dissipation of absorbed radiant energy by the canopy, making it a valuable indicator for assessing physiological responses related to environmental stress or photoprotective regulation mechanisms.

In the present study, Decagon sensors were used to monitor NDVI and PRI directly in the field on spontaneous urban vegetation (Figure 33). Data collected by the Decagon loggers were downloaded and processed using the Zentra Utility software, which provides calibrated radiance and irradiance values for each waveband. For NDVI, the software uses reflectance measured in the red (approximately 650 nm) and near-infrared (approximately 810 nm) wavebands. For PRI, reflectance is measured in the 531 nm and 570 nm narrow wavebands. Zentra Utility automatically computes NDVI and PRI from these calibrated spectral measurements for all sunlit periods and enables data visualization, quality control, and export of datasets for subsequent statistical analyses. This workflow ensures that the spectral indices used in the assessment represent consistent, high-quality measurements of vegetation condition over time.

The use of these indices allowed for an integrated assessment of vegetation vigor and photosynthetic efficiency, providing complementary information to direct physiological surveys such as soil respiration and chlorophyll content. The combination of NDVI and PRI enabled the detection of not only the extent of vegetation cover but also variations in the physiological functioning of plants in response to treatments with micronized amendments.

Figure 33. *Decagon sensors were used to monitor NDVI and PRI directly in the plot on spontaneous urban vegetation.*

Leaf Temperature Monitoring Using a Digital Infrared Camera

Leaf temperature is a key physiological indicator for assessing plant water and thermal stress, as it reflects the balance between evapotranspiration, solar radiation absorption, and surrounding environmental conditions. Monitoring leaf temperature allows for the early detection of environmental stress signals, which can affect photosynthesis, respiration, and vegetative growth, providing complementary information to spectral indices such as NDVI and PRI or to soil physicochemical surveys.

In this study, the leaf temperature (°C) of spontaneous urban vegetation was measured using the Flir Ex-Series digital infrared camera, a portable and highly precise device that utilizes the infrared radiation emitted by objects to determine surface temperature without direct contact. Its operating principle is based on capturing the thermal energy emitted by leaves (typical emissivity of plant surfaces ~0.95) and converting it into temperature values through calibration algorithms embedded in the camera software.

Measurements were performed on fully expanded and representative leaves of each plot, avoiding damaged or shaded plants and minimizing interference due to leaf orientation or inclination. The camera was positioned at approximately 1 cm from the leaf surface, ensuring accurate and localized temperature readings.

The thermal images acquired by the infrared camera display different colors across the leaf surfaces, representing local temperature variations. Warmer tones (e.g., red or orange) correspond to areas with higher temperatures, while cooler tones (e.g., blue or purple) indicate cooler regions. These differences reflect the spatial distribution of transpiration and thermal stress within the vegetation, providing valuable information to identify leaves or areas of the plot exposed to different microclimatic conditions or water stress (Figure 34).

Furthermore, thermographic measurements were integrated with other physiological assessments (NDVI, PRI, chlorophyll content) to provide a comprehensive overview of plant functional status, enabling a non-invasive evaluation of plant responses to micronized amendment treatments. Systematic leaf temperature monitoring over time allowed the assessment of thermoregulation dynamics and the identification of significant differences among plots and treatments, contributing to the understanding of plant adaptation mechanisms in urban environments.

Figure 34. *Leaf temperature measurement in the experimental plot using the Flir Ex-Series infrared camera.*

Agronomic Surveys

Soil Volumetric Water Content and Temperature Monitoring Using the TDR FieldScout (Spectrum Technologies)

Soil volumetric water content (VWC) and soil temperature are fundamental agronomic parameters for assessing water availability, energy balance, and the physiological status of vegetation, especially in urban contexts characterized by heterogeneous, compacted soils and variable local microclimates. Monitoring these parameters allows correlating soil conditions with plant growth, transpiration, soil respiration, and other physiological indicators such as leaf temperature, chlorophyll content, and spectral indices NDVI and PRI.

In the present study, surveys were conducted using the FieldScout TDR (Time Domain Reflectometry) by Spectrum Technologies, a portable, non-destructive device designed to estimate VWC (%) and soil temperature (°C). The operating principle for water content is based on the dielectric constant of the soil: electromagnetic pulses are sent along metal probes inserted into the soil, and the propagation speed varies according to the soil permittivity, which depends on the water content, since water has a dielectric constant (~80) much higher than that of solid particles (~4) or air (~1).

For soil temperature, the TDR probes directly measure the temperature of the soil at the same depth as the moisture probes, providing accurate, real-time values.

Simultaneous surveys of VWC and temperature are particularly important in soils treated with micronized amendments, as these materials can alter the physical and chemical properties of the soil, affecting water retention capacity, thermal conductivity, and nutrient availability. Monitoring these parameters therefore allows understanding how the treatments influence soil microclimate, water dynamics, and the physiological adaptation of urban spontaneous vegetation.

Surveys were carried out by inserting the probes at depths representative of the root zone (typically 5–20 cm for spontaneous herbaceous vegetation), avoiding root damage and preserving the natural soil structure (Figure 35a). Multiple surveys were taken at different points within each plot to account for the spatial variability of soil texture and composition.

The data collected were recorded on the FieldScout digital display and subsequently downloaded and analyzed (Figure 35b).

a) b)

Figure 35. *VWC and soil temperature surveys using the FieldScout TDR (Spectrum Technologies): (a) Insertion of TDR probes at representative root zone depths to measure VWC and soil temperature without disturbing roots or soil structure; (b) Data recorded on the FieldScout digital display.*

Herbaceous and Leaf Biomass Assessment in Urban Spontaneous Vegetation Using Fresh and Dry Weight Surveys

The herbaceous and leaf biomass of the experimental plots was measured to assess the response of urban spontaneous vegetation to treatments with micronized amendments. In urban environments, vegetation often grows in compacted, heterogeneous soils with limited water and nutrient availability; the application of amendments can directly influence soil fertility, water retention, and nutrient availability, thereby affecting plant productivity and vigor.

Biomass surveys were conducted considering both fresh weight (FW), immediately after harvesting the vegetation, and dry weight (DW), obtained by oven-drying at 65 °C until constant weight was reached. FW provides information on the immediately available vegetation and on the current physiological status of the plants, while DW allows quantification of the actual biomass without the influence of water content, ensuring an accurate estimation of real productivity.

For each plot, a standardized sampling area (typically 40 × 40 cm) was delineated, avoiding the edges to minimize border effects, and all vegetation within this area was harvested using manual scissors, taking care not to damage roots or the substrate soil.

Immediately after collection, the biomass was cleaned of any soil particles and coarse debris and weighed using a precision laboratory balance accurate to 0.1 g. FW was recorded within a few minutes after the harvest to prevent moisture loss due to evaporation. Values were expressed as grams of fresh biomass per plot and subsequently normalized to the unit area (g m^{-2}). Samples intended for DW

determination were transferred to labeled containers and placed in a ventilated oven at 65 °C until constant weight was reached (typically 48–72 hours, depending on the amount of biomass). Once dried, the samples were weighed again using the same precision balance. DW was expressed as grams of dry biomass per plot and converted to g m^{-2}.

This methodological approach allowed for the collection of reliable and comparable data across plots, providing a clear assessment of the effects of the treatments on the productivity of urban spontaneous vegetation.

Statistical Analysis of the Data

All data collected during the study, including chemical and physical analyses of the soil, physiological surveys and agronomic surveys, were subjected to analysis of variance (ANOVA) to determine the presence of significant differences among the applied treatments.

To compare means between different treatments, Duncan's multiple range test was applied with a significance level of $p < 0.05$. This test reliably identifies which treatments differ significantly from each other while controlling for type I error. All analyses were conducted using GenStat.

Results

The Results section is organized by experimental site to preserve site-specific environmental conditions, soil characteristics, and management practices, which represent key sources of variability in urban soil systems.

Results of Chemical, Agronomic, and Physiological Assessments at the Urban Experimental Fields in Fisciano

Floristic Composition and Functional Trait Analysis at the Urban Experimental Fields of Fisciano

The identification of plant species present in the experimental fields was based on the data reported by Baldi *et al*. (2025), which serve as the reference for taxonomic identification and for the floristic-functional characterization of the analyzed plant communities. Therefore, the results presented in this chapter regarding species composition are derived from this reference.

In the urban experimental fields of Fisciano, Path, and Linden, which were intensively managed through frequent mowing, regular irrigation, and fertilization, a total of 49 spontaneous herbaceous species were identified (Table 1).

The floristic composition of the Fisciano, Path, and Linden fields was primarily dominated by the Poaceae family, followed by the Asteraceae, Fabaceae, and Convolvulaceae families.

From a seasonal perspective, the mean species richness was more homogeneous throughout the year than in the urban field of Avellino, with a reduction in seasonal variability. Certain perennial species, such as *Cynodon dactylon* L., *Oxalis corniculate* L., *Potentilla reptans* L., and *Trifolium repens* L., were present in all or almost all seasons, contributing to the compositional stability of the community.

Chorological analysis revealed a higher incidence of cosmopolitan and alien species including *Dichondra micrantha* Urb., *Erigeron canadiensis* L., *Paspalum dilatatum* Poir., and *Symphyotrichum squamatum* (Spreng.) G.L. Nesom. This composition suggests a typical flora of highly anthropized urban environments, characterized by simplified and homogenized ecological conditions.

Regarding life forms, the community was dominated by therophytes and hemicryptophytes, with a significant presence of rhizomatous and creeping species—functional strategies particularly suited to withstand frequent mowing and trampling. The presence of geophytes contributed to the persistence of vegetation cover throughout the year.

Table 1. *List of spontaneous herbaceous species identified in the urban experimental fields of Fisciano, Path, and Linden with corresponding floristic and functional characterization based on Baldi et al. (2025).*

Species	Family	Chorotype	Season
Artemisia vulgaris L.	Asteraceae	Boreal	Aut, Spr, Sum, Win
Avena barbata Pott ex Link	Poaceae	Eurymediterranean	Spr
Bromus hordeaceus L.	Poaceae	Cosmopolitan	Spr
Cardamine hirsuta L.	Brassicaceae	Cosmopolitan	Spr, Win
Carex distachya Desf.	Cyperaceae	Stenomediterranean	Win
Catapodium rigidum (L.) C.E. Hubb.	Poaceae	Eurymediterranean	Spr
Cerastium glomeratum ThuilL.	Caryophillaceae	Eurymediterranean	Spr, Win
Convolvolus arvensis L.	Convolvulaceae	Paleotemperate	Aut, Spr, Sum
Crepis bursifolia L.	Asteraceae	Endemic	Win
Crepis neglecta L.	Asteraceae	European	Win
Cynodon dactylon L.	Poaceae	Cosmopolitan	Aut, Spr, Sum, Win
Cyperus rotundus L.	Cyperaceae	Cosmopolitan	Aut
Dactylis glomerata L.	Poaceae	Paleotemperate	Spr, Sum, Win
Dichondra micrantha Urb.	Convolvulaceae	Alien	Aut, Spr, Sum, Win
Digitaria sanguinalis (L.) Scop.	Poaceae	Cosmopolitan	Aut
Erigeron canadensis L.	Asteraceae	Alien	Aut
Festuca ciliata Gouan	Poaceae	Eurymediterranean	Spr
Geranium rotundifolium L.	Geraniaceae	Paleotemperate	Aut, Spr, Win
Hypochaeris radicata L.	Asteraceae	European	Aut, Spr, Sum, Win
Lamium purpureum L.	Lamiaceae	Euro-Asiatic	Spr, Win
Malva sylvestris L.	Malvaceae	Euro-Asiatic	Aut, Spr, Sum, Win
Medicago arabica (L.) Huds.	Fabaceae	Eurymediterranean	Aut, Spr, Win
Medicago lupulina L.	Fabaceae	Paleotemperate	Aut, Spr, Sum
Medicago sativa L.	Fabaceae	Euro-Asiatic	Sum
Medicago tenuorea Ser.	Fabaceae	European	Win
Ornithogalum umbellatum L.	Asparagaceae	Eurymediterranean	Win
Oxalis corniculata L.	Oxalidaceae	Eurymediterranean	Aut, Spr, Sum, Win
Paspalum dilatatum Poir.	Poaceae	Alien	Aut, Sum, Win
Plantago lanceolata L.	Plantaginaceae	Euro-Asiatic	Spr, Sum, Win
Poa annua L.	Poaceae	Cosmopolitan	Spr, Win
Polygonum aviculare L.	Polygonaceae	Cosmopolitan	Spr, Sum
Portulaca oleracea L.	Portulacaceae	Cosmopolitan	Aut
Potentilla reptans L.	Rosaceae	Paleotemperate	Aut, Spr, Sum, Win

Prunella vulgaris L.	Lamiaceae	Boreal	Spr
Ranunculus arvensis L.	Ranunculaceae	Paleotemperate	Spr
Raphanus raphanistrum L.	Brassicaceae	Eurymediterranean	Spr
Rumex crispus L.	Polygonaceae	Cosmopolitan	Spr, Win
Senecio vulgaris L.	Asteraceae	Eurymediterranean	Win
Sherardia arvensis L.	Rubiaceae	Eurymediterranean	Aut, Spr, Win
Silene dioica (L.) Clairv.	Caryophillaceae	Paleotemperate	Spr, Sum, Win
Sonchus oleraceus L.	Asteraceae	Euro-Asiatic	Aut, Spr, Sum, Win
Sorghum halepense (L.) Pers.	Poaceae	Cosmopolitan	Spr, Sum, Win
Stellaria media (L.) VilL.	Caryophillaceae	Cosmopolitan	Spr, Sum, Win
Symphyotrichum squamatum (Spreng.) G.L. Nesom	Asteraceae	Alien	Aut
Trifolium campestre Schreb.	Fabaceae	Paleotemperate	Spr
Trifolium repens L.	Fabaceae	Paleotemperate	Aut, Spr, Sum, Win
Trifolium resupinatum L.	Fabaceae	Paleotemperate	Spr
Veronica persica Poir.	Plantaginaceae	Alien	Aut, Win, Spr
Vicia sativa L.	Fabaceae	Euro-Asiatic	Spr, Win

Soil Characterization and Post-Amendment Chemical and Physical Analyses in the Urban Experimental Fields of Fisciano

The characterization of soils from the urban experimental fields at Fisciano was carried out prior to the application of amendments, to establish the initial conditions of the experimental sites. The analyzed parameters included soil texture, classified according to the IUSS system using the sand–silt–clay ternary diagram; pH in aqueous solution; electrical conductivity; total carbonate content; soil organic matter; total nitrogen; and surface porosity. These surveys provided a comprehensive overview of the chemical and physical properties of the soils, which is essential for assessing their response to the experimental interventions.

At Fisciano experimental fields, the soils exhibited a sandy texture and slightly alkaline pH. The total carbonate content indicated slightly calcareous nature, while soil organic matter was 42.10 g/kg and total nitrogen was 4.85 g kg^{-1}. The electrical conductivity resulted 153.81 µS cm^{-1} and indicated a non-saline condition. The surface porosity reached 73%. These characteristics describe a well-structured, moderately fertile soil, suitable for supporting both spontaneous vegetation and the planned amendments.

In December 2024 (Table 2a), all amendment-based treatments led to an increase in cation exchange capacity (CEC), as compared to the control, with the highest values observed in soils amended with

Black Fluid (T4) and the combined *Humus Lombricò* + *Black Fluid* treatment (T5). Total carbon (C tot) and total nitrogen (N_tot) were significantly enhanced in treatments containing organic amendments, with the most pronounced increases recorded in soils treated with *Humus Lombricò* alone and in combination with *Black Fluid*, compared to the initial values of 42.10 g kg^{-1} for C_tot and 4.85 g kg^{-1} for N_tot. Soil respiration (SR) was particularly elevated in treatments containing *Black Fluid*, both alone and in combination with *Humus Lombricò*. At this early stage, total phosphorus (P_tot) did not differ significantly from the control.

By September 2025 (Table 2b), certain chemical properties appeared to stabilize, while others continued to evolve. CEC values tended to converge across all treatments, approaching those of the control, whereas C_tot remained slightly higher than the initial measurements. Soil respiration was consistently higher in the organic amendment treatments (T3 and T5). Notably, P_tot exhibited a significant increase in the mineral fertilizer treatment (T2), followed by the organic amendment treatments, indicating differential nutrient dynamics over time.

Table 2a. *Chemical and physical properties of soils at Fisciano experimental field measured in December 2024 after amendment application.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
CEC, cmol+/kg	20.58	b	**31.24**	**a**	29.76	a	33.82	a	32.66	a
C tot. g/kg	27.01	b	**34.84**	**a**	**32.37**	**a**	**32.47**	**a**	31.79	ab
N tot. g/kg	2.51	b	3.31	**a**	3.09	**a**	3.15	**a**	3.08	**a**
P tot. mg P/kg	0.91		0.99		1.00		0.97		0.96	
S.R. g CO_2 m^{-2} h^{-1}	0.73	b	0.70	b	0.89	ab	**1.05**	**a**	0.85	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; N tot.: Total nitrogen; P tot.: Total phosphorus; S.R: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 2b. *Chemical and physical properties of soils at Fisciano experimental field measured in September 2025 after amendment application.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
CEC, cmol+/kg	27.69		28.50		28.86		28.13		29.34	
C tot. g/kg	30.06		29.93		29.80		29.77		29.18	
P tot. mg P/kg	1.30	b	**1.57**	**a**	1.54	ab	1.49	ab	1.55	ab
S.R. g CO_2 m^{-2} h^{-1}	0.80	c	0.89	bc	**1.04**	**a**	0.92	abc	0.99	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; P tot.: Total phosphorus; S.R.: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Monitoring Vegetation Responses: Physiological and Agronomic Assessments at the Fisciano Experimental Field

Physiological and agronomic parameters were systematically recorded at bimonthly intervals starting from the first year of amendment application, which was repeated annually for three consecutive years. For each year of application, survey times are designated as T_n (T_1–T_5), corresponding to 2, 4, 6, 8, and 10 months after amendment application. The results obtained, which are representative of vegetation dynamics and treatment effects, are summarized in the tables below.

Table 3 shows the main physiological and agronomic surveys measured in the different treatments applied in the experimental field at Fisciano.

Regarding leaf indices, chlorophyll content (ChlM) was significantly higher in treatment T3 (*Humus Lombricò*) compared to the other ones, which did not differ significantly from each other. A similar trend was observed for the flavonol index (FlvM), with the maximum value recorded in T3, significantly higher than in the other treatments, while treatment T5 (*Humus Lombricò + Black Fluid)* showed the lowest value. The anthocyanin index (AnthM) differed significantly among treatments, showing positive values in T1 (control) and significantly lower values in the other treatments, which did not differ among themselves. The nitrogen-flavonol index (NFI) was significantly higher in treatment T5, whereas treatments T1, T2 (*Mineral Fertilizer)*, and T4 (*Black Fluid*) showed lower and statistically similar values; treatment T3 exhibited an intermediate value.

The Normalized Difference Vegetation Index (NDVI) was highest in T4, significantly higher than in the other treatments, with T1 showing an intermediate value. Regarding the Photochemical

Reflectance Index (PRI), the highest value was observed in treatment T4, significantly higher than in T5, while the remaining treatments showed intermediate values.

Canopy and soil temperatures did not show significant differences among the treatments. Soil water content (TDR) was significantly higher in treatments T1 and T2, while the lowest value was observed in T3; treatments T4 and T5 showed intermediate values.

Concerning agronomic parameters, fresh weight (FW) was significantly higher in the T1 and in treatment T4, while treatments T2 and T5 showed the lowest values; treatment T3 presented an intermediate value. Dry weight (DW) reached its maximum in treatment T3, significantly higher than in treatments T2 and T5, while T1 and T4 showed intermediate values.

Table 3. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 1 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.35	b	0.38	b	**0.62**	**a**	0.22	b	0.30	b
FlvM	0.61	b	0.67	b	**1.02**	**a**	0.55	b	0.33	c
AnthM	**0.03**	**a**	-0.15	b	-0.12	b	-0.16	b	-0.18	b
NFI	0.49	b	0.47	b	0.91	ab	0.74	b	**1.50**	**a**
NDVI	0.72	ab	0.69	b	0.62	b	**0.82**	**a**	0.65	b
PRI	0.06	ab	0.06	ab	0.09	ab	**0.10**	**a**	0.06	b
Canopy Temperature, °C	25.15		23.70		23.50		23.85		22.55	
Soil Temperature, °C	22.70		23.30		22.60		22.85		23.85	
TDR, % soil water content	**12.30**	**a**	**12.50**	**a**	5.55	b	9.80	ab	10.25	ab
FW, g m^{-2}	**1251.88**	**a**	502.50	b	638.13	ab	**1159.38**	**a**	491.88	b
DW, g m^{-2}	238.00	ab	127.06	b	**315.18**	**a**	216.87	ab	153.43	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 4 presents the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately four months after amendment application.

Regarding leaf physiological indices, ChlM did not show significant differences among treatments, displaying comparable values under all experimental conditions. In contrast, FlvM exhibited significant differences, with significantly higher values observed in all amended treatments and in the mineral fertilizer treatment compared to the control. AnthM showed significant variability among treatments: T4 had the highest value, T5 the lowest, and control along with the other treatments had intermediate values. The NFI index differed significantly among treatments, with the highest value in T1, significantly higher than all amended treatments, which did not differ from each other.

With respect to vegetation indices, NDVI reached the highest values in treatments T4 and T5, which were significantly higher than those observed in the control and the mineral fertilizer treatment; treatment T3 showed intermediate values. The PRI did not reveal significant differences among treatments at this sampling time.

Canopy temperature and soil temperature exhibited comparable values across treatments, with no statistically significant differences.

TDR surveys revealed significant differences among treatments, with the highest value observed in treatment T4, while the control exhibited the lowest value; treatments T2, T3, and T5 showed intermediate and statistically similar values.

Regarding agronomic parameters, FW was significantly higher in treatments T2, T4, and T5, whereas the lowest value was observed in treatment T3; the control showed intermediate values. DW exhibited significant differences among treatments, with higher values recorded in the control, T3, and T5, while treatment T4 showed the lowest value; treatment T2 displayed an intermediate value.

Table 4. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 1 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.68		0.54		0.42		0.33		0.52	
FlvM	0.16	b	**0.98**	**a**	**1.19**	**a**	**1.33**	**a**	**1.06**	**a**
AnthM	-0.14	bc	-0.02	ab	-0.11	bc	**0.08**	**a**	-0.18	c
NFI	**4.05**	**a**	0.59	b	0.51	b	0.50	b	0.30	b
NDVI	0.80	b	0.78	b	0.83	ab	**0.87**	**a**	**0.87**	**a**
PRI	0.05		0.04		0.05		0.07		0.06	
Canopy Temperature, °C	16.20		16.10		15.57		16.13		16.17	
Soil Temperature, °C	16.40		16.15		15.83		15.80		16.10	
TDR, % soil water content	10.50	c	13.30	b	12.95	b	**16.15**	**a**	13.60	b
FW, g m^{-2}	726.88	ab	**923.75**	**a**	636.25	b	**905.00**	**a**	**901.88**	**a**

DW, g m^{-2}	**370.88**	**a**	273.06	ab	**338.00**	**a**	196.44	b	**311.63**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 5 reported the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately six months after amendment application, shortly after mowing.

ChlM did not show significant differences among treatments, with comparable values across all experimental conditions. Similarly, FlvM did not differ significantly among treatments. AnthM showed significant differences among treatments, with the highest value observed in T1, which was significantly higher than those recorded in treatments T3 and T4, where the lowest values were detected; treatments T2 and T5 exhibited intermediate values. The NFI index did not show significant differences among treatments at this sampling time.

With respect to vegetation indices, NDVI showed significant differences among treatments, with the highest value observed in T1 and the lowest recorded in treatment T3; all other treatments showed intermediate and statistically similar values. The PRI displayed significant variability among treatments, with the highest value observed in treatment T2 and significantly lower values in the control, T3, and T5, while treatment T4 exhibited an intermediate value.

Canopy temperature, soil temperature, and TDR did not show significant differences among treatments.

Regarding agronomic parameters, FW showed significant differences among treatments, with the highest value recorded in treatment T2, which was significantly higher than all other treatments. The lowest FW value was observed in treatment T3, whereas the control and treatments T4 and T5 showed intermediate and statistically similar values. DW followed a similar pattern, with the maximum value observed in treatment T2 and significantly lower values in the remaining treatments, which did not differ significantly from each other.

Table 5. *Physiological and agronomic surveys measured at T_3 (6 months) during Year 1 in the different treatments of the Fisciano experimental field.*

Treatments	T1		T2		T3		T4		T5	
ChlM	0.37		0.31		0.37		0.44		0.36	
FlvM	1.28		1.19		1.43		1.09		1.14	
AnthM	**-0.01**	**a**	-0.06	bc	-0.07	c	-0.09	c	-0.03	ab
NFI	0.31		0.47		0.49		0.40		0.31	
NDVI	**0.83**	**a**	0.79	ab	0.69	b	0.80	ab	0.81	ab
PRI	0.02	bc	**0.07**	**a**	0.02	c	0.06	ab	0.03	bc
Canopy Temperature, °C	18.43		19.47		20.10		20.57		19.00	
Soil Temperature, °C	12.80		13.17		13.27		13.73		13.10	
TDR, % soil water content	22.45		22.97		29.00		26.35		27.20	
FW, g m^{-2}	890.00	b	**1630.63**	**a**	568.13	c	951.25	b	859.38	b
DW, g m^{-2}	182.50	b	**330.06**	**a**	160.63	b	188.06	b	206.00	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 6 reported the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately eight months after amendment application.

ChlM did not show significant differences among treatments, with comparable values across all experimental conditions. Similarly, FlvM and AnthM did not exhibit statistically significant differences, showing comparable values across treatments. The NFI index also remained similar among the different experimental conditions.

NDVI did not differ significantly among treatments, whereas PRI showed some variation: the highest value was observed in T2, significantly higher than in T1 and T3, while the other treatments had intermediate values. Canopy temperature and soil temperature did not show significant differences among treatments. Soil water content showed significant variation: the highest value was recorded in T2, followed by T3, T4, and T5, whereas the control showed the lowest value.

Regarding agronomic parameters, FW exhibited significant differences among treatments, with the highest values recorded in T3, followed by T2; treatments T4 and T5 showed intermediate values,

while the control displayed the lowest value. The DW did not show significant differences among treatments, with comparable values observed across all experimental conditions.

Table 6. *Physiological and agronomic surveys measured at T_4 (8 months) during Year 1 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.45		0.44		0.43		0.30		0.49	
FlvM	1.33		1.34		1.38		0.96		1.20	
AnthM	-0.17		-0.20		-0.17		-0.17		-0.20	
NFI	0.40		0.43		0.43		0.39		0.31	
NDVI	0.89		0.85		0.81		0.82		0.89	
PRI	0.04	b	**0.08**	**a**	0.03	b	0.05	ab	0.05	ab
Canopy Temperature, °C	22.07		22.93		22.97		22.73		23.73	
Soil Temperature, °C	24.87		24.57		24.67		24.80		24.77	
TDR, % soil water content	7.47	c	**17.45**	**a**	11.07	b	10.53	b	10.93	b
FW, g m^{-2}	465.63	c	1103.13	ab	**1287.50**	**a**	962.50	abc	940.63	abc
DW, g m^{-2}	309.24		316.25		327.44		319.65		318.12	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 7 shows the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately ten months after amendment application.

ChlM differed significantly among treatments, with the highest value observed in the control, which was significantly higher than all other treatments, among which no significant differences were observed. FlvM did not show significant differences among treatments. Anthocyanin was significantly lower in T4 compared to all other treatments, which did not differ significantly from each other. The nitrogen flavonol index exhibited significant differences among treatments, with the highest value observed in the control, intermediate values in T2, T3, and T4, and the lowest value in T5.

Regarding vegetation indices, NDVI did not show significant differences among treatments. PRI showed some variation, with the highest values observed in T1, T3, and T4, and significantly lower values in T5; T2 showed an intermediate value.

Canopy temperature and soil temperature did not differ significantly among treatments. TDR showed significant differences, with the highest value recorded in T5, followed by T3; T1 and T4 exhibited intermediate values, whereas T2 showed the lowest value.

Fresh biomass reported significant differences among treatments, with the highest values observed in T4 and T5, followed by T2 and T3; the control showed the lowest value. Dry biomass also exhibited significant differences, with the maximum value in T4, followed by T5; T1, T2, and T3 reported intermediate values.

Table 7. *Physiological and agronomic surveys measured at T_5 (10 months) during Year 1 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	**1.03**	**a**	0.38	b	0.25	b	0.46	b	0.39	b
FlvM	1.25		1.28		1.29		1.36		1.26	
AnthM	**-0.12**	**a**	**-0.09**	**a**	**-0.13**	**a**	-0.25	b	**-0.09**	**a**
NFI	**0.71**	**a**	0.40	b	0.20	bc	0.26	bc	0.08	c
NDVI	0.68		0.60		0.65		0.59		0.66	
PRI	**0.05**	**a**	0.04	ab	**0.05**	**a**	**0.05**	**a**	0.01	b
Canopy Temperature, °C	29.80		26.63		29.63		26.73		29.40	
Soil Temperature, °C	25.63		25.00		25.53		24.77		25.50	
TDR, % soil water content	9.70	abc	6.92	bc	13.20	ab	9.67	abc	**14.05**	**a**
FW, g m^{-2}	540.63	c	800.00	bc	675.00	bc	**1170.63**	**a**	**1129.38**	**a**
DW, g m^{-2}	358.31	bc	379.19	abc	360.44	bc	**520.81**	**a**	412.50	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 8 shows the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately two months after second amendment application.

ChlM showed significant differences among treatments, with the highest value observed in the control and lower, but comparable, values in T2, T4, and T5; the lowest value was recorded in T3. Flavonol content varied significantly, with the highest values in T5 and T4, and lower values in T3 and T2. Anthocyanin content was significantly lower in T4 and T5 compared to the ones. NFI index showed the highest value in T3, with intermediate values in T4 and T2, and lower values in T1 and T5. NDVI did not differ significantly among treatments, whereas PRI showed minor variations, with the highest values in T1 and lowest values in T2 and T5.

Canopy and soil temperatures were similar across treatments. TDR differed significantly, with the highest values recorded in T5, intermediate values in T1 and T3, and the lowest value in T4.

FW showed significant differences among treatments, with the highest values in T4 and T3, intermediate values in T2, and the lowest values in T1 and T5. DW followed a similar trend, with the highest values observed in T2, T3, and T4, and intermediate to lower values in T5 and T1.

Table 8. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 2 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	**1.28**	**a**	0.72	ab	0.51	b	1.01	ab	0.77	ab
FlvM	1.13	abc	0.70	c	0.94	bc	1.34	ab	**1.57**	**a**
AnthM	**-0.05**	**a**	**-0.09**	**a**	**-0.10**	**a**	-0.21	b	-0.25	b
NFI	0.72	b	0.77	b	**1.15**	**a**	0.91	b	0.50	c
NDVI	0.85		0.87		0.83		0.84		0.87	
PRI	**-0.07**	**a**	-0.10	b	-0.08	ab	-0.08	ab	-0.09	b
Canopy Temperature, °C	21.33		20.33		21.20		21.00		20.37	
Soil Temperature, °C	16.10		16.00		16.93		16.70		15.77	
TDR, % soil water content	32.43	ab	26.45	b	29.75	ab	12.55	c	**33.15**	**a**
FW, g m^{-2}	318.75	c	425.00	bc	656.25	ab	**715.63**	**a**	368.75	c
DW, g m^{-2}	112.50	b	**181.19**	**a**	**170.81**	**a**	**159.38**	**a**	143.75	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 9 shows the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately four months after second amendment application.

ChlM showed significant differences among treatments, with the highest value observed in T4, which was significantly higher than all other treatments; T1 showed intermediate values, while T2, T3, and T5 reported lower values. FlvM was significantly higher in T1, T3, and T4 compared to T2 and T5. AnthM differed significantly among treatments, with higher values observed in T1, T3, and T4 compared to T2; T5 exhibited intermediate values. The NFI index showed the highest value in T5, significantly higher than in the other treatments; T4 reported intermediate values, while T1, T2, and T3 showed lower values.

Regarding vegetation indices, NDVI was significantly higher in T1, T4, and T5 compared to T2 and T3. PRI showed significant differences among treatments, with the highest value observed in T4, followed by T2 and T5; T3 exhibited intermediate values, while T1 showed the lowest value.

Canopy temperature showed significant differences, with the highest value observed in T4; T5 reported intermediate values, whereas T1, T2, and T3 showed lower values. Soil temperature did not differ significantly among treatments. TDR showed significant differences, with the highest values recorded in T1 and T2; T3 and T5 exhibited intermediate values, while T4 showed the lowest value.

Regarding agronomic parameters, FW did not differ significantly among treatments, except for T5, which showed significantly lower values than all other treatments. DW did not show significant differences among treatments, with comparable values observed across all experimental conditions.

Table 9. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 2 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.75	b	0.46	d	0.55	c	**1.00**	**a**	0.60	c
FlvM	**1.38**	**a**	0.93	b	**1.62**	**a**	**1.55**	**a**	0.82	b
AnthM	**0.37**	**a**	0.15	b	**0.41**	**a**	**0.36**	**a**	0.35	ab
NFI	0.51	c	0.57	c	0.59	bc	0.74	ab	**0.87**	**a**
NDVI	**0.79**	**a**	0.65	b	0.68	b	**0.77**	**a**	**0.79**	**a**
PRI	0.04	d	0.15	b	0.10	c	**0.19**	**a**	0.12	bc
Canopy Temperature, °C	11.63	b	12.00	b	11.70	b	**13.00**	**a**	12.57	ab
Soil Temperature, °C	16.50		16.35		15.87		15.70		15.30	
TDR, % soil water content	**65.60**	**a**	**62.85**	**a**	52.00	b	42.30	c	47.15	bc
FW, g m^{-2}	**352.06**	**a**	**409.38**	**a**	**390.63**	**a**	**350.00**	**a**	240.63	b
DW, g m^{-2}	140.63		166.69		150.00		159.38		141.69	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 10 shows the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately six months after the second amendment application, shortly after mowing.

ChlM showed significant differences among treatments, with the highest values observed in T1 and T5, which were significantly higher than in T2 and T3; T4 showed intermediate values. FlvM was significantly higher in T2, T3, T4, and T5 compared to control, with no significant differences among these treatments. AnthM was significantly lower in all amended treatments and in mineral fertilizer (T2–T5) compared to the control. The NFI index showed the highest value in T1, significantly higher than in T3 and T4; T2 and T5 exhibited intermediate values.

NDVI did not differ significantly among treatments. PRI showed significant differences, with the highest values observed in T1 and T2, followed by T4 and T5; the lowest value was recorded in T3.

Canopy temperature showed significant differences, with the highest value observed in T4, followed by T2 and T3; T1 and T5 exhibited lower values. Soil temperature was significantly higher in T2, while the other treatments showed intermediate or similar values. Soil water content differed significantly, with the highest values recorded in T2 and T3; T4 and T5 showed intermediate values, whereas the control had an intermediate-high value.

FW showed significant differences among treatments, with the highest value observed in T3, followed by T4; T1, T2, and T5 exhibited intermediate values. DW did not show significant differences among treatments, with comparable values across all experimental conditions.

Table 10. *Physiological and agronomic surveys measured at T_3 (6 months) during Year 2 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	**1.02**	**a**	0.66	b	0.32	c	0.58	bc	**1.00**	**a**
FlvM	0.63	b	**1.50**	**a**	**1.67**	**a**	**1.57**	**a**	**1.57**	**a**
AnthM	**-0.04**	**a**	-0.28	b	-0.27	b	-0.21	b	-0.22	b
NFI	**0.93**	**a**	0.41	ab	0.20	b	0.36	b	0.56	ab

NDVI	0.78		0.79		0.82		0.82		0.83	
PRI	**0.12**	**a**	**0.11**	**a**	0.06	c	0.08	b	0.08	bc
Canopy Temperature, °C	12.83	c	15.70	ab	14.47	bc	**16.27**	**a**	13.77	c
Soil Temperature, °C	10.87	b	**13.90**	**a**	11.97	b	12.57	ab	11.23	b
TDR, % soil water content	54.60	ab	**58.35**	**a**	**58.85**	**a**	38.85	bcd	41.30	bc
FW, g m^{-2}	231.25	abcd	243.75	abc	**308.31**	**a**	290.63	ab	243.75	abc
DW, g m^{-2}	131.25		131.25		137.50		134.38		133.31	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 11 shows the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately eight months after the second amendment application. ChlM reported significant differences among treatments, with the highest values observed in T1, T2, and T5; T4 showed intermediate values, while the lowest value was recorded in T3. FlvM was significantly higher in T2, T3, and T5 compared to T4; T1 showed intermediate values. AnthM was significantly lower in T4 compared to all other treatments, which did not differ significantly from each other. The NFI index showed the highest values in T2 and T4, intermediate values in T1 and T5, and the lowest value in T3.

Regarding vegetation indices, NDVI was significantly higher in T5 compared to T1; T2, T3, and T4 showed intermediate and statistically similar values. PRI differed significantly among treatments, with the highest values observed in T2 and T3, intermediate values in T4 and T5, and the lowest value in T1.

Canopy temperature showed significant differences, with the highest values recorded in T4 and T1, intermediate values in T5, and the lowest values in T2 and T3. Soil temperature did not differ significantly among treatments. TDR exhibited significant differences, with the highest value in T2; T1, T3, T4, and T5 showed lower and comparable values.

Fresh biomass showed significant differences among treatments, with the highest values observed in T3, T4, and T5, followed by T2; the lowest value was recorded in T1. Dry biomass followed a similar trend, with the highest values in T3, T4, and T5, intermediate values in T2, and the lowest value in T1.

Table 11. *Physiological and agronomic surveys measured at T_4 (8 months) during Year 2 in the different treatments of the Fisciano experimental field.*

Treatments	T1		T2		T3		T4		T5	
ChlM	**0.62**	**a**	**0.62**	**a**	0.42	b	0.54	ab	**0.63**	**a**
FlvM	1.26	ab	**1.53**	**a**	**1.60**	**a**	1.06	b	**1.46**	**a**
AnthM	**0.26**	**a**	**0.27**	**a**	**0.29**	**a**	0.06	b	**0.23**	**a**
NFI	0.46	ab	**0.49**	**a**	0.33	b	**0.55**	**a**	0.43	ab
NDVI	0.74	b	0.78	ab	0.78	ab	0.77	ab	**0.83**	**a**
PRI	0.07	b	**0.12**	**a**	**0.13**	**a**	0.12	ab	0.09	ab
Canopy Temperature, °C	**24.20**	**a**	20.37	c	21.60	bc	**25.75**	**a**	23.55	ab
Soil Temperature, °C	18.50		17.80		18.40		18.70		19.13	
TDR, % soil water content	24.20	b	**26.35**	**a**	25.10	b	24.70	b	24.05	b
FW, g m^{-2}	446.88	b	**887.50**	**a**	**1062.50**	**a**	**933.13**	**a**	**1059.38**	**a**
DW, g m^{-2}	122.19	b	**304.38**	**a**	**368.13**	**a**	**361.25**	**a**	**362.06**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 12 shows the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately ten months after the second amendment application.
ChlM reported significant differences among treatments, with the highest values recorded in T1 and T2; T3, T4, and T5 showed significantly lower values. FlvM was significantly lower in T5 compared to all other treatments, which did not differ between each other. AnthM was significantly lower in all amended treatments (T2–T5) compared to the control (T1). The NFI index was highest in T1 and T2, intermediate in T3 and T5, and lowest in T4.
NDVI showed significant differences among treatments, with the highest value in T1, intermediate values in T3 and T4, and the lowest value in T5. PRI did not differ substantially among most amendments, with the highest value observed in T2.
Canopy temperature exhibited significant differences, with the highest values in T3 and T5, intermediate values in T4, and the lowest values in T1 and T2. Soil temperature and TDR did not show significant differences among treatments.

Regarding agronomic parameters, FW reported significant differences, with the highest values recorded in T1, T2, and T3; T4 showed intermediate values, and T5 reported the lowest value. DW showed a similar trend, with the highest value in T1, intermediate values in T2 and T3, and lower values in T4 and T5.

Table 12. *Physiological and agronomic surveys measured at T_5 (10 months) during Year 2 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	**0.80**	**a**	**0.87**	**a**	0.34	b	0.25	b	0.22	b
FlvM	**1.28**	**a**	**1.39**	**a**	**1.10**	**a**	**1.23**	**a**	0.66	b
AnthM	**0.16**	**a**	-0.11	b	-0.13	b	-0.12	b	-0.14	b
NFI	**0.69**	**a**	**0.71**	**a**	0.34	bc	0.20	c	0.36	b
NDVI	**0.81**	**a**	0.57	bc	0.72	ab	0.69	ab	0.42	c
PRI	0.04	b	**0.09**	**a**	0.06	ab	0.06	ab	0.06	ab
Canopy Temperature, °C	25.30	b	26.45	b	**34.10**	**a**	27.70	b	**33.00**	**a**
Soil Temperature, °C	25.73		24.70		25.43		25.73		24.50	
TDR, % soil water content	10.25		9.55		9.20		10.50		10.05	
FW, g m^{-2}	**778.13**	**a**	**762.50**	**a**	**739.38**	**a**	606.25	ab	540.63	b
DW, g m^{-2}	**390.63**	**a**	318.75	ab	306.25	ab	272.94	bc	258.31	bc

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 13 shows the physiological and agronomic parameters measured across the different treatments at the Fisciano experimental field approximately two months after the third amendment application. ChlM showed significant differences among treatments, with the highest values observed in T1, T3, T4, and T5; T2 exhibited the lowest value. FlvM and AnthM did not differ significantly among treatments. The NFI index was highest in T2, significantly higher than in T1, T3, T4, and T5, which showed lower and comparable values.

Regarding vegetation indices, NDVI did not show significant differences among treatments. PRI differed significantly, with the highest value in T4, intermediate values in T1 and T3, and the lowest values in T2 and T5.

Canopy temperature showed significant differences, with the highest value observed in T4; T3 and T5 exhibited intermediate values, and T1 and T2 showed the lowest values. Soil temperature did not differ significantly among treatments, whereas TDR showed significant differences, with the highest value observed in T1, the lowest in T4, and intermediate values in T2, T3, and T5.

FW showed significant differences among treatments, with the highest values recorded in T4 and T5, followed by T3; T1 and T2 exhibited slightly lower but comparable values. DW was highest in T4 and T5, intermediate in T3, and lowest in T1 and T2.

Table 13. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 3 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	**0.91**	**a**	0.43	b	**0.78**	**a**	**0.86**	**a**	**0.75**	**a**
FlvM	1.44		1.49		1.54		1.54		1.23	
AnthM	0.18		0.16		0.16		0.19		0.18	
NFI	0.55	b	**0.88**	**a**	0.44	b	0.47	b	0.53	b
NDVI	0.82		0.82		0.84		0.80		0.89	
PRI	-0.04	ab	-0.08	d	-0.06	bc	**-0.02**	**a**	-0.07	cd
Canopy Temperature, °C	25.33	b	25.50	b	26.80	ab	**28.10**	**a**	26.90	ab
Soil Temperature, °C	27.43		27.53		27.40		27.47		27.47	
TDR, % soil water content	**23.55**	**a**	11.55	c	11.25	c	6.95	c	18.45	b
FW, g m^{-2}	1100.00	bc	1081.00	c	1175.00	b	**1200.00**	**a**	**1192.00**	**a**
DW, g m^{-2}	253.10	c	304.20	bc	325.00	b	**409.40**	**a**	**390.60**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 14 shows the physiological and agronomic surveys measured across the different treatments at the Fisciano experimental field approximately four months after the third amendment application. This represents the final survey conducted on this experimental field.

ChlM differed significantly among treatments, with the highest value observed in T2, significantly higher than in T1, T3, and T4; T5 showed intermediate values. FlvM was significantly higher in T3 and T4 compared to T1, T2, and T5. AnthM was significantly lower in T2 compared to the ones which did not differ significantly. The NFI index was highest in T2, intermediate in T5 and T4, and lowest in T3; T1 showed intermediate values.

NDVI did not show significant differences among treatments. PRI differed significantly, with the highest value in T2, intermediate values in T1 and T4, and the lowest values in T3 and T5.

Canopy temperature showed significant differences, with the highest value observed in T2, intermediate values in T1 and T4, and the lowest in T5; T3 showed intermediate-high values. Soil temperature was significantly higher in T2, T3, T4, and T5 compared to T1. TDR differed significantly, with the highest value in T3, the lowest in T5, and intermediate values in T1, T2, and T4.

Regarding agronomic parameters, FW showed significant differences among treatments, with the highest values recorded in T1, T2, and T4, intermediate in T3, and the lowest in T5. DW followed a similar trend, with the highest values in T1 and T3, intermediate values in T2 and T4, and the lowest value in T5.

Table 14. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 3 in the different treatments of the Fisciano experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.47	b	**1.31**	**a**	0.40	b	0.74	b	0.79	ab
FlvM	0.76	b	0.57	b	**1.37**	**a**	**1.51**	**a**	0.71	b
AnthM	**0.18**	**a**	0.04	b	**0.21**	**a**	**0.19**	**a**	**0.21**	**a**
NFI	0.64	b	**1.00**	**a**	0.29	d	0.49	c	0.57	bc
NDVI	0.83		0.86		0.86		0.84		0.85	
PRI	-0.05	b	**-0.02**	**a**	-0.07	c	-0.05	b	-0.09	d
Canopy Temperature, °C	26.25	abc	**28.70**	**a**	25.85	bc	28.20	ab	25.43	c
Soil Temperature, °C	25.97	b	**27.90**	**a**	**28.13**	**a**	**27.97**	**a**	**27.93**	**a**
TDR, % soil water content	11.85	ab	9.85	bc	**13.85**	**a**	10.30	abc	7.65	c
FW, g m^{-2}	**631.20**	**a**	**625.00**	**a**	535.40	ab	**687.50**	**a**	504.20	b
DW, g m^{-2}	**218.80**	**a**	170.80	ab	**225.00**	**a**	206.20	ab	162.50	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 15 and Figure 36, obtained from the Fisciano Experimental Field, illustrate the temporal dynamics of chlorophyll under the different soil treatments applied. Following amendment, the treatment with *Humus Lombricò* (T3) and the combination of *Humus Lombricò + Black Fluid* (T5) exhibited marked and statistically significant increases compared to the control (T1). Notably, T5 consistently displayed higher and significant values throughout the entire observation period, indicating that the combination of *Humus Lombricò + Black Fluid* represents the most effective treatment for enhancing the measured parameter. Treatments with mineral fertilizer alone (T2) or *Black Fluid* alone (T4) showed more modest and less consistent increases.

Table 15. *Temporal dynamics of chlorophyll under different soil treatments at the Fisciano Experimental Field.*

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	0.35	b	0.38	b	**0.62**	**a**	0.22	b	0.30	b
17/11/2023	0.68		0.54		0.42		0.33		0.52	
22/01/2024	0.37		0.31		0.37		0.44		0.36	
21/03/2024	0.45		0.44		0.43		0.30		0.49	
16/05/2024	**1.03**	**a**	0.38	b	0.25	b	0.46	b	0.39	b
30/09/2024	**1.28**	**a**	0.72	ab	0.51	b	1.01	ab	0.77	ab
06/11/2024	0.75	b	0.46	d	0.55	c	**1.00**	**a**	0.60	c
17/01/2025	**1.02**	**a**	0.66	b	0.32	c	0.58	bc	**1.00**	**a**
13/03/2025	**0.62**	**a**	**0.62**	**a**	0.42	b	0.54	ab	**0.63**	**a**
14/05/2025	**0.80**	**a**	**0.87**	**a**	0.34	b	0.25	b	0.22	b
23/09/2025	**0.91**	**a**	0.43	b	**0.78**	**a**	**0.86**	**a**	**0.75**	**a**
26/11/2025	0.47	b	**1.31**	**a**	0.40	b	0.74	b	0.79	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

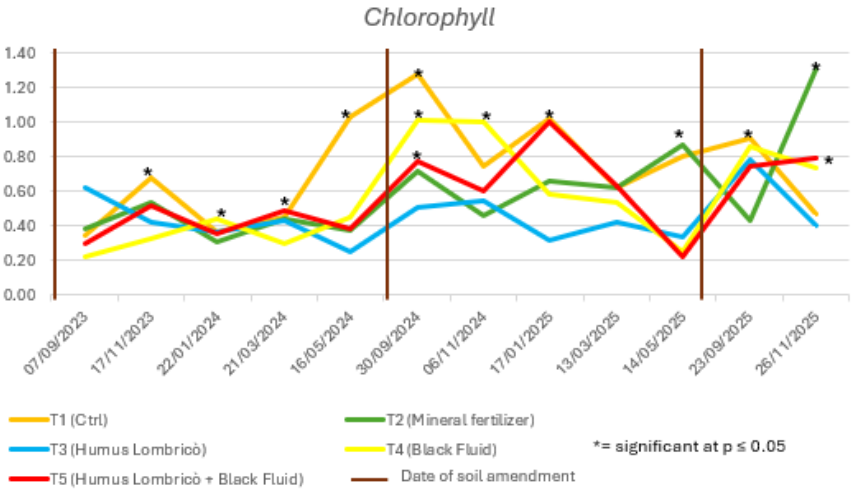


Figure 36. *Temporal dynamics of chlorophyll under different soil treatments at the Fisciano Experimental Field.*

Table 16 and Figure 37, obtained from the Fisciano Experimental Field, illustrate the temporal dynamics of NDVI index under the different soil treatments applied. The combination of *Humus Lombricò* + *Black Fluid* (T5) exhibited the highest performance, with significantly higher and more stable NDVI values throughout the entire monitoring period. Vegetative response was superior compared both to the control and to the individual treatments, indicating a clear synergistic effect between the two amendments.

Table 16. *Temporal dynamics of NDVI index under different soil treatments at the Fisciano Experimental Field.*

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	0.72	ab	0.69	b	0.62	b	**0.82**	**a**	0.65	b
17/11/2023	0.80	b	0.78	b	0.83	ab	**0.87**	**a**	**0.87**	**a**
22/01/2024	**0.83**	**a**	0.79	ab	0.69	b	0.80	ab	0.81	ab
21/03/2024	0.89		0.85		0.81		0.82		0.89	
16/05/2024	0.68		0.60		0.65		0.59		0.66	
30/09/2024	0.85		0.87		0.83		0.84		0.87	
06/11/2024	**0.79**	**a**	0.65	b	0.68	b	**0.77**	**a**	**0.79**	**a**
17/01/2025	0.78		0.79		0.82		0.82		0.83	
13/03/2025	0.74	b	0.78	ab	0.78	ab	0.77	ab	**0.83**	**a**

14/05/2025	**0.81**	**a**	0.57	bc	0.72	ab	0.69	ab	0.42	c
23/09/2025	0.82		0.82		0.84		0.80		0.89	
26/11/2025	0.83		0.86		0.86		0.84		0.85	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

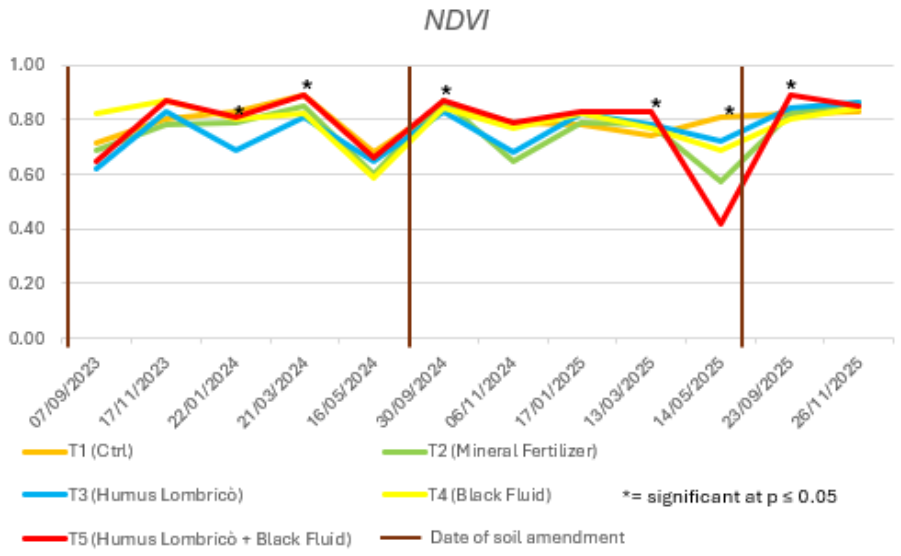


Figure 37. *Temporal dynamics of NDVI index under different soil treatments at the Fisciano Experimental Field.*

Table 17 and Figure 38, obtained from the Fisciano Experimental Field, illustrate the temporal dynamics of aboveground fresh weight under the different soil treatments applied. The combination of *Humus Lombricò + Black Fluid* (T5) exhibited the highest performance in terms of aboveground fresh biomass, with higher values and a more consistent response throughout the entire monitoring period. After each amendment, the T5 curve (Figure 38) increased more markedly compared to the other treatments, maintaining superior levels even in subsequent stages, indicative of a prolonged effect and an enhanced ability of the crop to utilize the provided resources. The mineral fertilizer (T2) occasionally reached high values, but its response was more irregular and tended to decline rapidly, reflecting a more immediate but less persistent effect. Treatments T3 and T4 improved production relative to the control but did not reach the levels achieved by the combination of the two amendments: T3 showed a more gradual and stable increase, whereas T4 exhibited more pronounced fluctuations. The control (T1) consistently remained the least productive treatment, confirming the importance of organic amendments.

Table 17. *Temporal dynamics of aboveground fresh weight under different soil treatments at the Fisciano Experimental Field.*

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	**1251.88**	**a**	502.50	b	638.13	ab	**1159.38**	**a**	491.88	b
17/11/2023	726.88	ab	**923.75**	**a**	636.25	b	**905.00**	**a**	**901.88**	**a**
22/01/2024	890.00	b	**1630.63**	**a**	568.13	c	951.25	b	859.38	b
21/03/2024	465.63	c	1103.13	ab	**1287.50**	**a**	962.50	abc	940.63	abc
16/05/2024	540.63	c	800.00	bc	675.00	bc	**1170.63**	**a**	**1129.38**	**a**
30/09/2024	318.75	c	425.00	bc	656.25	ab	**715.63**	**a**	368.75	c
06/11/2024	**352.06**	**a**	**409.38**	**a**	**390.63**	**a**	**350.00**	**a**	240.63	b
17/01/2025	231.25	abcd	243.75	abc	**308.31**	**a**	290.63	ab	243.75	abc
13/03/2025	446.88	b	**887.50**	**a**	**1062.50**	**a**	**933.13**	**a**	**1059.38**	**a**
14/05/2025	**778.13**	**a**	**762.50**	**a**	**739.38**	**a**	606.25	ab	540.63	b
23/09/2025	1100.00	bc	1081.00	c	1175.00	b	**1200.00**	**a**	**1192.00**	**a**
26/11/2025	**631.20**	**a**	**625.00**	**a**	535.40	ab	**687.50**	**a**	504.20	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

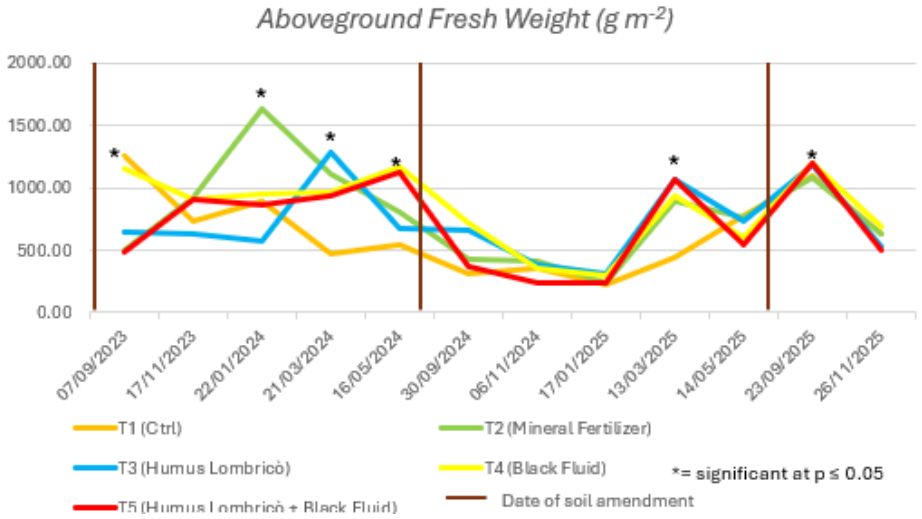


Figure 38. *Temporal dynamics of aboveground fresh weight under different soil treatments at the Fisciano Experimental Field.*

Table 18 and Figure 39, obtained from the Fisciano Experimental Field, illustrate the temporal dynamics of aboveground dry weight under the different soil treatments applied. The T5 treatment was once again the most effective for aboveground dry biomass, and Figure 39 shows a very clear trend. After each amendment, the T5 curve (Figure 39) increased more rapidly and reached higher values than all other treatments, maintaining superior performance throughout the entire monitoring period. This sustained response indicates that the combination of the two amendments not only stimulates immediate growth but also contributes to long-term improvement of soil conditions, promoting a more efficient accumulation of dry biomass. T2 showed rapid increases and occasionally high values, but its effectiveness was less stable: peaks were often followed by marked declines, suggesting a more immediate but less persistent effect. The single organic treatments (T3 and T4) improved production relative to the control but did not reach the levels achieved by the combination of the two amendments.

Table 18. *Temporal dynamics of aboveground dry weight under different soil treatments at the Fisciano Experimental Field.*

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	238.00	ab	127.06	b	**315.18**	**a**	216.87	ab	153.43	b
17/11/2023	**370.88**	**a**	273.06	ab	**338.00**	**a**	196.44	b	**311.63**	**a**
22/01/2024	182.50	b	**330.06**	**a**	160.63	b	188.06	b	206.00	b
21/03/2024	309.24		316.25		327.44		319.65		318.12	
16/05/2024	358.31	bc	379.19	abc	360.44	bc	**520.81**	**a**	412.50	ab
30/09/2024	112.50	b	**181.19**	**a**	**170.81**	**a**	**159.38**	**a**	143.75	ab
06/11/2024	140.63		166.69		150.00		159.38		141.69	
17/01/2025	131.25		131.25		137.50		134.38		133.31	
13/03/2025	122.19	b	**304.38**	**a**	**368.13**	**a**	**361.25**	**a**	**362.06**	**a**
14/05/2025	**390.63**	**a**	318.75	ab	306.25	ab	272.94	bc	258.31	bc
23/09/2025	253.10	c	304.20	bc	325.00	b	**409.40**	**a**	**390.60**	**a**
26/11/2025	**218.80**	**a**	170.80	ab	**225.00**	**a**	206.20	ab	162.50	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

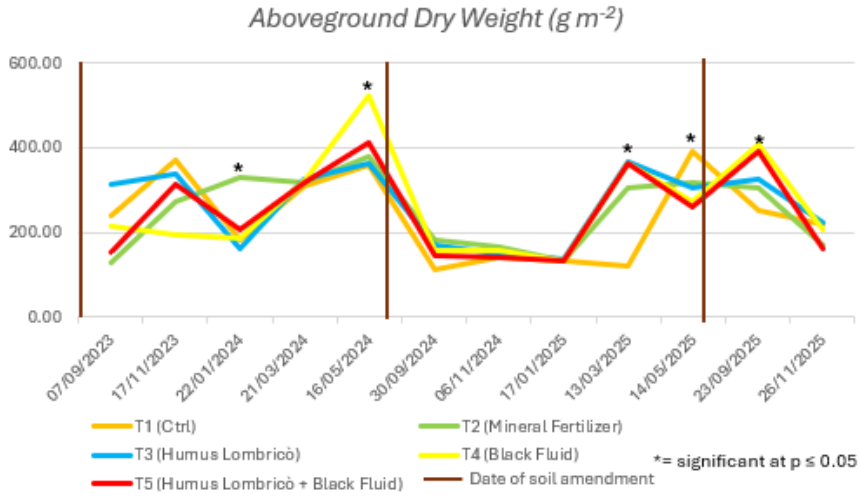


Figure 39. *Temporal dynamics of aboveground dry weight under different soil treatments at the Fisciano Experimental Field.*

Results of Chemical, Agronomic, and Physiological Assessments at the Urban Experimental Fields in Path (Fisciano)

Soil Characterization and Post-Amendment Chemical and Physical Analyses in the Urban Experimental Fields of Path (Fisciano)

As for the initial soil characterization, the Path experimental field exhibited chemical and physical properties comparable to those described for the other experimental sites in Fisciano, including a sandy texture, slightly alkaline pH, non-saline conditions, and moderate levels of organic matter and nutrients. These similarities allowed for a direct comparison of the soil response to amendment application among the Fisciano experimental fields.

In December 2024 (Table 19a), significant differences among treatments were observed for several chemical and biological parameters. Cation exchange capacity (CEC) increased in all amended soils compared to the control, with the highest value recorded in the *Humus Lombricò* treatment (T2), followed by the combined *Humus Lombricò* + *Black Fluid* treatment (T4). Total carbon (C_tot) and total nitrogen (N_tot) were significantly enhanced in soils receiving organic amendments, particularly in the combined treatment (T4), which exhibited the highest C_tot and N_tot values. Total phosphorus (P_tot) showed a significant increase only in soils amended with *Black Fluid* alone (T3). Soil respiration (SR) was significantly higher in the combined treatment (T4).

By September 2025 (Table 19b), CEC values increased across all treatments, with amended soils maintaining higher values than the control and the highest CEC observed in the *Black Fluid* treatment (T3). In contrast to the December sampling, total carbon and total phosphorus did not show

statistically significant differences among treatments. Soil respiration remained significantly higher in amended soils, particularly in the combined *Humus Lombricò + Black Fluid* treatment (T4).

***Table 19a**. Chemical and physical properties of soils at Path experimental field measured in December 2024 after amendment application.*

Treatments	**T1**		**T2**		**T3**		**T4**	
CEC, cmol+/kg	23.56	c	**27.51**	**a**	24.79	bc	26.04	ab
C tot. g/kg	24.23	b	24.47	b	26.52	ab	**30.13**	**a**
N tot. g/kg	2.33	b	2.39	b	2.4	b	**2.99**	**a**
P tot. mg P/kg	0.60	b	0.59	b	**0.81**	**a**	0.62	b
S.R. g CO_2 m^{-2} h^{-1}	0.89	b	1.03	ab	0.99	ab	**1.13**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; N tot.: Total nitrogen; P tot.: Total phosphorus; S.R: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

***Table 19b.** Chemical and physical properties of soils at Path experimental field measured in September 2025 after amendment application.*

Treatments	**T1**		**T2**		**T3**		**T4**	
CEC, cmol+/kg	26.74	b	28.88	ab	**30.38**	**a**	28.14	ab
C tot. g/kg	23.59		24.67		24.33		25.09	
P tot. mg P/kg	1.54		1.61		1.63		1.56	
S.R. g CO_2 m^{-2} h^{-1}	0.96	c	1.14	ab	1.06	bc	**1.21**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; P tot.: Total phosphorus; S.R: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Monitoring Vegetation Responses: Physiological and Agronomic Assessments at the Path (Fisciano) Field

Physiological and agronomic surveys in the Path field were measured systematically at bimonthly intervals starting from the first year of amendment application, which was conducted in 2024 and repeated in 2025. Based on the initial phase at Fisciano, treatment T2 (mineral fertilizer) was

eliminated in the Path field to focus the analysis on the effects of increased doses of organic amendments. For each year of application, survey times are designated as T_n (T_1–T_5), corresponding to 2, 4, 6, 8, and 10 months after amendment application. The results obtained, reflecting vegetation dynamics and treatment effects, are reported in the tables below.

Table 20 shows the physiological and agronomic surveys measured across the different treatments at the Path field approximately two months after the first amendment application. Leaf chlorophyll content (ChlM) differed significantly among treatments, with the highest values observed in T2 (*Humus Lombricò*) and T4 (*Humus Lombricò* + *Black Fluid*), which were significantly higher than in T3 (*Black Fluid*); T1 (Control) showed intermediate values. Leaf flavonol content (FlvM) was significantly lower in T3 compared to T1, T2, and T4, which did not differ significantly. Leaf anthocyanin content (AnthM) was lowest in T2 and T1, intermediate in T3, and highest in T4. The nitrogen-flavonol index (NFI) showed significant differences, being highest in T1, lowest in T4, and intermediate in T2 and T3.

NDVI varied significantly, with the lowest value in T3, highest in T4, and intermediate in T1 and T2. PRI differed significantly, with the lowest value in T4, while T1, T2, and T3 showed intermediate values.

No significant differences were observed in canopy or soil temperature among treatments. Soil water content (TDR) was significantly lower in T2 compared to all other treatments, which did not differ among each other.

Fresh weight (FW) and dry weight (DW) differed significantly among treatments, with the highest values in T4, intermediate in T1 and T3, and the lowest in T2.

Table 20. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 1 in the different treatments of the Path field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.58	ab	**0.69**	**a**	0.35	b	**0.59**	**a**
FlvM	**1.81**	**a**	**1.61**	**a**	1.02	b	**1.45**	**a**
AnthM	-0.23	bc	-0.27	c	-0.16	b	**-0.04**	**a**
NFI	**0.65**	**a**	0.40	bc	0.57	b	0.28	c
NDVI	0.71	ab	**0.80**	**a**	0.63	b	**0.83**	**a**
PRI	**-0.03**	**a**	-0.06	ab	-0.07	ab	-0.09	b
Canopy Temperature, °C	21.20		23.60		21.70		23.63	
Soil Temperature, °C	18.57		18.33		17.47		18.60	
TDR, % soil water content	**31.50**	**a**	13.55	b	**28.65**	**a**	**28.90**	**a**

FW, g m^{-2}	500.00	b	259.38	c	518.75	b	**887.50**	**a**
DW, g m^{-2}	190.63	b	134.38	b	187.50	b	**312.50**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 21 reports the physiological and agronomic surveys measured at four months during Year 1 in the Path experimental field.

Significant variation in ChlM was observed among treatments, with T1 having the highest value, T2 and T3 lower values, and T4 intermediate. FlvM was significantly lower in T3 compared to T1 and T2, with T4 showing intermediate values. AnthM was highest in T1 and T2, intermediate in T3, and lowest in T4. The NFI index was highest in T3, lowest in T2, and intermediate in T1 and T4.

NDVI values were significantly higher in T1, while T2, T3, and T4 showed lower and similar values. PRI was significantly higher in T1 and T2, with T3 and T4 showing lower values.

Canopy temperature showed significant variation among treatments, with T4 being the highest, and T1, T2, and T3 having comparable lower values. No significant differences in soil temperature were observed among treatments. TDR was highest in T4, lowest in T2 and T3, and intermediate in T1.

FW was highest in T2, intermediate in T1 and T4, and lowest in T3. DW was highest in T1, intermediate in T2, and lowest in T3 and T4.

Table 21. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 1 in the different treatments of the Path field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	**0.72**	**a**	0.59	b	0.57	b	0.63	ab
FlvM	**1.50**	**a**	**1.31**	**a**	0.65	b	1.10	ab
AnthM	**0.18**	**a**	**0.19**	**a**	0.09	b	0.06	c
NFI	0.50	b	0.29	c	**1.25**	**a**	0.62	b
NDVI	**0.86**	**a**	0.79	b	0.77	b	0.77	b
PRI	**0.24**	**a**	**0.25**	**a**	0.18	b	0.15	b
Canopy Temperature, °C	12.75	b	12.60	b	12.45	b	**14.00**	**a**
Soil Temperature, °C	16.30		15.40		16.35		16.20	

TDR, % soil water content	42.30	ab	37.75	b	38.30	b	**47.45**	**a**
FW, g m^{-2}	856.25	ab	**971.88**	**a**	571.88	c	668.75	bc
DW, g m^{-2}	**353.13**	**a**	278.13	ab	218.75	b	239.56	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 22 shows the physiological and agronomic surveys measured across the different treatments at the Path field approximately six months after the first amendment application shortly after mowing. ChlM showed significant differences among treatments, with higher values in T3 and T4 than in T1 and T2. FlvM was significantly lower in the control (T1), while T2, T3, and T4 showed similarly higher values. AnthM was significantly higher in all amended treatments compared to the control. The NFI index was highest in T1 and T3, lowest in T2, and intermediate in T4.

NDVI values were significantly lower in T2, whereas T1, T3, and T4 showed similar and higher values. PRI differed significantly among treatments, with the lowest value observed in T4, while T1 and T2 showed the highest values and T3 intermediate values.

No significant differences were observed in canopy or soil temperature among treatments. TDR was significantly higher in T1 and T2 compared to T3 and T4.

Regarding agronomic parameters, FW increased progressively from T1 to T4, with the highest value recorded in T4 and the lowest in control. DW showed a similar trend, with the highest value in T4, intermediate values in T2 and T3, and the lowest in T1.

Table 22. *Physiological and agronomic surveys measured at T_3 (6 months) during Year 1 in the different treatments of the Path field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.43	b	0.48	b	**0.70**	**a**	**0.68**	**a**
FlvM	0.63	b	**1.22**	**a**	**1.16**	**a**	**1.31**	**a**
AnthM	0.14	b	**0.22**	**a**	**0.20**	**a**	**0.26**	**a**
NFI	**0.67**	**a**	0.41	c	**0.63**	**a**	0.52	b
NDVI	**0.78**	**a**	0.68	b	**0.71**	**a**	**0.71**	**a**
PRI	**0.18**	**a**	**0.16**	**a**	0.15	ab	0.08	b

Canopy Temperature, °C	16.00		15.00		14.20		16.10	
Soil Temperature, °C	13.40		13.43		12.55		13.00	
TDR, % soil water content	**44.30**	**a**	**45.20**	**a**	35.80	b	37.75	b
FW, g m^{-2}	237.50	c	321.88	b	368.75	ab	**421.88**	**a**
DW, g m^{-2}	115.63	b	150.00	ab	150.00	ab	**165.63**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 23 shows the physiological and agronomic surveys measured across the different treatments at the Path field approximately eight months after the first amendment application. ChlM showed significant differences among treatments, with the highest value recorded in T2, while T1 showed the lowest value; T3 and T4 reported intermediate values. FlvM was significantly higher in T2 compared to all other treatments, which did not differ among each other. AnthM was lowest in control (T1), intermediate in T3, and highest in T2 and T4. The NFI index was significantly higher in T4, while T2 showed the lowest value; T1 and T3 presented intermediate values.

NDVI did not show significant differences among treatments. PRI differed significantly, with the highest values in T1 and T3, intermediate values in T4, and the lowest in T2. Canopy temperature showed significant differences, being highest in T4 and lowest in T2, while T1 and T3 had intermediate values. Soil temperature did not differ among treatments.

TDR was significantly higher in control compared to the ones which showed similarly lower values. Regarding agronomic parameters, FW and dry weight DW differed significantly among treatments, with the highest values recorded in T3, intermediate values in T4, and the lowest in T1 and T2.

Table 23. *Physiological and agronomic surveys measured at T_4 (8 months) during Year 1 in the different treatments of the Path field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.43	b	**0.75**	**a**	0.54	ab	0.52	ab
FlvM	0.56	b	**1.45**	**a**	0.79	b	0.75	b
AnthM	0.04	c	**0.20**	**a**	0.11	b	0.18	a
NFI	0.51	b	0.31	c	0.53	b	**0.86**	**a**

NDVI	0.73		0.75		0.70		0.75	
PRI	**0.19**	**a**	0.08	c	**0.18**	**a**	0.10	b
Canopy Temperature, °C	27.37	b	22.45	c	27.25	b	**28.60**	**a**
Soil Temperature, °C	17.80		18.70		18.70		18.67	
TDR, % soil water content	**14.65**	**a**	7.30	b	5.40	b	6.45	b
FW, g m^{-2}	309.38	c	447.94	bc	**978.13**	**a**	615.63	b
DW, g m^{-2}	147.19	b	194.19	b	**394.38**	**a**	208.13	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 24 shows the physiological and agronomic surveys measured across the different treatments at the Path field approximately ten months after the first amendment application. ChlM was significantly lower in T3 compared to the other treatments, which showed similar higher values. FlvM was highest in control, while T4 showed the lowest values; T2 and T3 reported intermediate values. AnthM was highest in T4 and lowest in T2, with T1 and T3 showing intermediate values. NFI was significantly higher in T4, whereas T3 showed the lowest value; T1 and T2 had intermediate values.

NDVI differed significantly among treatments, with the highest value recorded in T4, the lowest in T3, and intermediate values in T1 and T2. PRI showed significant differences, with the highest value in T3, while T1 and T4 had lower and similar values; T2 reported intermediate values.

Canopy temperature showed significant differences among treatments, being higher in T2 and T3, intermediate in T4, and lower in T1. Soil temperature did not show differences. TDR was significantly higher in T1 and T4 compared to T2 and T3. FW and DW were highest in T4, lowest in T2, and intermediate in T1 and T3.

Table 24. *Physiological and agronomic surveys measured at T_5 (10 months) during Year 1 in the different treatments of the Path field.*

Treatments	T1		T2		T3		T4	
ChlM	**0.55**	**a**	**0.67**	**a**	0.35	b	**0.56**	**a**
FlvM	**1.74**	**a**	1.47	ab	1.23	bc	1.11	c
AnthM	-0.21	ab	-0.25	b	-0.18	ab	**-0.11**	**a**
NFI	0.34	ab	0.44	ab	0.29	b	**0.56**	**a**
NDVI	0.56	bc	0.74	ab	0.47	c	**0.81**	**a**
PRI	-0.09	b	-0.07	ab	**-0.01**	**a**	-0.09	ab
Canopy Temperature, °C	21.93	b	**25.55**	**a**	**25.00**	**a**	24.27	ab
Soil Temperature, °C	18.50		18.77		17.40		18.80	
TDR, % soil water content	**31.50**	**a**	14.85	b	13.30	b	**32.35**	**a**
FW, g m^{-2}	521.90	b	271.90	c	514.60	b	**800.00**	**a**
DW, g m^{-2}	196.90	ab	134.40	b	183.30	ab	**285.40**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 25 reports the physiological and agronomic surveys measured at two months during Year 2, corresponding to the early stage of the second year of amendment application, in the Path experimental field.

ChlM showed significant differences among treatments, with the highest value observed in T4, followed by T3 and T2, while the control showed the lowest value. FlvM was significantly higher in T2 and T3 compared to T1, with T4 showing intermediate values. AnthM was significantly higher in all amended treatments compared to the control. The NFI index was significantly higher in T2, T3, and T4 than in the control, with no differences among the amended treatments.

NDVI values were significantly lower in T2, while T1, T3, and T4 showed similarly higher values. PRI showed significant differences among treatments, with the highest value recorded in T3, followed by T4, while T1 and T2 showed lower values.

No significant differences were observed in canopy or soil temperature among treatments. TDR was significantly higher in T2 and T4 compared to T1 and T3.

Regarding agronomic parameters, FW and DW showed significant differences among treatments, with the highest values recorded in T4, intermediate values in T1, T2, and T3, and the lowest DW in T2.

Table 25. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 2 in the different treatments of the Path field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.03	c	0.41	bc	0.58	b	**1.59**	**a**
FlvM	0.88	b	**1.44**	**a**	**1.41**	**a**	1.31	ab
AnthM	-0.42	b	**0.32**	**a**	**0.20**	**a**	**0.25**	**a**
NFI	0.04	b	**0.38**	**a**	**0.32**	**a**	**0.26**	**a**
NDVI	**0.80**	**a**	0.64	b	**0.77**	**a**	**0.80**	**a**
PRI	0.06	c	0.04	d	**0.12**	**a**	0.10	b
Canopy Temperature, °C	25.23		25.70		25.35		25.57	
Soil Temperature, °C	28.33		28.43		28.37		28.33	
TDR, % soil water content	11.95	b	**16.30**	**a**	11.77	b	**17.20**	**a**
FW, g m^{-2}	570.80	ab	552.10	ab	510.40	ab	**620.80**	**a**
DW, g m^{-2}	172.90	ab	145.80	b	150.00	ab	**181.20**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 26 reports the physiological and agronomic surveys measured at four months during Year 2, representing the final survey conducted in the Path experimental field.

ChlM showed significant differences among treatments, with the lowest value observed in the control and the highest values in T3 and T4; T2 showed intermediate values. AnthM was significantly lower in T1, while all amended treatments showed similarly higher values. The NFI index increased progressively from the control to the amended treatments, reaching the highest value in T4. FlvM did not show significant differences among treatments.

NDVI did not show significant differences among treatments. PRI differed significantly, with the highest value recorded in T3, intermediate values in T4, and the lowest values in T1 and T2.
No significant differences were observed in canopy or soil temperature. TDR did not show significant differences among treatments.
Regarding agronomic parameters, FW was significantly lower in T3, while T1, T2, and T4 showed similarly higher values. No significant differences were detected in DW among treatments.

Table 26. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 2 in the different treatments of the Path field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.27	b	0.45	ab	**0.61**	**a**	**0.52**	**a**
FlvM	1.45		1.40		1.70		1.40	
AnthM	0.19	b	**0.26**	**a**	**0.27**	**a**	**0.25**	**a**
NFI	0.20	c	0.33	bc	0.36	b	**0.56**	**a**
NDVI	0.77		0.80		0.79		0.81	
PRI	0.06	bc	0.04	c	**0.09**	**a**	0.07	b
Canopy Temperature, °C	25.90		25.17		25.17		25.90	
Soil Temperature, °C	28.20		28.23		28.03		28.23	
TDR, % soil water content	17.35		11.40		14.85		14.90	
FW, g m^{-2}	**527.10**	**a**	**570.80**	**a**	466.70	b	**512.50**	**a**
DW, g m^{-2}	145.80		150.00		145.80		150.00	

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 27 and Figure 40, obtained from the Path Experimental Field, illustrate the temporal dynamics of chlorophyll under the different soil treatments applied. The T4 treatment exhibited the most pronounced response in terms of chlorophyll content, with a clear increase following the amendment date and a highly pronounced peak during the central phase of the monitoring period. The red curve (Figure 40) stands out distinctly from the others, reaching higher values and maintaining more sustained growth over time, indicating greater photosynthetic efficiency and a more favorable

nutritional status of the crop. The other treatments showed more moderate trends, T2 treatment displayed improvement relative to control, but with lower values and a less dynamic response; T3 treatment exhibited an intermediate increase, with more irregular fluctuations and without reaching the levels achieved by the combination of the two amendments. The control consistently remained the treatment with the lowest chlorophyll values, indicating reduced photosynthetic capacity and a less vigorous physiological status.

Table 27. *Temporal dynamics of chlorophyll under different soil treatments at Path Experimental Field.*

Date of Surveys	T1		T2		T3		T4	
30/09/2024	0.58	ab	**0.69**	**a**	0.35	b	**0.59**	**a**
06/11/2024	**0.72**	**a**	0.59	b	0.57	b	0.63	ab
17/01/2025	0.43	b	0.48	b	**0.70**	**a**	**0.68**	**a**
13/03/2025	0.43	b	**0.75**	**a**	0.54	ab	0.52	ab
14/05/2025	**0.55**	**a**	**0.67**	**a**	0.35	b	**0.56**	**a**
23/09/2025	0.03	c	0.41	bc	0.58	b	1.59	a
26/11/2025	0.27	b	0.45	ab	**0.61**	**a**	**0.52**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

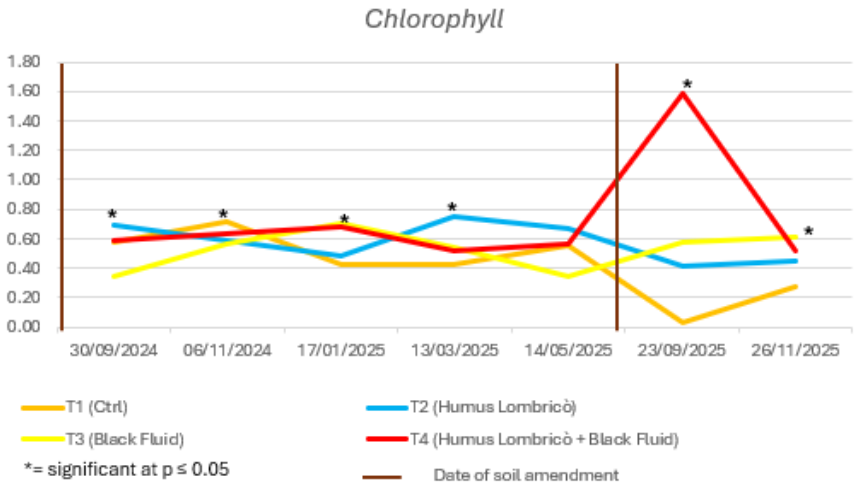


Figure 40. *Temporal dynamics of chlorophyll under different soil treatments at Path Experimental Field.*

Table 28 and Figure 41, obtained from the Path Experimental Field, illustrate the temporal dynamics of NDVI index under the different soil treatments applied. The T4 treatment exhibited the highest response in terms of NDVI, with a marked increase following the amendment date and consistently higher values compared to the other treatments, indicating more vigorous vegetation, greater photosynthetic efficiency, and an improved physiological status of the crop. The other treatments showed more moderate trends, T2 displayed improvement relative to the control but with more moderate values; T3 exhibited an intermediate increase, with more irregular fluctuations and without reaching the levels achieved by the combination; the control consistently remained the treatment with the lowest values, reflecting less developed and less photosynthetically active vegetation.

Table 28. *Temporal dynamics of NDVI index under different soil treatments at Path Experimental Field.*

Date of Surveys	T1		T2		T3		T4	
30/09/2024	0.71	ab	**0.80**	**a**	0.63	b	**0.83**	**a**
06/11/2024	**0.86**	**a**	0.79	b	0.77	b	0.77	b
17/01/2025	**0.78**	**a**	0.68	b	**0.71**	**a**	**0.71**	**a**
13/03/2025	0.73		0.75		0.70		0.75	
14/05/2025	0.56	bc	0.74	ab	0.47	c	**0.81**	**a**
23/09/2025	**0.80**	**a**	0.64	b	**0.77**	**a**	**0.80**	**a**
26/11/2025	0.77		0.80		0.79		0.81	

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

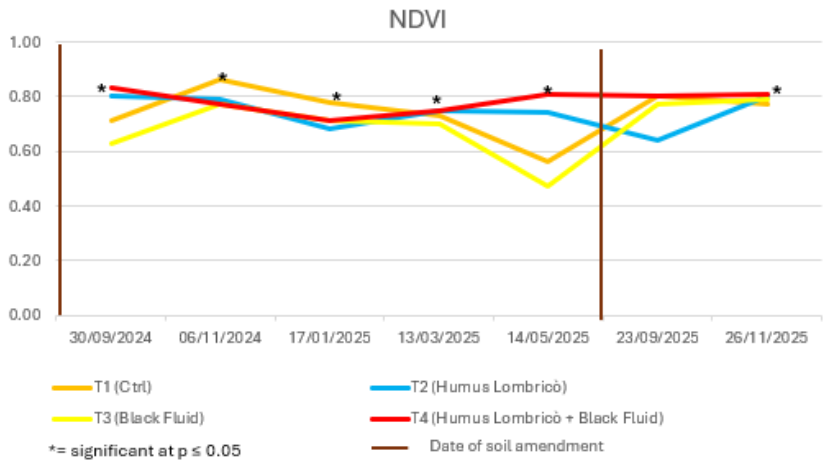


Figure 41. *Temporal dynamics of NDVI index under different soil treatments at Path Experimental Field.*

Table 29 and Figure 42, obtained from the Path Experimental Field, illustrates the temporal dynamics of aboveground fresh weight under the different soil treatments applied. The T4 treatment exhibited the highest and most stable aboveground fresh biomass values throughout the entire observation period, indicating a more vigorous and sustained vegetative response. The other treatments showed more moderate increases. T2 improved relative to the control but did not reach the levels of T4, while T3 displayed an intermediate and more irregular response. T1 consistently remained the least productive treatment.

Table 29. *Temporal dynamics of aboveground fresh weight under different soil treatments at Path Experimental Field.*

Date of Surveys	T1		T2		T3		T4	
30/09/2024	500.00	b	259.38	c	518.75	b	**887.50**	**a**
06/11/2024	856.25	ab	**971.88**	**a**	571.88	c	668.75	bc
17/01/2025	237.50	c	321.88	b	368.75	ab	**421.88**	**a**
13/03/2025	309.38	c	447.94	bc	**978.13**	**a**	615.63	b
14/05/2025	521.90	b	271.90	c	514.60	b	**800.00**	**a**
23/09/2025	570.80	ab	552.10	ab	510.40	ab	**620.80**	**a**
26/11/2025	**527.10**	**a**	**570.80**	**a**	466.70	b	**512.50**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

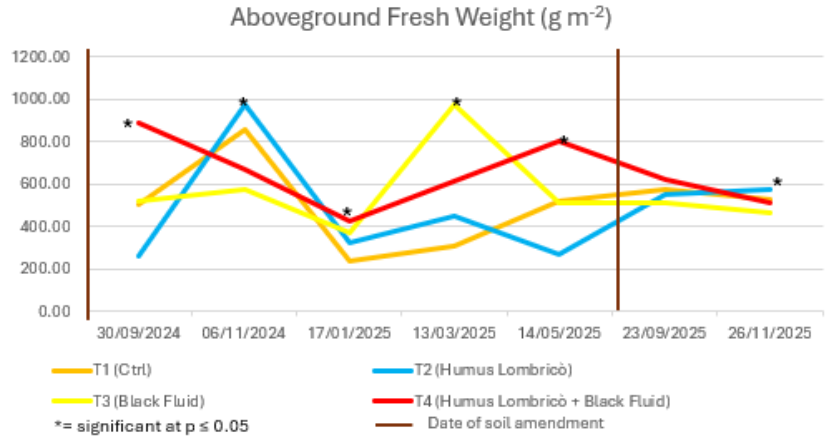


Figure 42. *Temporal dynamics of aboveground fresh weight under different soil treatments at Path Experimental Field.*

Table 30 and Figure 43, obtained from the Path Experimental Field, illustrate the temporal dynamics of aboveground dry weight under the different soil treatments applied. Regarding dry weight, the T4 treatment, compared to the other treatments, exhibited the most pronounced ability to increase aboveground dry biomass, with consistently higher values throughout the entire observation period. This indicates a more efficient vegetative response and an enhanced capacity of the crop to convert fresh biomass into stable structural tissues.

Table 30. *Temporal dynamics of aboveground dry weight under different soil treatments at Path Experimental Field.*

Date of Surveys	T1		T2		T3		T4	
30/09/2024	190.63	b	134.38	b	187.50	b	**312.50**	**a**
06/11/2024	**353.13**	**a**	278.13	ab	218.75	b	239.56	b
17/01/2025	115.63	b	150.00	ab	150.00	ab	**165.63**	**a**
13/03/2025	147.19	b	194.19	b	**394.38**	**a**	208.13	b
14/05/2025	196.90	ab	134.40	b	183.30	ab	**285.40**	**a**
23/09/2025	172.90	ab	145.80	b	150.00	ab	**181.20**	**a**
26/11/2025	145.80		150.00		145.80		150.00	

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

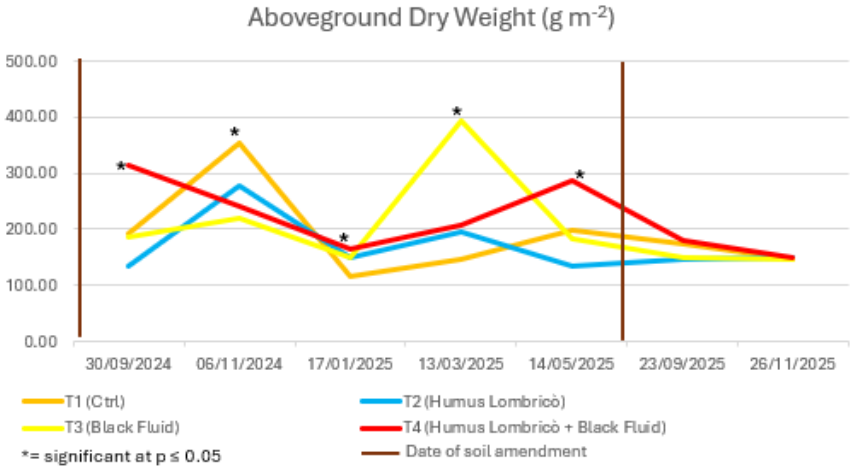


Figure 43. *Temporal dynamics of aboveground dry weight under different soil treatments at Path Experimental Field.*

Results of Chemical, Agronomic, and Physiological Assessments at the Urban Experimental Fields in Linden (Fisciano)

Soil Characterization and Post-Amendment Chemical and Physical Analyses in the Urban Experimental Fields of Linden (Fisciano)

As for the initial soil characterization, the Linden experimental field showed chemical and physical properties comparable to those described for the other experimental sites located in Fisciano, including a sandy texture, slightly alkaline pH, non-saline conditions, and moderate levels of organic matter and nutrients. This homogeneity in baseline soil conditions allowed for a consistent evaluation of the effects of amendment application across the Fisciano experimental fields.

In December 2024 (Table 31a), the application of amendments resulted in moderate variations in soil chemical properties. Cation exchange capacity (CEC) tended to be higher in amended soils compared to the control, with the highest value observed in the *Humus Lombricò* treatment (T2), although differences among treatments were not statistically significant. Total carbon (C_tot) and total phosphorus (P_tot) did not show marked differences among treatments. In contrast, total nitrogen (N_tot) was significantly higher in soils amended with *Humus Lombricò* (T2) and in the combined *Humus Lombricò + Black Fluid treatment* (T4) compared to the control. Soil respiration (SR) values were generally low and showed no significant differences among treatments at this sampling time.

By September 2025 (Table 31b), a clearer differentiation among treatments emerged, particularly for soil biological activity and phosphorus availability. While CEC values remained relatively stable and comparable across treatments, total phosphorus (P_tot) increased significantly in amended soils, with the highest value observed in the combined *Humus Lombricò + Black Fluid treatment* (T4). Soil respiration showed a marked increase in all amended soils compared to the control, with significantly higher SR values in treatments T2, T3, and T4. Total carbon exhibited some variability among treatments but did not differ significantly, suggesting stabilization of soil organic carbon content over time.

Table 31a. *Chemical and physical properties of soils at Linden experimental field measured in December 2024 after amendment application.*

Treatments	**T1**	**T2**	**T3**	**T4**
CEC, cmol+/kg	27.15	32.24	30.17	30.09
C tot. g/kg	24.67	25.87	23.30	24.67

N tot. g/kg	2.33	b	**2.78**	**a**	2.61	ab	**2.68**	**a**
P tot. mg P/kg	1.14		1.22		1.16		1.16	
S.R. g CO_2 m^{-2} h^{-1}	0.40		0.39		0.43		0.39	

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; N tot.: Total nitrogen; P tot.: Total phosphorus; S.R: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 31b. *Chemical and physical properties of soils at Linden experimental field measured in September 2025 after amendment application.*

Treatments	**T1**		**T2**		**T3**		**T4**	
CEC, cmol+/kg	28.81		30.11		29.48		30.10	
C tot. g/kg	21.16		23.50		22.82		21.45	
P tot. mg P/kg	1.16	c	1.22	bc	1.27	b	**1.37**	**a**
S.R. g CO_2 m^{-2} h^{-1}	0.51	b	**0.83**	**a**	**0.82**	**a**	**0.94**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; P tot.: Total phosphorus; S.R: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Monitoring Vegetation Responses: Physiological and Agronomic Assessments at the Linden (Fisciano) Field

In the Linden field, physiological and agronomic parameters were systematically recorded at bimonthly intervals starting from the first year of amendment application, conducted in 2024 and repeated in 2025. As in the Path field, treatment T2 (mineral fertilizer) was omitted to allow a focused assessment of the effects of the increased doses of organic amendments. For each year, survey times are labeled as T_n (T_1–T_5), corresponding to 2, 4, 6, 8, and 10 months following amendment application. The results obtained, reflecting vegetation dynamics and treatment effects, are reported in the tables below.

Table 32 reports the physiological and agronomic surveys measured two months after the first amendment application, in the Linden experimental field. Leaf chlorophyll content (ChlM) shows differences among treatments, although the highest values were observed in the control (T1) and T2 (*Humus Lombricò*), while T3 (*Black Fluid*) and T4 (*Humus Lombricò + Black Fluid*) showed slightly lower values. Leaf flavonol content (FlvM) was significantly lower in T2 compared to the other

treatments, which did not differ among each other. Leaf anthocyanin content (AnthM) was significantly lower in control, whereas all amended treatments showed similarly higher values. The nitrogen-flavonol index (NFI) was highest in T2, lowest in T3, and intermediate in T1 and T4.

No significant differences were observed in NDVI or PRI among treatments. Canopy temperature differed significantly, with the highest value recorded in T4 and the lowest in T3; T1 and T2 showed intermediate values. Soil temperature did not differ significantly among treatments.

Soil water content (TDR) showed significant differences, with the highest values in T2 and T3, intermediate values in T4, and the lowest value in the control.

Regarding agronomic parameters, fresh weight (FW) and dry weight (DW) were significantly higher in T1 and T2 compared to T3 and T4.

Table 32. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 1 in the different treatments of the Linden field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	**1.09**	**a**	**0.94**	**a**	0.86	ab	0.82	ab
FlvM	**0.74**	**a**	0.27	b	**0.94**	**a**	**0.71**	**a**
AnthM	-0.11	b	**-0.02**	**a**	**-0.05**	**a**	**-0.05**	**a**
NFI	1.36	ab	**1.59**	**a**	0.94	c	1.16	bc
NDVI	0.85		0.90		0.86		0.83	
PRI	-0.04		-0.07		-0.06		-0.06	
Canopy Temperature, °C	21.47	ab	20.20	ab	19.77	b	**22.35**	**a**
Soil Temperature, °C	17.20		17.50		16.13		16.10	
TDR, % soil water content	18.00	c	**29.15**	**a**	28.30	ab	20.00	bc
FW, g m^{-2}	**768.75**	**a**	**737.50**	**a**	543.75	b	490.63	b
DW, g m^{-2}	**228.13**	**a**	**196.88**	**a**	171.88	b	162.50	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 33 shows the physiological and agronomic surveys measured at four months during Year 1 in the Linden experimental field.

ChlM showed significant differences among treatments, with the highest value observed in T2, followed by T4, while T1 showed the lowest value; T3 displayed intermediate values. FlvM was significantly higher in T2 compared to all other treatments, with T4 showing intermediate values and T1 the lowest. AnthM was significantly higher in T2, whereas no differences were observed among the remaining treatments. The NFI index showed the highest value in T4, while T2 had the lowest; T1 and T3 presented intermediate values.

NDVI did not show significant differences among treatments. PRI differed significantly, with the highest value recorded in T4, while T1, T2, and T3 showed similar lower values.

Canopy temperature showed significant differences among treatments, being higher in T2 and T3 and lower in T4, with T1 showing intermediate values. Soil temperature increased significantly from T1 to T4.

TDR was significantly higher in T3, while T1 showed the lowest value; T2 and T4 reported intermediate values.

Regarding agronomic parameters, no significant differences were observed in FW among treatments. DW differed significantly, with the highest value recorded in T1 and the lowest in T4; T2 and T3 showed intermediate values.

Table 33. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 1 in the different treatments of the Linden field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.50	c	**0.88**	**a**	0.59	bc	0.67	b
FlvM	0.69	d	**1.47**	**a**	0.81	c	0.95	b
AnthM	0.05	b	**0.30**	**a**	0.07	b	0.08	b
NFI	0.73	ab	0.62	b	0.74	ab	**0.83**	**a**
NDVI	0.87		0.89		0.89		0.90	
PRI	0.09	b	0.10	b	0.10	b	**0.13**	**a**
Canopy Temperature, °C	13.30	ab	**14.40**	**a**	**14.15**	**a**	13.00	b
Soil Temperature, °C	14.90	b	15.50	ab	15.70	ab	**16.20**	**a**
TDR, % soil water content	34.05	b	39.50	ab	**45.45**	**a**	39.75	ab
FW, g m^{-2}	921.88		876.88		898.13		953.13	
DW, g m^{-2}	412.50	**a**	337.50	ab	329.19	ab	293.75	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI:

nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 34 reports the physiological and agronomic surveys measured six months after the first amendment application and following mowing, in the Linden experimental field.

ChlM did not show significant differences among treatments. FlvM was significantly higher in the T1, followed by T3, while T2 and T4 showed lower values. AnthM was highest in T1 and lowest in T2 and T3, with intermediate values in T4. The NFI index was highest in T2, lowest in T4, and intermediate in T1 and T3.

NDVI did not show significant differences among treatments. PRI showed significant differences, with the highest value observed in T3, followed by T4, while T1 and T2 showed lower values.

Canopy temperature showed significant differences among treatments, being highest in T2 and lowest in T4, with intermediate values in T1 and T3. Soil temperature did not show marked differences among treatments.

TDR was significantly higher in T4 compared to all other treatments, which showed similar and lower values.

Regarding agronomic parameters, FW and DW were highest in T2, intermediate in T1 and T3, and lowest in T4.

Table 34. *Physiological and agronomic surveys measured at T_3 (6 months) during Year 1 in the different treatments of the Linden field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.39		0.40		0.33		0.43	
FlvM	**1.24**	**a**	0.56	c	0.85	b	0.63	c
AnthM	**0.54**	**a**	0.08	c	0.10	c	0.25	b
NFI	0.59	ab	**0.82**	**a**	0.64	ab	0.37	b
NDVI	0.80		0.74		0.74		0.79	
PRI	0.06	c	0.04	d	**0.12**	**a**	0.10	b
Canopy Temperature, °C	13.77	ab	**15.95**	**a**	15.10	ab	12.97	b
Soil Temperature, °C	11.93		13.10		12.83		11.97	
TDR, % soil water content	25.00	b	28.05	ab	24.90	b	**37.75**	**a**
FW, g m^{-2}	309.38	ab	**390.63**	**a**	284.38	b	162.50	c
DW, g m^{-2}	106.25	b	**168.75**	**a**	118.75	b	87.50	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 35 reports the physiological and agronomic surveys measured eight months during Year 1 in the Linden experimental field.

ChlM showed significant differences among treatments, with the highest value observed in T3, followed by T4, while T1 showed the lowest value. FlvM was significantly higher in T3 compared to T4, with T1 and T2 showing intermediate values. AnthM was highest in T3, lowest in T4, and intermediate in T1 and T2. The NFI index was significantly higher in T2, while the lowest value was observed in T1; T3 and T4 showed intermediate values.

NDVI did not show significant differences among treatments. PRI differed significantly, with lower values in T2 compared to the other treatments, which showed similar and higher values.

Canopy temperature showed significant differences among treatments, with the highest value recorded in T4, while T1, T2, and T3 showed similar lower values. Soil temperature did not differ among treatments.

TDR was significantly higher in T1, while T4 showed the lowest value; T2 and T3 reported intermediate values.

FW and DW were highest in T2 and lowest in T4, with T1 and T3 showing intermediate values.

Table 35. *Physiological and agronomic surveys measured at T_4 (8 months) during Year 1 in the different treatments of the Linden field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.57	c	0.62	bc	**0.84**	**a**	0.78	ab
FlvM	0.82	ab	0.85	ab	**1.10**	**a**	0.71	b
AnthM	0.09	ab	0.15	ab	**0.18**	**a**	0.05	b
NFI	0.53	c	**0.91**	**a**	0.75	bc	0.78	bc
NDVI	0.74		0.72		0.70		0.72	
PRI	**0.08**	**a**	0.04	b	**0.06**	**a**	**0.07**	**a**
Canopy Temperature, °C	21.15	b	18.90	b	19.90	b	**24.00**	**a**
Soil Temperature, °C	19.63		20.25		20.00		19.35	
TDR, % soil water content	**11.13**	**a**	8.00	abc	9.30	ab	7.75	bc

FW, g m^{-2}	781.25	ab	**868.75**	**a**	750.00	ab	591.88	b
DW, g m^{-2}	253.75	ab	**286.56**	**a**	233.13	ab	201.88	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 36 presents the physiological and agronomic surveys measured at ten months during Year 1 in the Linden experimental field.

ChlM was significantly lower in T2 compared to the other treatments, which showed similarly higher values. FlvM was significantly lower in T3, while T1, T2, and T4 showed no significant differences. AnthM did not show significant differences among treatments. The NFI index was highest in T1, lowest in T3, and intermediate in T2 and T4.

NDVI did not show significant differences among treatments. PRI differed significantly, with the highest value in T1 and progressively lower values in T2, T3, and T4.

Canopy temperature differed significantly among treatments, being lower in T3 compared to the other treatments. Soil temperature was highest in T4 and lowest in T2 and T3.

TDR was significantly higher in all amended treatments compared to the control.

Regarding agronomic parameters, FW and DW were significantly higher in T1 and T2, lower in T3, and intermediate in T4.

Table 36. *Physiological and agronomic surveys measured at T_5 (10 months) during Year 1 in the different treatments of the Linden field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	**0.95**	**a**	0.40	b	**0.83**	**a**	**0.79**	**a**
FlvM	**0.27**	**a**	**0.29**	**a**	0.18	b	**0.26**	**a**
AnthM	-0.07		-0.06		-0.07		-0.06	
NFI	**3.77**	**a**	1.35	bc	1.05	c	1.88	b
NDVI	0.81		0.86		0.87		0.87	
PRI	**-0.04**	**a**	-0.06	b	-0.06	b	-0.08	c
Canopy Temperature, °C	**22.80**	**a**	**22.30**	**a**	19.17	b	**21.30**	**a**
Soil Temperature, °C	17.85	ab	16.20	b	15.97	b	**18.75**	**a**

TDR, % soil water content	18.40	b	**28.25**	**a**	**28.05**	**a**	**26.70**	**a**
FW, g m^{-2}	**768.60**	**a**	**678.10**	**a**	525.00	b	556.20	b
DW, g m^{-2}	**303.10**	**a**	**321.90**	**a**	187.50	b	250.00	ab

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 37 reports the physiological and agronomic surveys measured at to two months after the second amendment application, in the Linden experimental field.

ChlM differed significantly among treatments, with the highest value observed in T3, while T1, T2, and T4 showed similarly lower values. FlvM was highest in T1 and lowest in T2, with T3 and T4 showing intermediate values. AnthM was significantly higher in T3 and T4 compared to T1 and T2. The NFI index was markedly higher in T2, while no significant differences were observed among the remaining treatments.

NDVI differed significantly, with the highest value recorded in the control, while the amended treatments showed slightly lower and similar values. PRI did not show significant differences among treatments.

No significant differences were observed in canopy or soil temperature among treatments. TDR was significantly higher in T3 compared to all other treatments.

Regarding agronomic parameters, no significant differences were observed in FW among treatments. DW showed slightly higher values in T4, T1, and T2, while T3 displayed intermediate values.

Table 37. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 2 in the different treatments of the Linden field.*

Treatments	**T1**		**T2**		**T3**		**T4**	
ChlM	0.47	b	0.37	b	**0.78**	**a**	0.46	b
FlvM	**0.33**	**a**	0.09	b	0.14	ab	0.27	ab
AnthM	0.02	b	0.03	b	**0.07**	**a**	**0.08**	**a**
NFI	1.73	b	**5.82**	**a**	0.91	b	1.60	b
NDVI	**0.86**	**a**	0.74	ab	0.77	ab	0.77	ab
PRI	**0.24**	**a**	**0.20**	**a**	**0.18**	**a**	0.15	ab

Canopy Temperature, °C	24.93		25.50		25.47		24.90	
Soil Temperature, °C	24.57		24.60		24.40		24.20	
TDR, % soil water content	19.75	b	18.75	b	**28.30**	**a**	21.61	b
FW, g m^{-2}	541.70		500.00		552.10		491.70	
DW, g m^{-2}	**133.30**	**a**	**133.30**	**a**	118.80	ab	**137.50**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 38 shows the physiological and agronomic surveys corresponding to four months after the second amendment application and representing the final survey conducted in this field.

ChlM showed significant differences among treatments, with the highest value recorded in T3, while T2 and T4 reported lower values; the control showed intermediate values. FlvM was significantly higher in T4 compared to T1 and T2, while T3 showed intermediate values. AnthM was highest in T4, whereas the control showed the lowest value. The NFI index was significantly higher in all amended treatments (T2, T3, and T4) compared to the control.

NDVI values were significantly higher in the amended treatments compared to the control, indicating improved canopy vigor. PRI differed significantly among treatments, with the highest value observed in the control and progressively lower values in T4, T2, and T3.

Canopy temperature was significantly higher in the control, while all amended treatments showed lower and similar values. Soil temperature did not show significant differences among treatments. TDR did not differ significantly among treatments, although slightly higher values were observed in T2.

Regarding agronomic traits, FW was significantly higher in T1, while T2 and T4 showed lower values and T3 exhibited intermediate values. A similar trend was observed for dry weight DW, with the control showing the highest value and T2 the lowest.

Table 38. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 2 in the different treatments of the Linden field.*

Treatments	T1		T2		T3		T4	
ChlM	0.58	ab	0.55	b	**0.62**	**a**	0.52	b
FlvM	0.31	b	0.32	b	0.39	ab	**0.48**	**a**
AnthM	-0.15	b	-0.11	ab	-0.12	ab	**-0.08**	**a**
NFI	0.78	b	**1.76**	**a**	**1.29**	**a**	**1.29**	**a**
NDVI	0.77	ab	**0.82**	**a**	**0.84**	**a**	**0.80**	**a**
PRI	**-0.01**	**a**	-0.09	c	-0.09	c	-0.06	b
Canopy Temperature, °C	**22.37**	**a**	18.25	b	18.27	b	17.90	b
Soil Temperature, °C	17.30		15.85		16.27		17.00	
TDR, % soil water content	24.15		29.35		24.45		24.60	
FW, g m^{-2}	**487.50**	**a**	237.50	b	331.20	ab	290.60	b
DW, g m^{-2}	**200.00**	**a**	84.40	b	140.60	ab	115.60	ab

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 39 and Figure 44, obtained from the Linden Experimental Field, illustrate the temporal dynamics of chlorophyll under the different soil treatments applied. The T4 exhibited the highest and most stable response in terms of chlorophyll content, with a pronounced peak immediately after the amendment and consistently higher values compared to the other treatments. T2 improved relative to the control but did not reach the levels of T4, while T3 showed an intermediate and less stable response. The control consistently remained the treatment with the lowest values, indicating lower photosynthetic efficiency and a weaker vegetative status.

Table 39. *Temporal dynamics of chlorophyll under different soil treatments at Linden Experimental Field.*

Date of Surveys	T1		T2		T3		T4	
30/09/2024	1.09	a	**0.94**	**a**	0.86	ab	0.82	ab
06/11/2024	0.50	c	**0.88**	**a**	0.59	bc	0.67	b

17/01/2025	0.39		0.40		0.33		0.43	
13/03/2025	0.57	c	0.62	bc	**0.84**	**a**	0.78	ab
14/05/2025	**0.95**	**a**	0.40	b	**0.83**	**a**	**0.79**	**a**
23/09/2025	0.47	b	0.37	b	**0.78**	**a**	0.46	b
26/11/2025	0.58	ab	0.55	b	**0.62**	**a**	0.52	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

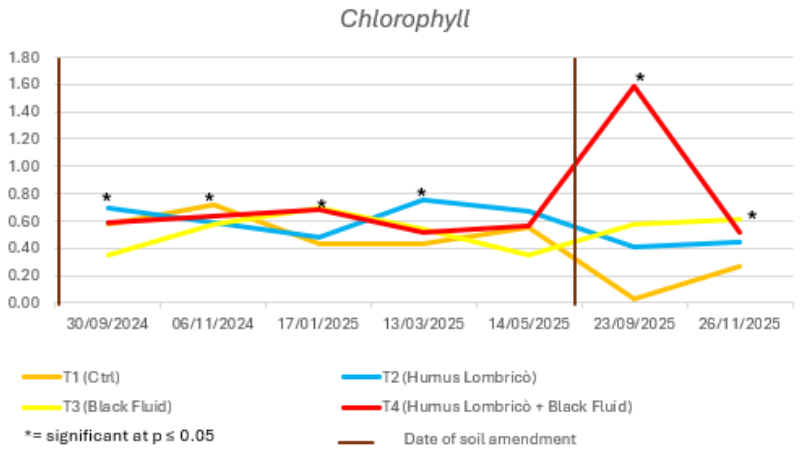


Figure 44. *Temporal dynamics of chlorophyll under different soil treatments at Linden Experimental Field.*

Table 40 and Figure 45, obtained from the Linden Experimental Field, illustrate the temporal dynamics of NDVI index under the different soil treatments applied. The T4 treatment exhibited the clearest ability to enhance NDVI, with consistently higher values compared to the other treatments and a marked increase following the amendment date. T2 improved relative to the control but did not reach the levels of T4; T3 showed an intermediate and less consistent response, whereas the control consistently remained the treatment with the lowest values, indicating weaker vegetative growth.

Table 40. *Temporal dynamics of NDVI index under different soil treatments at Linden Experimental Field.*

Date of Surveys	T1	T2	T3	T4
30/09/2024	0.85	0.90	0.86	0.83
06/11/2024	0.87	0.89	0.89	0.90
17/01/2025	0.80	0.74	0.74	0.79
13/03/2025	0.74	0.72	0.70	0.72

14/05/2025	0.81		0.86		0.87		0.87	
23/09/2025	**0.86**	**a**	0.74	ab	0.77	ab	0.77	ab
26/11/2025	0.77	ab	**0.82**	**a**	**0.84**	**a**	**0.80**	**a**

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

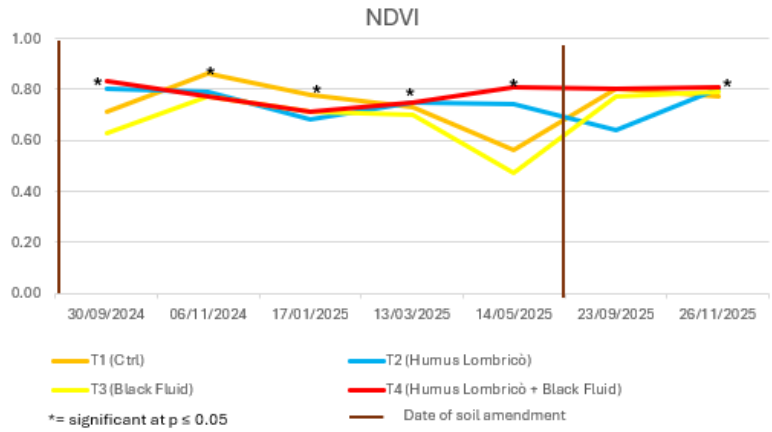


Figure 45. *Temporal dynamics of NDVI index under different soil treatments at Linden Experimental Field.*

Table 41 and Figure 46, obtained from the Linden Experimental Field, illustrate the temporal dynamics of aboveground fresh weight under the different soil treatments applied. The T4 treatment exhibited the highest and most stable aboveground fresh biomass values throughout the entire observation period compared to the other treatment. Following the amendment, it maintained superior levels until the end of the monitoring period, indicating a more vigorous and sustained vegetative response.

Table 41. *Temporal dynamics of aboveground fresh weight under different soil treatments at Linden Experimental Field.*

Date of Surveys	T1		T2		T3		T4	
30/09/2024	**768.75**	**a**	**737.50**	**a**	543.75	b	490.63	b
06/11/2024	921.88		876.88		898.13		953.13	
17/01/2025	309.38	ab	**390.63**	**a**	284.38	b	162.50	c
13/03/2025	781.25	ab	**868.75**	**a**	750.00	ab	591.88	b
14/05/2025	**768.60**	**a**	**678.10**	**a**	525.00	b	556.20	b

23/09/2025	541.70		500.00		552.10		491.70	
26/11/2025	**487.50**	**a**	237.50	b	331.20	ab	290.60	b

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

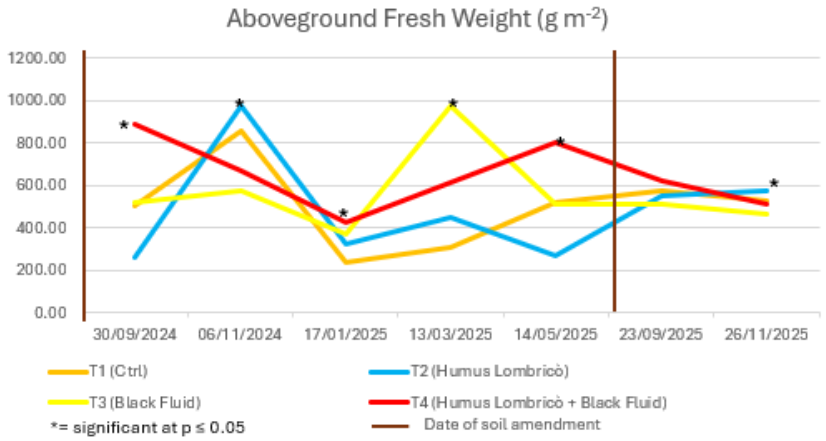


Figure 46. *Temporal dynamics of aboveground fresh weight under different soil treatments at Linden Experimental Field.*

Dry biomass followed a trend like that observed for fresh biomass (Table 42 and Figure 47). The T4 treatment consistently maintained higher dry weight values throughout the monitoring period, reflecting not only the accumulation of aboveground tissues but also the crop's ability to efficiently convert fresh biomass into stable structural components. This correspondence between fresh and dry biomass indicates that the vegetative growth promoted by the amendment was both substantial and persistent, resulting in a more robust and physiologically active crop.

Table 42. *Temporal dynamics of aboveground dry weight under different soil treatments at Linden Experimental Field.*

Date of Surveys	T1		T2		T3		T4	
30/09/2024	**228.13**	**a**	**196.88**	**a**	171.88	b	162.50	b
06/11/2024	**412.50**	**a**	337.50	ab	329.19	ab	293.75	b
17/01/2025	106.25	b	**168.75**	**a**	118.75	b	87.50	b
13/03/2025	253.75	ab	**286.56**	**a**	233.13	ab	201.88	b
14/05/2025	**303.10**	**a**	**321.90**	**a**	187.50	b	250.00	ab

23/09/2025	**133.30**	**a**	**133.30**	**a**	118.80	ab	**137.50**	**a**
26/11/2025	**200.00**	**a**	84.40	b	140.60	ab	115.60	ab

T1: Control; T2: Humus Lombricò; T3: Black Fluid; T4: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

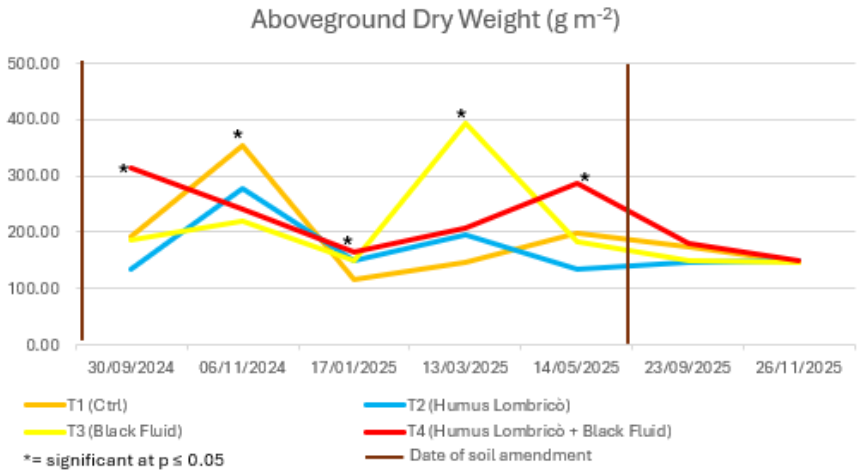


Figure 47. *Temporal dynamics of aboveground dry weight under different soil treatments at Linden Experimental Field.*

Results of Chemical, Agronomic, and Physiological Assessments at the Urban Experimental Fields in Avellino

Floristic Composition and Functional Trait Analysis at the Urban Experimental Fields of Avellino

In the urban experimental fields of Avellino, characterized by limited management and the absence of irrigation and fertilization, a total of 47 spontaneous herbaceous plant species were identified (Table 43). The species belong to a broad taxonomic and functional spectrum, reflecting a heterogeneous plant community subject to marked seasonal fluctuations.

From a taxonomic perspective, the most represented families were Fabaceae, Plantaginaceae, and Poaceae, which together constitute the dominant portion of the flora recorded at the site. Other families present included Asteraceae, Brassicaceae, Caryophyllaceae, and Rubiaceae, often represented by a smaller number of species.

Analysis of seasonal species distribution revealed considerable variability throughout the year. The average number of species per season was highest in spring, whereas a marked decline was observed

during summer and autumn. The flora at the site included both annual taxa (therophytes), such as *Capsella bursa-pastoris* (L.) Medik., *Arabidopsis thaliana* (L.) Heynh., and *Papaver rhoeas* L., as well as perennial species, including *Cynodon dactylon* L., *Plantago lanceolata* L., and *Trifolium repens* L., which persisted across multiple seasons.

From a chorological perspective, the Avellino site was predominantly characterized by palaeotemperate and eurymediterranean species, with a smaller proportion of cosmopolitan and alien species. This composition reflects a flora typical of semi-natural Mediterranean habitats or areas with low-intensity disturbance, exhibiting a strong seasonal imprint.

The dominant biological forms were primarily scapose therophytes, accompanied by hemicryptophytes and geophytes, contributing to the structural variability of the community throughout the year. The presence of species with diverse ecological strategies indicates a dynamic plant community sensitive to seasonal environmental factors.

Table 43. *List of spontaneous herbaceous species identified in the urban experimental fields of Avellino, with corresponding floristic and functional characterization based on Baldi et al. (2025).*

Species	Family	Chorotype	Season
Anchusella cretica (MilL.) Bigazzi, E. Nardi & Selvi	Boraginaceae	Stenomediterranean	Spr
Arabidopsis thaliana (L.) Heynh.	Brassicaceae	Paleotemperate	Spr, Win
Artemisia vulgaris L.	Asteraceae	Boreal	Spr
Avena barbata Pott ex Link	Poaceae	Eurymediterranean	Spr, Sum, Win
Briza media L.	Poaceae	Euro-Asiatic	Sum
Calepina irregularis (Asso) ThelL.	Brassicaceae	Eurymediterranean	Spr
Capsella bursa-pastoris (L.) Medik.	Brassicaceae	Cosmopolitan	Spr, Win
Cardamine hirsuta L.	Brassicaceae	Cosmopolitan	Win
Carex distachya Desf.	Cyperaceae	Stenomediterranean	Win
Cerastium glomeratum ThuilL.	Caryophyllaceae	Eurymediterranean	Spr, Win
Cota tinctoria (L.) J. Gay	Asteraceae	European	Aut, Win
Crepis neglecta L.	Asteraceae	Euro-Montane	Sum
Crepis sancta L.	Asteraceae	Eurymediterranean	Aut, Spr, Win
Cynodon dactylon L.	Poaceae	Cosmopolitan	Aut, Spr, Sum, Win
Daucus carota L. subsp. *carota*	Apiaceae	Paleotemperate	Aut, Spr, Sum, Win
Digitaria sanguinalis (L.) Scop.	Poaceae	Cosmopolitan	Aut
Equisetum telmateja Ehrh.	Equisetaceae	Boreal	Sum
Erigeron sumatrensis Retz.	Asteraceae	Alien	Spr, Sum

Erodium cicutarium (L.) L'Hér	Geraniaceae	Cosmopolitan	Spr
Hypericum perforatum L.	Hypericaceae	Paleotemperate	Aut, Spr, Sum, Win
Hypochaeris radicata L.	Asteraceae	European	Spr
Lamium purpureum L.	Lamiaceae	Euro-Asiatic	Spr, Win
Lolium perenne L.	Poaceae	Boreal	Sum
Medicago arabica (L.) Huds.	Fabaceae	Eurymediterranean	Aut, Spr, Sum, Win
Medicago lupulina L.	Fabaceae	Paleotemperate	Spr, Sum
Minuartia hybrida (VilL.) Schischk	Caryophyllaceae	Paleotemperate	Spr
Myosotis ramosissima Rochel subsp. *ramosissima*	Boraginaceae	European	Spr
Ornithogalum umbellatum L.	Asparagaceae	Eurymediterranean	Spr, Win
Ornithopus compressus L.	Fabaceae	Eurymediterranean	Aut, Spr, Sum, Win
Papaver rhoeas L.	Papaveraceae	Euro-Montane	Spr
Petrorhagia prolifera (L.) P.W. Ball & Heywood	Caryophyllaceae	Eurymediterranean	Sum
Picris hieraciodes L.	Asteraceae	Euro-Asiatic	Sum
Plantago lanceolata L.	Plantaginaceae	Euro-Asiatic	Aut, Spr, Sum, Win
Poa annua L.	Poaceae	Cosmopolitan	Spr, Win
Raphanus raphanistrum L.	Brassicaceae	Eurymediterranean	Aut, Sum
Senecio vulgaris L.	Asteraceae	Eurymediterranean	Spr
Setaria pumila (Poir.) Roem & Schult.	Poaceae	Cosmopolitan	Aut, Sum
Sherardia arvensis L.	Rubiaceae	Eurymediterranean	Aut, Spr, Sum, Win
Silene gallica L.	Caryophyllaceae	Eurymediterranean	Spr
Sorghum halepense (L.) Pers.	Poaceae	Cosmopolitan	Aut, Sum
Trifolium arvense L.	Fabaceae	Paleotemperate	Spr
Trifolium campestre Schreb.	Fabaceae	Paleotemperate	Spr, Sum
Trifolium pratense L.	Fabaceae	Euro-Asiatic	Aut, Spr, Sum, Win
Trifolium repens L.	Fabaceae	Paleotemperate	Aut, Spr, Sum, Win
Valerianella carinata Loisel.	Valerianaceae	Eurymediterranean	Spr, Win
Veronica arvensis L.	Plantaginaceae	Paleotemperate	Aut, Spr, Win
Vicia sativa L.	Fabaceae	Eurymediterranean	Aut, Spr, Sum, Win

Soil Characterization and Post-Amendment Chemical and Physical Analyses in the Urban Experimental Fields of Avellino

The soils of the Avellino experimental field were characterized prior to the application of amendments to establish baseline conditions.

The soils exhibited a sandy texture, a neutral to slightly acidic pH, and were slightly calcareous. Electrical conductivity (EC) measured 309.05 µS cm^{-1}, indicating non-saline conditions. Total nitrogen (N_tot) was 1.60 g kg^{-1} and soil organic matter (SOM) 25.30 g kg^{-1}, while superficial porosity reached 77%, describing a moderately fertile and well-structured soil suitable for amendment application.

In March 2025 (Table 44a), following the application of micronized amendments, several chemical and biological parameters showed treatment-specific responses. Cation exchange capacity (CEC) was generally higher in amended soils compared to the control, with the highest values observed in soils treated with Mineral Fertilizer (T2) and the combined *Humus Lombricò + Black Fluid treatment* (T5). Total carbon (C_tot) and total nitrogen (N_tot) increased in soils receiving organic amendments, particularly in T2, T4, and T5, although some treatments showed limited effects. Total phosphorus (P_tot) exhibited modest increases across treatments, with no statistically significant differences. Soil respiration (SR) was enhanced in amended soils compared to the control, reflecting stimulation of microbial activity, particularly in T2.

By September 2025 (Table 44b), the dynamics of soil properties became more pronounced. CEC reached the highest value in control (T1), while amended soils maintained slightly lower but relatively stable values. Total carbon was significantly enhanced in soils treated with Mineral Fertilizer (T2), *Humus Lombricò* (T3), and *Black Fluid* (T4), compared to the control, indicating persistent accumulation of organic carbon in response to amendments. Total phosphorus continued to show moderate increases, with the highest values in T4 and T5, although differences were not statistically significant. Soil respiration exhibited a marked increase in amended soils, with the combined *Humus Lombricò + Black Fluid treatment* (T5) showing the highest SR values.

Table 44a. *Chemical and physical properties of soils at Avellino experimental field measured in March 2025 after amendment application.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
CEC, cmol+/kg	23.72		25.79		24.98		24.32		25.76	
C tot. g/kg	18.56	bc	22.52	ab	16.18	c	22.43	ab	**23.02**	**a**
N tot. g/kg	1.45	bc	**1.93**	**a**	1.45	bc	1.74	ab	1.36	c
P tot. Mg P/kg	0.66		0.74		0.70		0.71		0.75	
S.R. g CO_2 m^{-2} h^{-1}	0.44		0.63		0.50		0.56		0.53	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; N tot.: Total nitrogen; P tot.: Total

phosphorus; S.R: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 44b. *Chemical and physical properties of soils at Avellino experimental field measured in September 2025 after amendment application.*

Treatments	T1		T2		T3		T4		T5	
CEC, cmol+/kg	**29.52**	**a**	25.94	ab	23.14	b	25.19	b	25.60	ab
C tot. g/kg	14.48	b	**19.36**	**a**	**18.40**	**a**	**19.99**	**a**	**17.80**	**a**
P tot. Mg P/kg	0.79		0.92		0.92		0.95		0.94	
S.R. g CO_2 m^{-2} h^{-1}	0.48	c	0.68	b	0.73	ab	0.69	b	**0.82**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; CEC: Cation exchange capacity; C. tot.: Total organic carbon; P tot.: Total phosphorus; S.R: Soil respiration. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Monitoring Vegetation Responses: Physiological and Agronomic Assessments at the Avellino Experimental Field

Table 45 shows the physiological and agronomic surveys corresponding to two months after the first amendment application.

Analysis of the main leaf pigments showed that leaf chlorophyll content (ChlM) did not differ significantly among treatments. A similar pattern was observed for the flavonol index (FlvM), which also exhibited no statistically significant differences.

In contrast, the anthocyanin index (AnthM) showed significant differences among treatments, with a positive and significantly higher value in T4 (*Black Fluid)* compared to the ones which showed negative and statistically similar values. The nitrogen flavonol index (NFI) did not differ significantly among treatments, remaining high and comparable under all experimental conditions.

Regarding vegetation indices, neither NDVI nor PRI showed significant differences among treatments, with similar values recorded across all plots.

Canopy and soil temperatures did not differ significantly among treatments, and soil water content measured by time domain reflectometry (TDR) was uniformly low and showed no significant variation among treatments.

With respect to agronomic parameters, fresh biomass (FW) showed significant differences among treatments, with the highest values observed in the control (T1) and in T5 (*Humus Lombricò + Black*

Fluid), both significantly higher than in T2 (Mineral Fertilizer*)* and T4, while T3 (*Humus Lombricò)* exhibited intermediate values. Dry biomass (DW) did not differ significantly among treatments and remained comparable across all experimental conditions.

Table 45. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 1 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	2.06		2.23		2.69		2.69		2.80	
FlvM	0.63		0.63		0.77		0.80		0.75	
AnthM	-0.14	b	-0.16	b	-0.09	b	**0.17**	**a**	-0.08	b
NFI	4.85		3.71		4.42		4.82		4.72	
NDVI	0.61		0.54		0.53		0.59		0.51	
PRI	0.01		0.01		0.02		0.01		0.02	
Canopy Temperature, °C	29.93		28.87		28.70		28.43		28.50	
Soil Temperature, °C	21.37		21.10		21.10		21.60		20.80	
TDR, % soil water content	2.93		2.70		2.80		2.60		2.87	
FW, g m^{-2}	**247.31**	**a**	184.25	b	214.69	ab	188.38	b	**256.56**	**a**
DW, g m^{-2}	185.25		180.25		173.56		145.50		185.75	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 46 shows the physiological and agronomic surveys corresponding to four months after the first amendment application.

ChlM showed significant differences among treatments, with higher values in T2 and T3 compared to the control; T4 and T5 reported intermediate values that did not differ significantly from either the highest treatments or the control. FlvM was significantly higher in T3 and T4 than in T1 and T5, while T2 exhibited intermediate values. AnthM did not show significant differences among treatments, remaining comparable across all experimental conditions. The NFI index differed significantly, with the highest values observed in T2 and T3, significantly higher than in the lowest-performing treatments; T1, T4, and T5 showed intermediate values.

Regarding vegetation indices, NDVI differed significantly among treatments, with the highest value in T2 followed by T3; T1, T4, and T5 showed significantly lower and mutually similar values. PRI did not exhibit significant differences among treatments.

Canopy temperature, soil temperature, and TDR did not differ significantly among treatments.

With respect to agronomic parameters, FW showed significant differences, with the highest values in T4 and T5, both significantly higher than the control; T2 and T3 exhibited intermediate values. DW followed a similar pattern, with significantly higher values in T2, T4, and T5 compared to the control, while T3 showed intermediate values.

Table 46. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 1 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.24	b	**0.40**	**a**	**0.44**	**a**	0.31	ab	0.30	ab
FlvM	0.76	b	0.82	ab	**0.99**	**a**	**1.09**	**a**	0.71	b
AnthM	-0.07		-0.11		-0.03		0.05		-0.09	
NFI	0.35	ab	**0.58**	**a**	**0.52**	**a**	0.30	ab	0.43	ab
NDVI	0.61	b	**0.78**	**a**	0.71	ab	0.66	b	0.65	b
PRI	0.02		0.02		0.05		0.02		0.04	
Canopy Temperature, °C	16.07		15.97		15.93		16.03		16.07	
Soil Temperature, °C	18.63		15.93		17.77		17.80		15.90	
TDR, % soil water content	25.93		25.33		26.80		26.00		25.30	
FW, g m^{-2}	268.63	b	406.94	ab	393.31	ab	**509.06**	**a**	**471.06**	**a**
DW, g m^{-2}	78.19	b	**122.56**	**a**	93.44	ab	**130.00**	**a**	**123.25**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 47 shows the physiological and agronomic surveys corresponding to six months after the first amendment application and following mowing.

ChlM differed significantly among treatments, with the highest value observed in T3, which was significantly higher than in the control (T1), T2, and T5; T4 showed intermediate values. An opposite trend was observed for FlvM, with significantly higher values in T1 and T2 than in the amended

treatments T3, T4, and T5, which did not differ from each other. AnthM also showed significant differences, with the highest (i.e. least negative) values recorded in T1 and T2, followed by T5, while the lowest values were observed in T3 and T4. The NFI index differed significantly among treatments, with the highest value observed in T3, which was significantly higher than all other treatments, whose values were comparable.

Regarding vegetation indices, NDVI was significantly higher in T2 and T4 than in the control, whereas T3 and T5 exhibited intermediate values. PRI also differed significantly, with the highest values in T2 and T3, followed by T4, and the lowest values in T1 and T5.

Canopy temperature, soil temperature, and TDR did not differ significantly among treatments.

With respect to agronomic parameters, FW showed significant differences, with the highest values recorded in T4 and T5, both significantly higher than in T3.; T2 exhibited intermediate values, while the control showed lower values than the highest-yielding treatments. DW followed a similar pattern, with T2, T4, and T5 showing the highest values, well above T1 and T3.

Table 47. *Physiological and agronomic surveys measured at T_3 (6 months) during Year 1 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.36	b	0.35	b	**0.46**	**a**	0.40	ab	0.28	c
FlvM	**0.99**	**a**	**0.98**	**a**	0.58	b	0.56	b	0.59	b
AnthM	**-0.02**	**a**	**-0.03**	**a**	-0.21	c	-0.19	bc	-0.16	b
NFI	0.36	b	0.36	b	**0.81**	**a**	0.54	b	0.54	b
NDVI	0.57	b	**0.65**	**a**	0.64	ab	**0.65**	**a**	0.64	ab
PRI	0.01	b	**0.10**	**a**	**0.11**	**a**	0.05	ab	0.03	b
Canopy Temperature, °C	14.90		14.60		14.47		14.95		15.37	
Soil Temperature, °C	16.93		17.25		16.70		16.45		16.73	
TDR, % soil water content	13.40		12.45		13.40		11.95		10.65	
FW, g m^{-2}	316.69	bc	416.69	ab	222.94	c	**479.19**	**a**	**569.81**	**a**
DW, g m^{-2}	72.44	b	**105.81**	**a**	51.50	b	**127.19**	**a**	**124.13**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 48 reports physiological and agronomic surveys measured eight months after the first amendment application.

Significant differences among treatments were observed for FlvM, with the lowest value recorded in T4, significantly lower than all other treatments, which did not differ among themselves. AnthM showed significant differences, with the highest values in T3, T4, and T5, while T1 and T2 exhibited slightly lower values. ChlM and NFI index did not differ significantly among treatments.

For vegetation indices, NDVI differed significantly among treatments, with the highest value observed in T5, followed by T3 and T4, whereas T1 showed the lowest value. PRI did not show significant differences across treatments.

Among microclimatic parameters, canopy temperature varied significantly, with T1 exhibiting the highest value and T2 the lowest; T3, T4, and T5 showed intermediate values. Soil temperature did not differ significantly, while TDR was significantly lower in T2 compared to the ones which were comparable.

Regarding agronomic parameters, FW was highest in T2, significantly higher than in T1, T3, and T5, with T4 showing intermediate values. DW was highest in T2, followed by T1 and T3, whereas T4 showed the lowest value; significant differences were observed mainly between T2 and T4.

Table 48. *Physiological and agronomic surveys measured at T_4 (8 months) during Year 1 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.44		0.34		0.35		0.44		0.39	
FlvM	**1.11**	**a**	**0.94**	**a**	**1.15**	**a**	0.43	b	**1.15**	**a**
AnthM	-0.10	ab	-0.14	b	**-0.04**	**a**	**-0.06**	**a**	**-0.07**	**a**
NFI	0.40		0.34		0.35		0.43		0.36	
NDVI	0.56	c	0.60	bc	0.66	ab	0.66	ab	**0.70**	**a**
PRI	0.01		0.01		0.02		0.02		0.02	
Canopy Temperature, °C	**26.53**	**a**	20.27	b	22.37	ab	24.50	ab	21.87	ab
Soil Temperature, °C	15.30		15.83		15.03		14.87		15.23	
TDR, % soil water content	**20.97**	**a**	13.55	b	**22.60**	**a**	**19.40**	**a**	**22.93**	**a**
FW, g m^{-2}	546.88	b	**850.00**	**a**	562.50	b	696.88	ab	506.25	b
DW, g m^{-2}	163.31	ab	**180.69**	**a**	102.88	ab	85.38	b	138.25	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin

contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 49 presents physiological and agronomic surveys measured ten months after the first amendment application.

ChlM differed significantly among treatments, with the highest value observed in T5, which was significantly higher than in all other treatments that did not differ among themselves. NFI index was also significantly higher in T5 compared to T2, while T1, T3, and T4 showed intermediate values. FlvM and AnthM content did not differ significantly among treatments.

PRI showed significant differences, with the highest values in T5, followed by T3 and T4, whereas T1 and T2 exhibited the lowest values. NDVI did not differ significantly across treatments.

No significant differences were observed for canopy and soil temperatures. TDR differed among treatments, with T4 showing the highest value, well above T1 and T5; T2 and T3 had intermediate values. FW and DW showed some variation among treatments. DW was significantly higher in T2, T3, and T5 compared to T1 and T4, whereas FW did not differ significantly.

Table 49. *Physiological and agronomic surveys measured at T_5 (10 months) during Year 1 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.28	b	0.25	b	0.32	b	0.32	b	**0.59**	**a**
FlvM	0.98		1.04		0.94		0.83		1.10	
AnthM	-0.14		-0.09		-0.13		-0.09		-0.10	
NFI	0.31	ab	0.25	b	0.34	ab	0.41	ab	**0.56**	**a**
NDVI	0.67		0.72		0.76		0.71		0.76	
PRI	0.01	c	0.01	c	0.03	ab	0.02	ab	**0.03**	**a**
Canopy Temperature, °C	31.00		27.20		29.50		27.83		29.20	
Soil Temperature, °C	39.30		38.67		38.00		38.87		37.57	
TDR, % soil water content	11.35	b	13.87	ab	16.27	ab	**18.65**	**a**	12.54	b
FW, g m^{-2}	1158.13		1175.00		1148.13		1145.63		1193.75	
DW, g m^{-2}	296.44	ab	**346.44**	**a**	**360.19**	**a**	295.38	ab	**354.19**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation

index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 50 presents physiological and agronomic surveys measured two months after the second amendment application.

Significant differences were observed for ChlM, with the highest values recorded in T2 and T5, which were significantly higher than T4, while T1 and T3 showed intermediate values. AnthM differed among treatments, with the highest values observed in T3, followed by T2, T4, and T5, whereas T1 showed the lowest value. FlvM and NFI index did not differ significantly among treatments.

Among vegetation indices, PRI differed significantly, with the highest values recorded in T1, followed by T5; T2, T3, and T4 showed lower values. NDVI did not differ significantly across treatments.

No significant differences were observed for canopy and soil temperatures or for soil water content (TDR).

For agronomic parameters, FW was highest in T4, significantly higher than T1, T2, T3, and T5, which did not differ among themselves. DW showed a similar pattern, with the highest values in T4 and T5, followed by T2; T1 and T3 exhibited lower values.

Table 50. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 2 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.20	ab	**0.26**	**a**	0.14	ab	0.06	b	**0.32**	**a**
FlvM	0.89		0.93		1.05		0.81		0.95	
AnthM	-0.22	b	-0.14	ab	**-0.06**	**a**	-0.16	ab	-0.12	ab
NFI	0.23		0.28		0.32		0.25		0.33	
NDVI	0.59		0.57		0.54		0.56		0.60	
PRI	**0.07**	**a**	0.03	bc	0.02	bc	0.02	bc	0.05	ab
Canopy Temperature, °C	32.37		36.07		34.57		33.67		34.60	
Soil Temperature, °C	16.07		16.37		16.13		16.47		16.57	
TDR, % soil water content	6.27		6.90		6.67		6.93		6.27	
FW, g m^{-2}	331.25	ab	368.75	ab	331.25	ab	**439.56**	**a**	358.31	ab
DW, g m^{-2}	206.25	abc	245.81	ab	195.81	abc	**275.00**	**a**	**256.25**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 51 reports physiological and agronomic surveys measured four months after the second amendment application.

Significant differences were observed for ChlM, with the highest values recorded in T2, T3, and T5, which were significantly higher than T1, while T4 showed intermediate values. FlvM differed among treatments, with the highest value observed in T2, followed by T5 and T1; T3 and T4 showed significantly lower values. AnthM was highest in T2, significantly higher than in T3 and T4, with T1 and T5 showing intermediate values. NFI index was highest in T3, followed by T4 and T5, whereas T1 and T2 showed lower values.

Vegetation indices showed significant differences for PRI, with the highest values in T3, intermediate values in T4 and T5, and lowest values in T1 and T2. NDVI did not differ significantly among treatments.

Canopy temperature varied significantly, with T2 showing the highest value, followed by T4; T1, T3, and T5 showed lower values. Soil temperature and TDR did not differ significantly among treatments.

Regarding agronomic parameters, FW and DW were highest in T2, significantly higher than in T1, T3, T4, and T5, which showed no significant differences among themselves.

Table 51. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 2 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.45	b	**0.78**	**a**	**0.83**	**a**	0.52	ab	**0.78**	**a**
FlvM	1.17	b	**1.50**	**a**	0.71	c	0.69	c	1.19	b
AnthM	-0.30	bc	**-0.42**	**a**	-0.15	c	-0.20	b	-0.24	bc
NFI	0.38	b	0.43	b	**0.83**	**a**	0.65	ab	0.55	ab
NDVI	0.76		0.74		0.74		0.68		0.73	
PRI	0.38	b	0.43	b	**0.83**	**a**	0.65	ab	0.55	ab
Canopy Temperature, °C	12.60	b	**16.50**	**a**	11.20	b	13.37	ab	10.65	b
Soil Temperature, °C	13.10		13.97		14.03		13.00		13.70	
TDR, % soil water content	17.55		17.00		16.50		15.40		14.33	

FW, g m^{-2}	277.06	ab	**456.25**	**a**	252.06	b	293.75	ab	304.19	ab
DW, g m^{-2}	116.69	b	**184.38**	**a**	112.50	b	120.81	b	116.69	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 52 presents physiological and agronomic surveys measured six months after the second amendment application and following mowing.

Significant differences were observed in the ChlM and NFI index, with the highest values recorded in T1, which were significantly higher than in all other treatments. FlvM and AnthM content did not differ significantly among treatments.

Vegetation indices (NDVI and PRI) showed no significant differences among treatments.

Microclimatic parameters, including canopy and soil temperatures and TDR, were comparable across treatments.

Regarding agronomic parameters, FW was highest in T5, followed by T4, while T1, T2, and T3 showed lower or intermediate values; significant differences were observed between T5 and T3. DW showed a similar pattern, with the highest values in T5 and T4, and lower values in T2 and T3, although differences were less pronounced.

Table 52. *Physiological and agronomic surveys measured at T_3 (6 months) during Year 2 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	**1.24**	**a**	0.52	b	0.77	b	0.82	b	0.51	b
FlvM	1.54		1.31		1.57		1.57		1.53	
AnthM	0.24		0.24		0.21		0.22		0.20	
NFI	**0.80**	**a**	0.38	b	0.50	b	0.52	b	0.32	b
NDVI	0.65		0.66		0.69		0.64		0.67	
PRI	0.02		0.02		0.02		0.03		0.03	
Canopy Temperature, °C	7.70		6.70		7.17		6.93		7.37	
Soil Temperature, °C	13.73		13.17		13.13		12.10		14.30	
TDR, % soil water content	43.73		44.13		46.20		43.13		44.13	

FW, g m^{-2}	284.38	ab	279.19	ab	259.38	b	343.75	ab	**356.25**	**a**
DW, g m^{-2}	171.88		137.50		137.50		168.75		184.38	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 53 reports physiological and agronomic surveys measured eight months after the second amendment application.

Significant differences were observed by ChlM, with the highest values recorded in T4 and T5, which were significantly higher than in T1, T2, and T3. FlvM was also highest in T4 and T5, followed by T3 and T1, with T2 showing the lowest value. AnthM differed significantly, with the highest value in T1, followed by T3 and T5, and the lowest in T2. NFI index was highest in T1, T2, T4, and T5, whereas T3 showed significantly lower values.

Among vegetation indices, NDVI was highest in T4, followed by T1, T2, and T5, while T3 showed the lowest value. PRI was significantly higher in T1, T3, T4, and T5 compared to T2.

Canopy temperature varied significantly, with the highest values in T4 and T5, followed by T3; T1 and T2 showed the lowest values. Soil temperature did not differ significantly among treatments. TDR was significantly lower in T4 compared to the ones.

Regarding agronomic parameters, FW was highest in T1, T2, and T5, whereas T3 and T4 showed lower values. DW was highest in T5, followed by T1 and T2, while T3 and T4 had the lowest values.

Table 53. *Physiological and agronomic surveys measured at T_4 (8 months) during Year 2 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.57	b	0.58	b	0.58	b	**0.72**	**a**	**0.73**	**a**
FlvM	1.17	ab	1.03	b	1.21	ab	**1.29**	**a**	**1.32**	**a**
AnthM	**0.34**	**a**	0.15	c	**0.31**	**a**	0.23	b	**0.33**	**a**
NFI	**0.60**	**a**	**0.60**	**a**	0.40	b	**0.58**	**a**	**0.55**	**a**
NDVI	0.42	ab	0.36	ab	0.30	b	**0.45**	**a**	0.37	ab
PRI	**0.19**	**a**	0.06	b	**0.16**	**a**	**0.17**	**a**	**0.16**	**a**
Canopy Temperature, °C	5.85	c	6.13	c	6.43	bc	**7.55**	**a**	7.20	ab

Soil Temperature, °C	12.87		12.80		12.87		12.80		13.20	
TDR, % soil water content	**44.00**	**a**	42.43	a	**43.17**	**a**	36.30	b	**43.93**	**a**
FW, g m^{-2}	**387.50**	**a**	**421.88**	**a**	254.19	b	262.50	b	**410.44**	**a**
DW, g m^{-2}	231.25	ab	234.38	ab	139.56	b	131.25	b	**265.63**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 54 shows physiological and agronomic surveys measured ten months after the second amendment application.

Significant differences were observed for ChlM, with the highest values recorded in T1, T2, and T4, while T3 and T5 showed lower values. FlvM varied significantly among treatments, with T1 and T2 showing the highest values, T3 and T5 intermediate values, and T4 the lowest. AnthM was highest in T1, T2, and T3, with T4 and T5 showing significantly lower values. NFI index was highest in T4, followed by T5 and T2, whereas T1 and T3 showed lower values.

Among vegetation indices, NDVI was highest in T1, followed by T4, T3, and T5, while T2 exhibited the lowest value. PRI differed significantly, with the highest values observed in T1 and T3, and lower values in T2, T4, and T5.

Canopy temperature was highest in T2 and T4, while T3 had the lowest value. Soil temperature was highest in T5, with T1 and T3 showing lower values. TDR was highest in T3, significantly higher than in T1, T2, T4, and T5.

FW was highest in T3, followed by T5, while T1, T2, and T4 showed lower values. DW followed a similar pattern, with the highest value in T3, intermediate values in T5 and T2, and lower values in T1 and T4.

Table 54. *Physiological and agronomic surveys measured at T_5 (10 months) during Year 2 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	**0.61**	**a**	**0.51**	**a**	0.34	b	**0.52**	**a**	0.35	b
FlvM	**1.48**	**a**	1.36	ab	1.14	bc	0.61	d	0.86	cd
AnthM	**0.28**	**a**	**0.20**	**a**	**0.26**	**a**	0.09	b	0.08	b
NFI	0.33	c	0.38	b	0.28	d	**0.58**	**a**	0.42	b

NDVI	**0.72**	**a**	0.62	b	0.64	b	0.67	ab	0.66	b
PRI	**0.05**	**a**	0.01	b	**0.04**	**a**	0.01	b	0.02	b
Canopy Temperature, °C	21.90	bc	**24.60**	**a**	21.50	c	**24.25**	**a**	23.85	ab
Soil Temperature, °C	16.57	b	17.37	ab	16.63	b	17.30	ab	**17.85**	**a**
TDR, % soil water content	5.25	b	5.73	b	**8.23**	**a**	6.40	b	6.45	b
FW, g m^{-2}	264.56	b	337.50	b	**687.50**	**a**	334.38	b	475.00	ab
DW, g m^{-2}	128.63	b	167.88	ab	**247.75**	**a**	128.50	b	156.44	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 55 reports physiological and agronomic surveys measured two months after the third amendment application.

Significant differences were observed for ChlM, with the highest values recorded in T2 and T3, which were significantly higher than T1, while T4 and T5 showed intermediate values. FlvM was highest in T3, followed by T4 and T5, while T1 and T2 showed lower values. AnthM differed significantly, with the highest value in T5 and the lowest in T4; T1, T2, and T3 showed intermediate values. NFI index did not differ significantly among treatments.

Vegetation indices, NDVI and PRI, showed no significant differences across treatments.

TDR varied significantly, with the highest value observed in T5, followed by T4, T2, and T3; T1 showed the lowest value. Canopy and soil temperatures did not differ significantly among treatments.

Regarding agronomic parameters, FW was highest in T4, significantly higher than all other treatments, which did not differ among themselves. DW was highest in T2, T3, and T4, with T1 and T5 showing lower values.

Table 55. *Physiological and agronomic surveys measured at T_1 (2 months) during Year 3 in the different treatments of the Avellino experimental field.*

Treatments	**T1**		**T2**		**T3**		**T4**		**T5**	
ChlM	0.18	b	**0.27**	**a**	**0.29**	**a**	0.22	ab	0.25	ab
FlvM	0.75	b	0.80	b	**1.09**	**a**	0.90	ab	0.92	ab
AnthM	0.07	ab	0.03	ab	0.05	ab	0.01	b	**0.09**	**a**

NFI	0.24		0.29		0.28		0.26		0.27	
NDVI	0.59		0.41		0.54		0.47		0.58	
PRI	0.02		0.02		0.02		0.02		0.02	
Canopy Temperature, °C	32.20		36.07		34.80		33.43		34.73	
Soil Temperature, °C	20.55		20.20		19.47		19.90		18.10	
TDR, % soil water content	5.90	d	7.00	bc	6.93	c	7.87	b	**9.10**	**a**
FW, g m^{-2}	339.60	b	347.90	b	327.10	b	**531.20**	**a**	354.20	b
DW, g m^{-2}	150.00	ab	**195.80**	**a**	**185.40**	**a**	**208.30**	**a**	147.90	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

Table 56 reports physiological and agronomic surveys measured four months after the third amendment application and representing the final survey conducted in this field.

Significant differences were observed for ChlM, with the highest values recorded in T2 and T4, which were significantly higher than T5, while T1 and T3 showed intermediate values. FlvM was highest in T1 and T3, followed by T2 and T5, whereas T4 showed the lowest values. AnthM differed significantly, with the lowest value in T4; T1, T2, and T5 exhibited the highest values, and T3 showed intermediate levels. The NFI index was highest in T4, significantly above all other treatments.

Among vegetation indices, PRI was highest in T1, followed by T5; T2 and T3 showed intermediate values, and T4 exhibited the lowest value. NDVI did not differ significantly among treatments.

Microclimatic parameters, including canopy and soil temperatures, showed no significant differences among treatments. TDR was highest in T1 and T4, while T2, T3, and T5 exhibited intermediate values.

Regarding agronomic parameters, FW was highest in T4 and T5, significantly higher than T3, with T1 and T2 showing intermediate values. DW was highest in T4, followed by T5 and T3, whereas T1 and T2 showed lower values.

Table 56. *Physiological and agronomic surveys measured at T_2 (4 months) during Year 3 in the different treatments of the Avellino experimental field.*

Treatments	T1		T2		T3		T4		T5	
ChlM	0.63	ab	**0.74**	**a**	0.67	ab	**0.85**	**a**	0.54	b
FlvM	**0.71**	**a**	0.63	ab	**0.73**	**a**	0.48	b	0.50	b
AnthM	**0.10**	**a**	**0.10**	**a**	0.05	ab	0.02	b	**0.11**	**a**
NFI	0.54	b	0.90	b	0.97	b	**2.09**	**a**	0.68	b
NDVI	0.47		0.51		0.50		0.58		0.50	
PRI	**0.05**	**a**	0.03	abc	0.02	bc	0.02	c	0.05	ab
Canopy Temperature, °C	28.90		23.87		27.83		27.00		23.83	
Soil Temperature, °C	23.97		23.90		23.10		23.80		23.60	
TDR, % soil water content	**8.55**	**a**	5.80	b	7.43	ab	**8.17**	**a**	7.40	ab
FW, g m^{-2}	509.40	ab	585.40	ab	479.20	b	**709.40**	**a**	**659.40**	**a**
DW, g m^{-2}	231.20	b	220.80	b	262.50	ab	**368.80**	**a**	293.80	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid; ChlM: leaf chlorophyll content index; FlvM: leaf flavonol contents index; AnthM: leaf anthocyanin contents index; NFI: nitrogen-flavonol index (ChlM/FlvM ratio); NDVI: normalized difference vegetation index; PRI: photochemical reflectance index; TDR: time domain reflectometry; FW: fresh weight; DW: dry weight. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

The T5 treatment (*Humus Lombricò + Black Fluid*) exhibited a more dynamic chlorophyll compared to the ones (Table 57 and Figure 48), with distinct peaks following each amendment and values that remained elevated for prolonged periods. This response suggests not only an immediate improvement in photosynthetic functionality but also an enhanced ability of the plant to maintain an optimal physiological status over time. The alternation between growth and stabilization phases was more pronounced than in the other treatments, indicating a more responsive and better-nourished vegetative system. The other treatments showed more subdued profiles: T2 exhibited rapid but less persistent increases; T3 maintained a more regular trend but with lower values; T4 showed an intermediate response with more irregular fluctuations.

Table 57. Temporal dynamics of chlorophyll under different soil treatments at Avellino Experimental Field.

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	2.06		2.23		2.69		2.69		2.80	
17/11/2023	0.24	b	**0.40**	**a**	**0.44**	**a**	0.31	ab	0.30	ab
22/01/2024	0.36	b	0.35	b	**0.46**	**a**	0.40	ab	0.28	c
21/03/2024	0.44		0.34		0.35		0.44		0.39	
16/05/2024	0.28	b	0.25	b	0.32	b	0.32	b	**0.59**	**a**
30/09/2024	0.20	ab	**0.26**	**a**	0.14	ab	0.06	b	**0.32**	**a**
06/11/2024	0.45	b	**0.78**	**a**	**0.83**	**a**	0.52	ab	**0.78**	**a**
17/01/2025	**1.24**	**a**	0.52	b	0.77	b	0.82	b	0.51	b
13/03/2025	0.57	b	0.58	b	0.58	b	**0.72**	**a**	**0.73**	**a**
14/05/2025	**0.61**	**a**	**0.51**	**a**	0.34	b	**0.52**	**a**	0.35	b
23/09/2025	0.18	b	**0.27**	**a**	**0.29**	**a**	0.22	ab	0.25	ab
26/11/2026	0.63	ab	**0.74**	**a**	0.67	ab	**0.85**	**a**	0.54	b

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

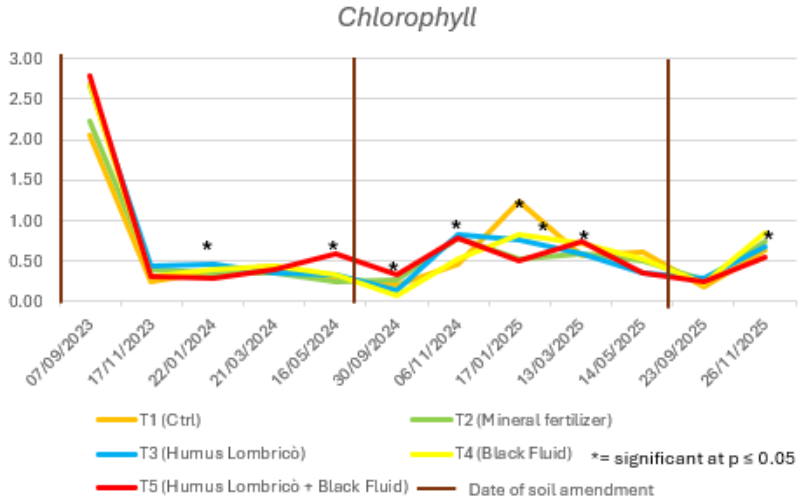


Figure 48. *Temporal dynamics of chlorophyll under different soil treatments at Avellino Experimental Field.*

During the experiment, T5 treatment exhibited a higher and more stable NDVI trend compared to the other treatments (Table 58 and Figure 49), with marked increases following each amendment and values that remained elevated throughout the entire observation period. This result suggests more

vigorous vegetation, capable of maintaining strong photosynthetic activity over time. The other treatments showed weaker or less continuous responses. T2 induced rapid but short-lived increases, T3 maintained a more regular trend but at lower levels, while T4 alone produced an intermediate and more variable response.

Table 58. *Temporal dynamics of NDVI index under different soil treatments at Avellino Experimental Field.*

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	0.61		0.54		0.53		0.59		0.51	
17/11/2023	0.61	b	**0.78**	**a**	0.71	ab	0.66	b	0.65	b
22/01/2024	0.57	b	**0.65**	**a**	0.64	ab	**0.65**	**a**	0.64	ab
21/03/2024	0.56	c	0.60	bc	0.66	ab	0.66	ab	**0.70**	**a**
16/05/2024	0.67		0.72		0.76		0.71		0.76	
30/09/2024	0.59		0.57		0.54		0.56		0.60	
06/11/2024	0.76		0.74		0.74		0.68		0.73	
17/01/2025	0.65		0.66		0.69		0.64		0.67	
13/03/2025	0.42	ab	0.36	ab	0.30	b	**0.45**	**a**	0.37	ab
14/05/2025	**0.72**	**a**	0.62	b	0.64	b	0.67	ab	0.66	b
23/09/2025	0.59		0.41		0.54		0.47		0.58	
26/11/2026	0.47		0.51		0.50		0.58		0.50	

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

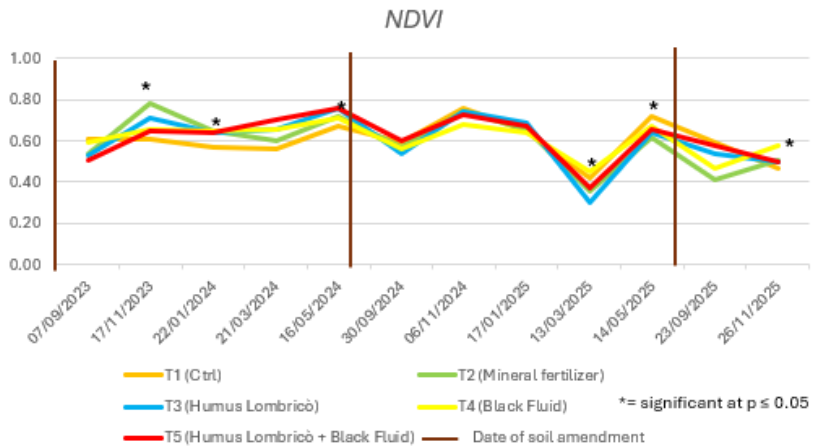


Figure 49. *Temporal dynamics of NDVI index under different soil treatments at Avellino Experimental Field.*

The T5 treatment exhibited a more consistent aboveground fresh biomass profile compared to the other treatments (Table 59 and Figure 50), with a greater ability to maintain elevated levels following the amendments. The other treatments showed more discontinuous responses. T2 induced rapid but less persistent increases, T3 maintained a more stable trend but at lower values, while T4 alone produced an intermediate and more variable response. The control consistently remained at low levels, indicating more limited growth.

Table 59. *Temporal dynamics of aboveground fresh weight under different soil treatments at Avellino Experimental Field.*

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	**247.31**	**a**	184.25	b	214.69	ab	188.38	b	**256.56**	**a**
17/11/2023	268.63	b	406.94	ab	393.31	ab	**509.06**	**a**	**471.06**	**a**
22/01/2024	316.69	bc	416.69	ab	222.94	c	**479.19**	**a**	**569.81**	**a**
21/03/2024	546.88	b	**850.00**	**a**	562.50	b	696.88	ab	506.25	b
16/05/2024	1158.13		1175.00		1148.13		1145.63		1193.75	
30/09/2024	331.25	ab	368.75	ab	331.25	ab	**439.56**	**a**	358.31	ab
06/11/2024	277.06	ab	**456.25**	**a**	252.06	b	293.75	ab	304.19	ab
17/01/2025	284.38	ab	279.19	ab	259.38	b	343.75	ab	**356.25**	**a**
13/03/2025	**387.50**	**a**	**421.88**	**a**	254.19	b	262.50	b	**410.44**	**a**
14/05/2025	264.56	b	337.50	b	**687.50**	**a**	334.38	b	475.00	ab
23/09/2025	339.60	b	347.90	b	327.10	b	**531.20**	**a**	354.20	b
26/11/2026	509.40	ab	585.40	ab	479.20	b	**709.40**	**a**	**659.40**	**a**

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

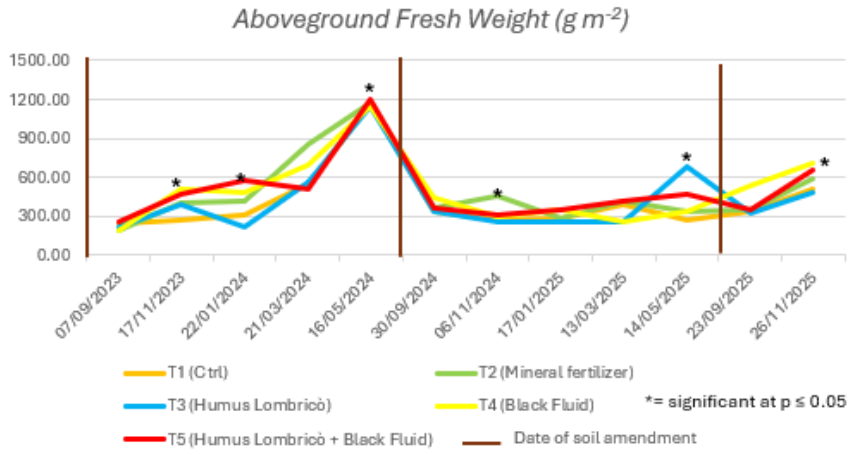


Figure 50. *Temporal dynamics of aboveground fresh weight under different soil treatments at Avellino Experimental Field.*

The T5 treatment exhibited a progressive aboveground dry biomass trend compared to the other treatments (Table 60 and Figure 51), with values increasing more markedly, particularly during the phases following the amendments. The other treatments showed more moderate dynamics in fact, T2induced rapid but less stable increases, T3 maintained a regular profile but at lower values, while T4 alone displayed an intermediate and more variable response.

Table 60. *Temporal dynamics of aboveground dry weight under different soil treatments at Avellino Experimental Field.*

Date of Surveys	T1		T2		T3		T4		T5	
07/09/2023	185.25		180.25		173.56		145.50		185.75	
17/11/2023	78.19	b	**122.56**	**a**	93.44	ab	**130.00**	**a**	**123.25**	**a**
22/01/2024	72.44	b	**105.81**	**a**	51.50	b	**127.19**	**a**	**124.13**	**a**
21/03/2024	163.31	ab	**180.69**	**a**	102.88	ab	85.38	b	138.25	ab
16/05/2024	296.44	ab	346.44	a	**360.19**	**a**	295.38	ab	**354.19**	**a**
30/09/2024	206.25	abc	245.81	ab	195.81	abc	**275.00**	**a**	**256.25**	**a**
06/11/2024	116.69	b	**184.38**	**a**	112.50	b	120.81	b	116.69	b
17/01/2025	171.88		137.50		137.50		168.75		184.38	
13/03/2025	231.25	ab	234.38	ab	139.56	b	131.25	b	**265.63**	**a**
14/05/2025	128.63	b	167.88	ab	**247.75**	**a**	128.50	b	156.44	ab
23/09/2025	150.00	ab	**195.80**	**a**	**185.40**	**a**	**208.30**	**a**	147.90	ab

26/11/2026	231.20	b	220.80	b	262.50	ab	**368.80**	**a**	293.80	ab

T1: Control; T2: Mineral Fertilizer; T3: Humus Lombricò; T4: Black Fluid; T5: Humus Lombricò + Black Fluid. Different letters indicate significant differences according to Duncan's test ($p \leq 0.05$).

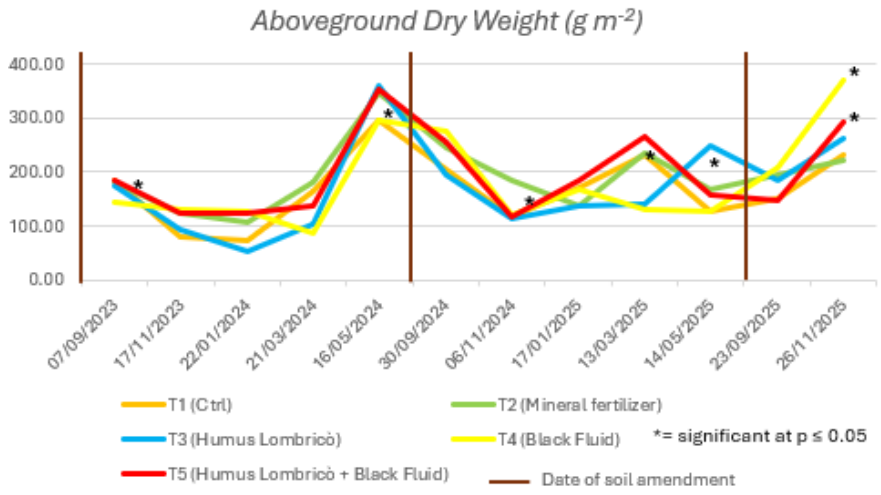


Figure 51. *Temporal dynamics of aboveground dry weight under different soil treatments at Avellino Experimental Field.*

Discussion

The discussion of the results obtained across the four experimental sites, Fisciano, Path, Linden, and Avellino, allows a delineation of a highly detailed picture of the dynamics governing urban soil functionality and spontaneous plant communities in response to different management strategies based on mineral fertilizers, micronized organic amendments, and their combinations. The dataset collected over the three-year monitoring period highlights that the response of urban ecosystems is strongly influenced not only by the type of treatment applied, but also by the ecological context, the management history of the sites, the structure of the plant communities, and local microclimatic conditions.

International literature highlights how urbanization induces profound changes in soils, vegetation, and biogeochemical cycles, creating heterogeneous and often degraded systems that, if properly managed, can provide significant ecosystem services (Pouyat *et al*., 2020; Morel *et al*., 2015; Lehmann & Stahr, 2007). This underscores that management interventions must be tailored to the specific characteristics of each site and cannot be applied uniformly. The results obtained across the four experimental sites support this perspective, demonstrating that micronized organic amendments, particularly *Humus Lombricò* and *Black Fluid*, especially when applied in combination, can enhance soil fertility, vegetation physiological functionality, and overall ecosystem performance, depending on site-specific conditions.

Soil chemical properties represent one of the key aspects of ecosystem functionality, directly influencing nutrient availability, structural stability, water-holding capacity, and the dynamics of soil organic carbon (SOC) and total nitrogen (N_tot) in terrestrial systems (Pouyat *et al*., 2010). At the experimental sites of Fisciano, Path, and Linden, characterized by sandy soils and relatively low organic matter content, the application of micronized organic amendments elicited clear and significant chemical responses, consistent with numerous published scientific findings. In these sites, the introduction of amendments resulted in substantial increases in cation exchange capacity (CEC), total organic carbon (C_tot), N_tot, and soil respiration (SR) compared to unamended controls (Tab. 2a, b; 15a, b; 23a, b). The increase in CEC was particularly pronounced in treatments with organic amendments rich in humic substances (e.g., *Humus Lombricò*) or in combinations of *Black Fluid*.

This trend is consistent with the literature, which shows that organic amendments rich in humified matter can increase exchange sites and thus enhance nutrient retention in soils (Clark *et al*., 2007; Agegnehu *et al*., 2016). The observed increases in C_tot and N_tot in the amended treatments indicate an enrichment of the soil organic fraction, at least in the short-term following application. Similar interpretations have been reported in recent studies, where the incorporation of organic amendments

led to significant increases in SOC content compared to unamended controls, confirming the effectiveness of these materials in enhancing organic carbon pools (Wu *et al*., 2024b). Over the medium term, comparisons between the two sampling times showed that some of the more pronounced effects tend to stabilize or diminish. At the Path site, for example, differences in C_tot among treatments became non-significant after approximately one year, although CEC remained generally higher in amended soils compared to the control. This suggests that a significant portion of the added carbon rapidly enters the soil biological cycle and is subject to mineralization, while a fraction is progressively stabilized in more resistant forms. Similar dynamics have also been observed for *Black Fluid*: the initial increase in SOC due to *Black Fluid* may decrease over time in terms of differentiation among treatments, while remaining higher than in unamended controls. This is likely because biochar particles become integrated into the soil matrix and associated with aggregates or stable particulate forms (Gross et al., 2024). Soil respiration, used as a proxy for microbial activity, was significantly higher in the amended treatments in the short term, indicating an acceleration of organic matter decomposition and turnover processes. Similarly, experimental studies on organic amendments have shown that applications of biochar and compost tend to increase CO_2 emissions after application, particularly when the amendment contains a readily decomposable fraction, reflecting an initial mineralization peak (Wang et al., 2025). The differentiation among amendments emerged as another key aspect of the results. *Black Fluid* exhibited a partially distinct behavior compared to more labile organic amendments: in some cases, such as at the Path site in 2025, the *Black Fluid* treatment showed the highest CEC values, consistent with its nature as a material rich in stable carbon and with high adsorptive and structuring properties. Numerous experimental studies and meta-analyses confirm that biochar application promotes the formation and stability of soil aggregates as well as the associated sequestration of organic carbon. Sun *et al*. (2023) reported that biochar use significantly increases the fraction of aggregates >2 mm and the carbon content associated with them, while also positively influencing microbial community structure. Broader meta-analyses indicate increases in macroaggregates, aggregate-associated carbon, and total SOC following biochar applications combined with fertilization, suggesting long-term improvements in soil physical structure and carbon storage capacity (Meng *et al*., 2023). In contrast, more reactive organic amendments exhibit faster responses but also greater variability, likely related to the decomposition and mineralization rates of labile organic compounds. This is reflected in the initial increase in soil respiration and available mineral nutrient pools, but also in a more rapid loss of organic carbon if not associated with physical and chemical stabilization processes. A consistent element between the experimental data obtained in the present study and the literature is the dependence of amendment-induced chemical responses on the intrinsic characteristics of the soil. In poorer and more degraded

soils, the effects of amendments were more pronounced and immediate compared to soils already richer in organic matter and with a well-established microbial community, where observed increases were more modest and less persistent. This behavior aligns with the concept that the response to organic amendments is greater in soils with organic matter deficits and limited retention capacity, whereas responses in already fertile soils are buffered by the presence of pre-existing organic pools and nutrient reservoirs. The effects of amendments on the stabilization of organic carbon in soils require long-term monitoring, as the formation of stable SOC pools is influenced by amendment quality, soil texture, and interactions with aggregates and microorganisms. Long-term field studies have shown that biochar applications can persistently increase SOC in silty soils over more than 10 years, whereas in coarse-textured soils stabilization may be less evident, highlighting the role of physical carbon protection in sequestration processes (Gross *et al*., 2024). Recent reviews indicate that the highly aromatic structure of biochar promotes carbon persistence in soil, but its interaction with stable aggregates and microbial communities is crucial for the formation of long-lasting carbon pools (Shyam *et al*., 2025).

The physiological and agronomic responses observed across the four experimental sites provide a highly detailed and complex picture of the dynamics governing urban vegetation functionality in relation to nutrient availability, soil structure, microclimatic conditions, and floristic composition. Physiological indices (ChlM, FlvM, AnthM, NFI) and vegetation indices (NDVI, PRI) serve as sensitive indicators of plant health and their capacity to respond to environmental stress, while agronomic parameters (FW, DW) provide information on productivity and biomass accumulation essential elements for understanding the role of vegetation in urban biogeochemical cycles.

Chlorophyll content (ChlM) proved to be one of the most sensitive indicators of nutrient availability and soil quality: at the managed sites, ChlM consistently increased in treatments with *Humus Lombricò* + *Black Fluid* combination and in the *Humus Lombricò*, confirming that organic amendments enhance nitrogen availability and the plants' capacity to synthesize photosynthetic pigments. This result is consistent with experimental studies in which the application of organic amendments led to significant increases in leaf pigment content, including chlorophyll, in *Beta vulgaris* L. and *Zea mays* L. compared to unamended controls, implying greater supply and availability of essential nutrients for photosynthesis (Libutti *et al*., 2020; Landorfa-Svalbe *et al*., 2022). More recent studies confirm that the increase in nutrient availability induced by organic amendments translates into improvements in photosynthetic parameters of crops (Islam *et al*., 2024). *Black Fluid* exhibited more variable responses: in some cases, it increased ChlM, while in others it reduced it. This variability, particularly observed at the Avellino site, can be interpreted in the context of the dynamic processes of nutrient release and immobilization in the soil. In products like so-called

“compost teas,” microbial and chemical composition can vary considerably depending on the source material and preparation method, resulting in positive effects on plant nutrition in some cases and weaker or contrasting outcomes in others (Pilla *et al*., 2023). Furthermore, the nutrient release dynamics are influenced by microbial immobilization processes, whereby rapidly released nutrients can be temporarily assimilated by microorganisms, reducing their immediate availability to plants, especially in soils with low buffering capacity or low organic matter content. The variability in carbon and nitrogen content of organic amendments further contributes to these heterogeneous responses over time (Roel-Rezk *et al*., 2025). At the Fisciano, Path, and Linden sites, characterized by richer soils and more complex plant communities, ChlM exhibited less pronounced variation among treatments, suggesting that nutrient availability is not a primary limiting factor. In this context, ChlM variability is more closely associated with floristic composition and seasonal dynamics rather than the direct effects of amendments. Flavonol and Anthocyanin indices provide valuable information on plant stress status and their capacity to activate defense mechanisms. Flavonols increase in response to light, thermal, or nutrient stress, while anthocyanins are often associated with water, heat, or oxidative stress. At the managed sites, FlvM tended to increase in treatments with *Black Fluid*, suggesting that this amendment may induce higher activity of phenolic pathways, possibly due to rapid mineralization or a temporary alteration of the nutrient balance. AnthM exhibited a more complex behavior: in some cases, they decreased with amendments, indicating a reduction in stress, while in other cases they increased, particularly at sites more exposed to water or thermal stress. At Avellino, AnthM was often higher, reflecting more severe environmental conditions, such as lower water availability. The NFI index, which represents the ratio between chlorophyll and flavonols, is a sensitive indicator of nitrogen use efficiency. At the managed sites, NFI consistently increased in the *Humus Lombricò* + *Black Fluid* combination treatments, confirming that organic amendments improve nitrogen availability and retention, thereby reducing oxidative stress. *Black Fluid* exhibited more variable responses, with significant increases in some phases and decreases in others, likely related to rapid nutrient dynamics and sensitivity to water conditions. At Avellino, NFI was more stable and less influenced by treatments, suggesting that nitrogen availability is not a primary limiting factor at this site.

Vegetation indices NDVI and PRI represent integrated indicators of plant health. NDVI consistently increased in the *Humus Lombricò* + *Black Fluid* combination treatments at the managed sites, indicating improved vegetative vigor and leaf cover. *Black Fluid* showed more variable responses, with significant increases at some stages and decreases at others. PRI, which reflects photochemical efficiency and the plant’s ability to dissipate excess energy, increased in the organic treatments,

particularly with *Humus Lombricò*. Mineral fertilizer often showed lower PRI values, suggesting that rapid growth not accompanied by improvements in soil structure may increase photochemical stress. Productivity is a fundamental indicator of ecosystem functionality, as it reflects the vegetation's capacity to accumulate biomass and contribute to carbon cycling. At the managed sites, FW and DW consistently increased in the *Humus Lombricò* + *Black Fluid* combination treatments, confirming that organic amendments enhance soil fertility and nutrient availability. *Black Fluid* showed more variable responses: in some cases, it increased productivity, while in others it reduced it, likely due to transient stress or nutrient imbalances. Mineral fertilizer increased productivity in the short term, but its effects tended to decline over the medium too long term, confirming that chemical fertilization alone is insufficient to improve soil structure and its capacity to retain nutrients and water. At Avellino, productivity was lower during the first months but increased significantly in the combination treatments, suggesting that even in semi-natural soils, organic amendments can enhance ecosystem functionality. The differences observed among the four experimental sites – Fisciano, Path, Linden, and Avellino, are consistent with the literature, which highlights how urban soils' responses to organic amendments are strongly modulated by site-specific conditions and land-use history. Recent meta-analyses indicate that the effectiveness of amendments in improving soil chemical and structural properties varies depending on land-use type and local pedological characteristics, reflecting heterogeneous rather than uniform responses (Malone *et al*., 2023). Similarly, comparative studies on urban soils with different management histories show that interventions with organic residues improve soil health more markedly in more degraded sites than in less deteriorated ones, emphasizing the importance of spatial variability and management history in determining responses to amendments (Una *et al*., 2022). Finally, differences in the chemical, microbiological, and physical properties of urban soils due to urbanization and anthropogenic artifacts reinforce the notion that each site responds uniquely to external inputs (Garcia *et al*., 2024; O'Riordan *et al*., 2021).

The comparison between Path and Linden highlights further differences related to the degree of urbanization and management history. Linden, although an urban site, has slightly richer soil and a more structured plant community, which responds more consistently to amendments. In contrast, Path exhibits greater sensitivity to environmental stress and a lower capacity to retain nutrients and water, factors that limit the response to amendments. Linden represents an example of how organic amendments can improve the functionality of moderately structured urban soils, while Path illustrates the limitations of interventions in highly degraded contexts.

The comparison between Fisciano and Avellino further emphasizes the differences between managed urban ecosystems and semi-natural ecosystems. Fisciano shows more linear and predictable responses to amendments, with consistent increases in soil fertility, productivity, and physiological

functionality. Avellino, on the other hand, exhibits more complex and less predictable responses, influenced by biodiversity, competition, and microclimatic conditions. This outcome confirms that organic amendments exert a stronger effect on poor and degraded soils, whereas in rich and complex soils their effectiveness is modulated by a variety of ecological factors.

Overall, the comparison among the sites demonstrates that responses to amendments are highly context dependent. In managed and degraded sites, organic amendments markedly improve soil fertility, vegetation physiological functionality, and productivity. In semi-natural sites, amendments have a more attenuated and complex effect, influenced by biodiversity and local ecological dynamics. These findings confirm that urban soil management must be adapted to local conditions and that interventions should be calibrated according to land-use history, plant community structure, and microclimatic conditions.

The analysis of the effects of individual amendments, *Humus Lombricò*, *Black Fluid*, and their combination, represents a crucial step in understanding the mechanisms through which organic management can enhance urban soil functionality and vegetation response. Although the treatments were applied across the four sites, their responses were strongly modulated by the ecological context, and plant community composition. Nevertheless, clear and consistent patterns emerge, allowing the specific role of each amendment to be delineated.

Humus Lombricò confirms its status as one of the most effective and stable amendments for improving soil fertility and vegetation functionality. Its highly humified nature, rich in stable organic compounds, humic and fulvic acids, along with the presence of a diverse and active microbial community, makes it capable of simultaneously enhancing soil physical structure, nutrient availability, and plant nutrient uptake. In the managed sites, *Humus Lombricò* led to substantial increases in CEC, C_tot, and N_tot, confirming its ability to enrich soils with stable organic matter and improve nutrient retention. This effect is particularly evident in poorer, where Humus *Lombricò* contributed to enhancing soil structure, increasing the capacity to retain water and nutrients, and reducing vulnerability to water stress. From a physiological perspective, *Humus Lombricò* significantly increased ChlM and the NFI index, indicating improved nutritional status and reduced oxidative stress. This behavior is consistent with literature showing that vermicompost enhances nitrogen availability and plant nitrogen-use efficiency, thanks to the presence of both organic and mineral N forms and stimulation of microbial biomass. Vegetation productivity also benefited from *Humus Lombricò* application, with consistent increases in fresh and dry biomass in the managed sites. This result confirms that Humus not only improves soil fertility but also supports vegetative growth in the medium too long term, due to its capacity to gradually release nutrients and enhance soil structure. In semi-natural sites, such as Avellino, the effect of *Humus Lombricò* was more attenuated,

likely because soil fertility and plant biodiversity already provide favorable conditions for ecosystem functionality. Nevertheless, even in this context, *Humus Lombricò* contributed to improving productivity and physiological performance, confirming its effectiveness in complex ecosystems.

Black Fluid represents an innovative organic amendment, characterized by a highly reactive nature and a composition rich in soluble and micronized organic compounds. Its application elicited more variable responses compared to *Humus Lombricò*, reflecting its capacity to rapidly influence nutrient availability and plant physiology, as well as its sensitivity to environmental conditions. In the managed sites, *Black Fluid* induced significant increases in C_tot and SR, indicating strong microbial community activation and rapid mineralization of organic matter. However, this effect was accompanied by greater variability in CEC and N_tot, suggesting that *Black Fluid* may trigger phases of microbial immobilization or nutrient imbalance, particularly in poorer soils. From a physiological standpoint, *Black Fluid* exhibited a complex behavior: at certain times it increased ChlM and the NFI index, while at other times it promoted higher FlvM and AnthM accumulation, indicating a possible induction of stress. This pattern is consistent with literature on organic liquid amendments, which shows that their rapid availability can trigger intense but transient physiological responses. Vegetation productivity also showed variable responses: in some sites and periods, *Black Fluid* led to significant increases in biomass, whereas in others the effects were more modest or even negative. This behavior suggests that Black Fluid may be particularly effective under conditions of moderate soil fertility, while its efficacy may be reduced in very poor or very rich soils.

The combination of *Humus Lombricò* and Black Fluid represents the most effective and stable treatment among those tested. The integration of a highly humified and stable amendment (*Humus Lombricò*) with a reactive and rapidly available amendment (*Black Fluid*) produced synergistic effects, simultaneously enhancing soil fertility, nutrient availability, plant physiological functionality, and productivity. In the managed sites, the combination resulted in the highest increases in CEC, C_tot, and N_tot, confirming that integrating stable and labile forms of organic matter is an effective strategy for improving soil fertility over the medium to long term. From a physiological perspective, the combination induced significant increases in ChlM, the NFI index, and photochemical efficiency, indicating improved nutritional status and reduced stress. Vegetation productivity also benefited markedly from the combination, with consistent increases in both fresh weight (FW) and dry weight (DW) across all managed sites. This outcome confirms that the combination represents an effective strategy for supporting plant growth and enhancing ecosystem functionality. In the semi-natural sites, the combination showed a more attenuated yet still significant effect, demonstrating that even in complex ecosystems, the integration of organic amendments can improve soil and vegetation functionality.

The overall results obtained across the four experimental sites provide insights into how organic amendments and the management practices applied influence not only soil fertility and plant productivity but also the capacity of urban ecosystems to deliver essential ecosystem services. These results can be contextualized within the broader literature on biochar and vermicompost in agricultural and horticultural systems. To date, no studies have specifically examined the effects of micronized organic amendments as such, with most research focusing on biochar, vermicompost, or their conventional combinations. Nevertheless, patterns observed in cultivated systems provide a useful reference for interpreting the dynamics recorded in urban soils.

In urban soil, micronized organic amendments increased SOC, CEC, and plant physiological responses, reflecting trends documented in agricultural systems. Meta-analyses indicate that biochar enhances SOC and CEC, though effects depend on soil type and application rates (Sun et al., 2022). Horticultural studies, for example on cucumber (*Cucumis sativus* L.), show that singular or combined biochar and vermicompost applications improve soil properties (pH and organic carbon) and increase yields by 29–56 % compared to controls, suggesting a synergistic effect on soil fertility and crop performance (Wang et al., 2021).

In crop rotations, vermicompost increases labile carbon fractions and soil respiration, whereas biochar stabilizes SOC and supports root and leaf biomass, though total yields may not differ significantly (Sarma et al., 2018). Mesocosm experiments with maize further demonstrate that combined biochar and vermicompost applications enhance soil fertility, water dynamics, and crop resilience under water stress (Doan et al., 2015). Overall, vermicompost frequently increases SOC by 18–50 % and improves CEC, while biochar promotes long-term carbon stabilization (Farooqi et al., 2024; Sun et al., 2022). Although many studies did not use micronized materials, the observed trends—enhanced nutrient retention and improved plant functionality—align with the responses in our urban soils. This suggests that the beneficial mechanisms induced by micronized organic amendments are broadly applicable across both urban and cultivated ecosystems, supporting the relevance and robustness of our findings in an international research context.

International literature highlights that urban soils represent a critical component of city sustainability, contributing to microclimate regulation, carbon sequestration, stormwater management, biodiversity, and human well-being. The findings of this study fully support this perspective, demonstrating how targeted interventions can significantly enhance the ecological functionality of urban green spaces.

One of the most relevant ecosystem services concerns soil fertility. Organic amendments, particularly *Humus Lombricò* and the *Humus Lombricò + Black Fluid* combination, markedly improved the soil's capacity to retain nutrients, increase carbon and nitrogen availability, and support plant growth. This outcome is especially important in degraded urban soils, where the loss of organic matter and

compaction represent limiting factors for ecosystem functionality. The observed increases CEC, C_tot, and N_tot in the managed sites confirm that organic amendments are an effective strategy to enhance soil fertility over the medium to long term, contributing to the resilience of urban ecosystems. Another fundamental ecosystem service concerns carbon storage and stabilization processes. These processes reflect the balance between carbon inputs, mineralization, and stabilization mechanisms rather than a unidirectional sequestration pathway. The observed increase in total organic carbon in the managed sites suggests that organic amendments not only improve soil fertility but can also enhance carbon storage potential, contributing to climate change mitigation. Meta-analyses have shown that organic matter amendments such as compost and biochar significantly increase soil organic carbon stocks in urban soils and improve overall soil quality (Malone *et al*., 2023; Fiorentino *et al*., 2025). Furthermore, reviews on urban soil carbon storage highlight how sustainable management practices, including the application of organic amendments and increased urban vegetation, enhance the role of urban soils as carbon reservoirs within the global carbon cycle (Fiorentino *et al*., 2025). In some urban contexts, increases in soil organic carbon have even been correlated with enhanced vegetation cover, indicating that urban soils can contribute to carbon storage under appropriate management (Zhang et *al*., 2022). However, the observed increase in soil respiration in some treatments suggests that a portion of the added carbon is rapidly mineralized, highlighting the need for strategies that promote long-term carbon stabilization. Microclimate regulation represents another highly relevant ecosystem service in urban areas, where the urban heat island effect constitutes a major environmental challenge. The results indicate that organic amendments, by improving soil structure and water availability, enhance transpiration and reduce canopy temperature, thereby contributing to the mitigation of urban heat effects. This effect is particularly evident in managed sites, where vegetation responds more clearly to the amendments. In semi-natural sites, such as Avellino, microclimate regulation is more complex and influenced by factors such as biodiversity, vegetation community structure, and local microclimatic conditions. Biodiversity represents another key component of ecosystem functionality. The results show that organic amendments promote the growth of perennial and nitrophilous species, increasing vegetation cover and structural complexity of the community. However, in semi-natural sites, biodiversity is influenced by a range of ecological factors, making the response to amendments more complex and less predictable. These findings confirm that the management of urban biodiversity requires an integrated approach that considers local ecological dynamics and species interactions. Organic amendments, by improving soil structure and water-holding capacity, contribute to reducing runoff and enhancing infiltration, thereby increasing the water resilience of urban ecosystems. This effect is particularly evident in the managed sites, where the *Humus Lombricò* + *Black Fluid* combination

significantly improved the soil's water retention capacity. Despite the highly promising results, the study presents some limitations that should be considered for proper data interpretation and for defining future research directions. However, beyond methodological limitations, it is important to consider that the application of organic amendments may also involve ecological and operational trade-offs. In particular, the increase in soil respiration observed in several treatments suggests the occurrence of short-term priming effects, potentially accelerating the mineralization of native soil organic carbon. In addition, the rapid release of nutrients from more reactive amendments may increase the risk of nutrient leaching, especially in coarse-textured or highly disturbed urban soils. From a practical perspective, the large-scale application of organic amendments in urban environments may also be constrained by economic costs, material availability, and logistical challenges related to application methods. Therefore, the benefits observed in this study should be interpreted within a broader sustainability framework, balancing soil improvement with potential environmental and management constraints. One of the main limitations concerns the study duration. Although three years represent a significant period to observe ecological dynamics, many processes related to carbon stabilization, aggregate formation, and vegetation succession require longer timescales to fully manifest. Long-term studies would be necessary to evaluate the sustainability of the observed effects and to better understand soil carbon stabilization dynamics. Another limitation relates to the spatial variability of the sites. Although the four sites represent a broad range of ecological conditions, their inherent variability makes it difficult to isolate the specific effects of the amendments from those driven by the ecological context. Future studies could benefit from a higher number of spatial replicates and a more stratified experimental design, allowing a more precise isolation of treatment effects.

Conclusion

The research presented in this thesis multidimensionally investigated the role of organic amendments *Humus Lombricò*, *Black Fluid*, and their combination, in urban soils and the functionality of spontaneous vegetation across a gradient of ecological and management contexts. The four experimental sites (Fisciano, Path, Linden, and Avellino) served as open-air laboratories, allowing the observation, under real-world conditions, of how anthropogenic, and heterogeneous soils subjected to varying management pressures respond to innovative organic interventions.

The results clearly indicate that organic amendments, particularly when applied in combination, can enhance soil fertility, nutrient availability, plant physiological functionality, and productivity, thereby significantly contributing to the provision of key ecosystem services. The observed increases in cation exchange capacity (CEC), total organic carbon, and total nitrogen at the Fisciano, Path, and Linden experimental fields confirm that organic amendments represent an effective strategy for enriching urban soils with stable organic matter and improving their capacity to retain nutrients and water. These findings are especially relevant in soil, where sandy soil texture and low water-holding capacity constitute limiting factors for ecosystem functionality such as Avellino. From a physiological perspective, organic amendments improved the nutritional status of vegetation by increasing chlorophyll content and nitrogen use efficiency, while reducing photochemical stress. Plant productivity was significantly enhanced under organic treatments, particularly with the *Humus Lombricò* + *Black Fluid* combination, which proved to be the most effective and stable strategy in the medium term. Although *Black Fluid* exhibited rapid and pronounced effects, its responses were more variable and sensitive to water conditions, confirming that its effectiveness is strongly context dependent.

The comparison among sites highlighted that the response to organic amendments is strongly modulated by the ecological context. In managed soils, such as Fisciano, Path, and Linden, organic amendments markedly improved soil fertility, vegetation physiological functionality, and productivity. In semi-natural soils, such as Avellino, the effects of amendments were more attenuated and complex, influenced by local biodiversity and ecological dynamics. This variability underscores that urban soil management requires adaptive, site-specific approaches capable of integrating management history, vegetation community structure, and microclimatic conditions.

The conclusions of this thesis directly address the limitations and gaps identified in the previous chapter. One of the main limitations in the literature is the lack of integrated studies simultaneously analyzing soil physical, chemical, and biological properties, vegetation physiology, biodiversity, and ecosystem services. The present research partially fills this gap by providing a multidiscipline

approach that integrates chemical, physiological, agronomic, and microclimatic data collected under real-urban conditions. This approach represents an original and significant contribution to the understanding of ecological dynamics in urban soils. Another limitation concerns the relative scarcity of studies conducted under real-urban conditions that account for the full complexity of urban environments. This research addresses this gap by working across four actual sites characterized by anthropogenic, and heterogeneous soils subjected to varying management pressures.

The lack of long-term studies represents an additional limitation in literature. Although the three-year duration of the present research is not sufficient to observe slow processes such as carbon stabilization or the formation of stable aggregates, the results already reveal clear and consistent patterns that confirm the effectiveness of organic amendments in enhancing soil fertility and vegetation functionality. Long-term studies will be essential to evaluate the sustainability of the observed effects and to gain a deeper understanding of soil carbon stabilization dynamics.

Moreover, the scarcity of studies on micronized organic amendments represents a particularly relevant gap. *Black Fluid*, the focus of this research, belongs to an emerging category of organic amendments for which the literature is extremely limited. The results indicate that *Black Fluid* exerts rapid and pronounced effects on nutrient availability and plant physiology, yet its effectiveness is strongly dependent on the ecological context. These findings constitute an original and significant contribution to the understanding of micronized amendment effects in urban soils.

In conclusion, this research demonstrates that organic amendments, particularly *Humus Lombricò* + *Black Fluid* combination, is effective tools to improve soil fertility and vegetation physiological functionality. The limitations of this study, rather than representing obstacles, provide valuable guidance for future research directions, which may further explore microbial dynamics, carbon stabilization, and the role of soil fauna in urban ecosystem regeneration. Overall, this thesis contributes to filling key gaps in the literature and provides a solid scientific basis for the sustainable management of urban soils and the planning of ecological regeneration interventions based on innovative organic amendments.

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