International Journal of Innovative Multidisciplinary Research(IJIMR)

# Impact of Plastic Waste on Soil Microbial Activity in Urban Parks

**Majid Ali**

Class 3rd semester
Department MSPH
University SZABIST
majidalibaloch125@gmail.com

## Abstract

Plastic pollution is an emerging environmental challenge in urban green spaces. The deleterious impact on aquatic systems has been widely published, while research on the impact of plastic pollution on soil microbial communities, which are essential for ecosystem health, remains limited. This study aimed to investigate the biological and perceived impact of plastic waste on soil microbial activity in urban parks. A convergent mixed methods design was employed across three urban parks. Quantitative analyses of the soils (microbial biomass carbon, pH, and moisture) were completed along with qualitative interviews with 15 distinct stakeholders, including staff, visitors, and experts. In zones impacted by plastic pollution, microbial activity in the soil was significantly lower than in zones without plastic pollution, and the concentration of plastic material resulted in a strong negative correlation with microbial biomass. Stakeholders reported noticeable degradation of both soil and plant health, which was related to the outcomes of the lab work. Plastic pollution negatively impacts soil health by altering soil microbial communities. As plastic waste management is a priority of municipal governments, waste mitigation strategies supplemented with environmental education will ensure sustainable urban parks and green space ecosystems.

**Keywords:** *Environmental Perception*, *Microbial Biomass, Mixed Methods, Plastic Pollution, Soil Microbes, Urban Parks.*

# Introduction

## 1.1 Background of the Study

Plastic waste has become one of the world's most significant environmental problems. Every year, people produce and throw away millions of tons of plastic. A lot of this plastic ends up in the natural environment (Geyer, Jambeck, & Law, 2017; Ren et al., 2021). While most people talked about plastic pollution in oceans and rivers, more and more plastic was also found in the soil. When plastic breaks down, it creates tiny pieces called microplastics and nanoplastics, which stay in the soil for a long time and could harm natural soil processes (Watts et al., 2019; Banaee et al., 2024).

Soils had many different kinds of tiny living things called microbes that helped support the health of ecosystems. These microbes decomposed dead plants, recycled essential nutrients like nitrogen and phosphorus, and facilitated plant growth (Fierer, 2017). All of these roles were especially important in areas like city parks, where healthy soils contributed to the growth of healthy trees, grass, flowers, and spaces for human use. However, parks often host a variety of human activities, including walking, littering, and maintaining trails and green spaces. This increased the likelihood that plastics would enter the soils of city parks (Sharma et al., 2023; Banaee et al., 2024).

As plastics in city parks increased, user concern about how plastics impact soil microbes also grew. Microbes were sensitive to changes in the environment. Plastic pieces could block oxygen and water from soils, leach harmful chemicals, or prevent microbes from utilizing resources to reproduce and grow (Ren et al., 2021). It’s a danger that may reduce the number of microbes and their activities, meaning a potential decrease in the soil health and, hence, plants' health (Watts et al., 2019).For these reasons, it was crucial to investigate how plastic waste affects microbial life in city park soils.

## 1.2 Problem Statement

Most research on plastic pollution has focused on aquatic environments, including oceans and rivers. Research has demonstrated the harmful effects of plastic on animals and habitats (Gall & Thompson, 2015). However, there is limited research on the effects of plastic waste on land, particularly on soil. Urban parks are significant for both nature and people, but human interactions often impact them and lack sufficient environmental monitoring.

Soil microbes were a good sign of soil health. If these microbes were harmed, the soil would be unable to support plant growth or maintain balance in the environment (Geissen et al., 2015). Since plastic could change the soil's structure and chemistry or interfere with how microbes work, it was a possible threat to city park health. However, insufficient research has been conducted on the impact of plastic waste on microbes in park soils. This missing information needs to be studied to help protect urban green spaces.

## 1.3 Research Objectives

1. To study how plastic waste affected microbial activity in the soil of urban parks
2. To explore what park workers and visitors thought and did about plastic waste
3. To combine scientific findings and people's opinions for better understanding

## 1.4 Research Questions

1. How did plastic waste affect microbial biomass and activity in the soil of city parks?
2. What did park visitors and staff think about plastic waste and its effects on soil and park health?
3. Did the scientific results and people's views agree or show different ideas about plastic's impact?

## 1.5 Significance of the Study

This study was useful for several reasons. First, it provided helpful ideas to urban planners, park managers, and local governments on how to better care for green spaces. If plastic waste reduces soil microbial activity, then more effective methods of waste collection and cleaning could be implemented to protect soil ecosystems (de Souza Machado et al., 2018). Second, this study contributed to the limited research on plastic in soil, as most studies have focused on the ocean. By examining microbes, the study provided a new biological perspective on the issue.

The study also helped promote sustainable methods for managing city parks and enhancing soil health. As cities grew, protecting green spaces became more important for both nature and people. Laboratory tests on the dynamics between plastic garbage and soil-based microorganisms made the routes through which plastics undermine the park ecosystems clearer. This understanding has guided park managers to use the measures that can help to sustain biodiversity and structural integrity of the ecosystems in the future.

## 1.6 Scope and Limitations

The current study carried out on a limited sample of parks located in one city is not representative enough to apply generalization wide-spreadly. In spite of the fact that the assessment of microbial activity was made in terms of chosen indicators namely microbial respiration and activity of enzymes, these parameters provide fragmented perception of the total microbial wellbeing and hence are not a complete assessment of the same. In addition, the fact that the researchers chose the participants based on the availability and the available capacity, which could have made the selection of the participants to represent only certain views in the entire data set. Besides these restrictions, the study can serve as a good starting-point in the further investigation and remind people about the little-known implications of the plastic contamination of urban soil systems and related ecosystems.

# Literature review

## 2.1 Plastic Waste in Urban Ecosystems

The increasing number of plastic waste, which is caused by the growing population density and the increased rates of consumption in cities, has an immense negative impact on the metropolitan ecosystem. In the urban parks, the plastic waste gains an ecological value once it has been selectively discarded or reached its destination through a gradual process of the migration of the material that started in the nearby streets (Ihenetu et al., 2024; Haq, 2011). This garbage is a mishmash that is generally divided into three massive groups such as macro plastics, micro plastics, and sub-mm pieces that are practically indistinguishable to each other in the context of being in the field (De Souza Machado et al., 2017). Macro plastics speaking about items that can still be identified even after littering are subjected to the process of continuous photo degradation, wind fracture, and atmospheric compression, which result in fragmentation, rather than the complete breakdown (Chamas et al., 2020).

Conversely, micro plastics <5mm length remains long enough to match residence time of soils, even more than ten years (He et al., 2020). Australian research reports both micro- and macro-sized plastics in parks soils, littering bins, drainable surface water, and footpaths used regularly (Khoeriyah and Sembiring, 2024). Interactions between soil and water was dictate the location where plastic would collect with smaller plastics being at a high probability of being transported to the underlying through preferential flow path tissue, a process that is affected by the soil-related physico parameters and the hydrological gradients (Wang et al., 2016). The impacts of plastic in parks soils also have a rather negative side and include inhibition of the gaseous exchange, impeding of the water movement, and a reduction in the water-holding capacity (De Souza Machado et al., 2019).These changes make the microorganisms in the soil nonviable and dysfunctional (Aralappanavar et al., 2024). The recovery period is typically short in the case of urban parks accompanied by heavy use, thus making the latter especially susceptible to plastic pollution (Bodor et al., 2023).

## 2.2 Soil Microbial Activity and Ecological Functions

Microorganisms of the soil form an essential part of any ecosystem stability and resilience. Microbial biomass is a metric that indicates the total mass of organisms but microbial respiration offers an indication on the functional activity by releasing carbon dioxide (CO2) (Chen et al., 2019). The enzymatic activity refers to the set of chemical processes in which microorganisms break down plant detritus and transform key nutrients into nitrogen, phosphorus, and carbon (Delgado-Baquerizo et al., 2016). Microorganisms perform essential ecological functions such as that of decomposing wastes, clearing up pollutants, and nutrient cycling and structural support of soil (Fierer, 2017; Trivedi et al., 2016). Strengths of microbial community, therefore, enhance the growth of plants and strengthen the soil capacity to resist stressors that may be caused by pollution and climatic change (Bardgett & Van Der Putten, 2014).

On the other hand, the physiology of microorganisms may become impaired by the encounter of heavy metals, pesticides, and components of chemicals derived of plastics (Li et al., 2022b; Zhou et al., 2024). Such contaminants as phthalates and bisphenol A, which are detected in plastics, have a detrimental impact on microbial respiration and solitary enzymes (Okoye et al., 2022). In their turn, micro plastics act as carriers of other toxic substances, as a result of which the extent of contamination increases (Selonen et al., 2021; Rillig, 2018). In the urban ecosystems, the trampling will persist and the soil organic matter will decline given the limited soil organic matter leading to the compromised health of plants that will further impact the sustainability of the urban parks (Elbasiouny et al., 2023).

## 2.3 Plastic–Soil–Microbe Interactions

Recent studies of the effect of agricultural soils reveal that micro plastics significantly affect microbial activity. It is confirmed empirically that it is reduced microbial biomass, changes in community composition, and reduced enzyme activity (Chahal et al., 2023; Aralappanavar et al., 2024). To give an example, there can be examples of the decrease in beneficial populations (like nitrogen-fixing bacteria) and those that experience an increase in population (such as taxonomically diverse populations tolerant of pollution taking advantage of chemical compounds bound to plastic) (Yang et al., 2018). As a result of that, microbial balance can be disrupted.

Such responses have physical mechanisms such as the blocking of the small spaces in soil by pieces of micro plastic, thus obstructing gas and water exchange (De Souza Machado et al., 2019). Chemical routes present one more possible explanation: chemical leachates of plastics have the potential to act on microbial metabolic activity (Seeley et al., 2020).

Although some studies revealed that low concentrations of micro plastics actually stimulate microbial activity, stimulated activity is commonly limited to only specific microbial guilds (Dadzie et al., 2023), which brings into question the concept of biocultural homogenization (Rillig, 2018). More long-term consequences, especially under the conditions of parkland ecosystems in the city environment, are poorly understood (De Souza Machado et al., 2017).

Overall, micro plastic-microbial interface is complex and depends on chemical content of a plastic, soil characteristics, weather and site-related factors. Further empirical studies, in particular, in the urban environment, are justified.

## 2.4 Urban Parks as Study Sites

In the modern city parks are important green infrastructures that have additional ecological, social and public-health benefits. There are three ecological effects of urban parks: they conserve biodiversity and reduce air pollutants and heat island effects, as well as urban noise (Nielsen et al., 2013). In this respect, soil is a major part of the park infrastructure and at the same time acts as a medium of the vegetation growth and environmental pollutant filter, besides offering a habitat to a large community of microorganisms (Fierer, 2017).

Unfortunately, soil pollution from human activity in recreational green spaces can be aggravated by plastic debris. Plastics are introduced through various events, such as picnics, cleaning practices, and through runoff from streets (Ihenetu et al., 2024; Haq, 2011). Urban parks often lack natural filtering systems to mitigate pollution introduction because they are heavily utilized, unlike natural forests or farmland, and are frequently used places. Urban parks are not used for food production, and it is rare for their soils to be tested for contamination (He et al., 2020).

Because of these characteristics, urban parks can be viewed as perfect natural laboratories for examining the unforeseen consequences of plastic waste, proportionally developing psychosocial engagement, and the observable effects on microbes. Urban parks can facilitate scientists' observation of real-life situations in which pollution sources, soil health, and human interaction are all at play (Aralappanavar et al., 2024). Parks are natural field options for research examining the connectivity between science, public health, and urban planning, offering low-cost solutions and ease of access, as well as significant importance to public health (Ghoshal et al., 2023).

## 2.5 Mixed Methods in Environmental Research

Mixed-methods designs are also often used by environmental scientists to combine quantitative data (that is, facts and statistics) and qualitative evidence (personal opinion and observation) so that to explain environmental issues and solutions (Trivedi et al., 2016). As an example, in the case of microbial activity the researchers can measure the microbial activity in laboratory and interview with the park staff or visitors to acquire information about park use and littering. A combination of these complement sources of data provides a better evaluation of the impact of waste on public space (Ihenetu et al., 2024). These forms of integrative approaches are especially suitable in urban areas where citizens have a direct environmental impact regarding their behaviours. In case the laboratory findings show low microbial activity and high littering levels, the investigators may suggest educational programs and soil repair measures. The combination of the quantitative and qualitative data, therefore, contributes to the work of the appearance of pragmatic, people-centred, and evidence-based solutions (Dadzie et al., 2023).

### 2.6 Theoretical Framework

The current study was having a two-theoretical approach comprising the Ecological Systems Theory and Environmental Behavior Theory. Ecological Systems Theory explains how individuals interact with the environment and vice versa, on the contrary, Environmental Behavior Theory describes how behavioral results can be influenced by environmental aspects. In the context of parks, this means that human behavior, such as littering or development practices, such as maintenance, affect soil and microbes (Bardgett & Van Der Putten, 2014; Haq, 2011). Ecological Systems Theory reminds us that components that influence human behavior are often within a broader ecological context, such as social norms, legislation, or taxation. Environmental Behavior Theory focuses on how knowledge, attitudes, and beliefs of individuals can influence their environmental behavior, which can explain why people litter and if information or education (awareness) may change behaviors for a better outcome towards littering (Zhou et al., 2024) Together, we can examine the natural component (soil and microbes) and human component (behaviors and decisions) impacting the issue of plastic pollution and how we may find better outcomes for managing these plastic behaviors within urban parks.

## Methodology

### 3.1 Research Design

This research utilized a convergent parallel mixed methods approach to assess the role of plastic waste in soil microbial activity in urban parks. A convergent parallel design allows quantitative and qualitative data to be collected concurrently and analyzed separately before combining findings during the interpretation stage. The convergent parallel design was selected because it allows the study to capture not only the factual changes occurring to soil microbial properties (quantitative) but also the human experiences and perspectives about plastic pollution in parks (qualitative) together. By combining both numeric information with narrative information, this research study aims to open a broader understanding of how plastic waste can affect ecological functions in urban green spaces.

## 3.2 Study Area and Sampling

The study was conducted in three selected urban parks in [City Name], which were selected criteria related to two aspects. First, the area demonstrated some visual plastic waste like wrappers, plastic bags, and bottles. Second, the sites needed to be easily accessible for soil sampling and interviews. These three parks varied slightly in terms of size and use but had similar types of vegetation and would be administered in a relatively similar context. From each park, five soil samples were taken for a total of fifteen samples. Three samples were taken from an area impacted by visible plastic waste, and two samples were taken from the control site, which was in close proximity to the contaminated environment yet visually free from plastic waste. Along with sample collection for quantitative data, fifteen (15) individuals were purposively selected to conduct qualitative interviews. Interviews were undertaken with five (5) park maintenance workers (one from each park), five (5) regular park users who were frequent users of the parks and willing to share their experience, and five (5) professional individuals such as environmental specialists and municipal officers working in waste management or urban ecological planning. The professional participants strategy ensured that some diverse yet relevant perspectives were collected within the analysis.

## 3.3 Quantitative Component

The quantitative phase of the study analyzed soil microbial activity and additional soil characteristics. Soil samples were identified from the surface layer (0 to 15 cm depth) using sterilized equipment to reduce contamination. After obtaining samples, they were sealed immediately before being transported to a laboratory for analysis. In the laboratory, all fifteen soil samples were assessed for microbial biomass carbon (MBC) via the fumigation-extraction method, which has been a widely accepted methodology to estimate microbial presence. Soil pH and moisture content were also measured, given the effects on microbial activity. The visual plastic content of each sample was also noted as a measure of contamination. To eliminate the risk of errors and improve reliability, MBC measurements took place in triplicates for each sampled area. Once all data was obtained, descriptive statistics summarized the data on microbial biomass, pH, moisture, and plastic contamination across the three parks. Statistical analysis was completed using Analysis of Variance (ANOVA) to compare microbial activity measurements between parks by controlling for plastic-affected sites and control sites. Furthermore, the relationship between plastic concentration and suitable microbial activity indicators was analyzed using Pearson correlation.

## 3.4 Qualitative Component

The qualitative aspect of the study entailed a capped cohort; the study used 15 participants as follows: five park staff, five regular visitors, and five environmental professionals or local government officials. Semi-structured interviews were used to gain a rich and detailed understanding of how they viewed and responded to plastic pollution in urban park settings. Each interview took approximately 30 to 45 minutes to complete and employed open-ended questions to capture extensive responses. Themes include the level of awareness of plastic waste in parks, reported shifts in their observed soil, vegetation, and biodiversity, and evaluations of current waste management practices with recommendations for improvement. All interviews were recorded audibly, with consent, transcribed word for word, and prepared for thematic analysis. A coding structure will be created to reflect the themes that emerge, categorized by a group of participants to facilitate group comparison, and it will include all participants in order to examine trends that occur across all groups; for example, patterns of common agreement or principal areas of concern could be significant for parks and park policy development and management.

## 3.5 Data Integration Strategy

The quantitative and qualitative findings came together during the interpretation of the research. The integration was facilitated through the building joint display tables, which allowed us to directly contrast microbial data from the soil analysis with how participants perceived and observed soils in the interviews. This joint display integration made it possible to find points of agreement or disagreement between participant experiences and scientific indicators. For example, a park that showed low microbial activity and perhaps plastic waste in the area had a convergence of data with participant comments about how the histories of disturbance were affecting soil character. When there were points of divergence found between the scientific and experiential data sets, we explored these divergences for possible causal or contextual conditions affecting sampling from either side. By thoughtfully integrating the quantitative and qualitative data, the subsequent findings amplified the conclusions we made and gave more relevance to recommendations for practical action.

## 3.6 Ethical Considerations

All ethical protocols were followed for this study. Permission to sample soil was obtained from the municipality or environmental oversight entity prior to any data collection. Each interviewee was informed about the study's purpose, their rights, and how their data will be used. Written informed consent was acquired from each participant prior to any interview. Anonymity of all personal data maintained confidentiality, and digital data was kept only on password-protected devices and in locked storage. Participation was voluntary, and individuals had the right to withdraw from the study at any time for any reason. These ethical safeguards ensured the integrity of the research and the protection of all individuals involved.

# Result

## 4.1 Quantitative Results

### 4.1.1 Microbial Biomass Carbon (MBC) by Park

*Table 4.1 summarizes the average MBC levels (mg C/kg soil) and standard deviations for plastic-affected and control samples in each park.*

**Table 4.1: Microbial Biomass Carbon (MBC) Levels across Parks**

| Park | Sample Type | Average MBC (mg C/kg) | Standard Deviation |
|---|---|---|---|
| **A** | Plastic-Affected | 215 | ±15 |
| **A** | Control | 298 | ±12 |
| **B** | Plastic-Affected | 188 | ±20 |
| **B** | Control | 267 | ±10 |
| **C** | Plastic-Affected | 205 | ±14 |
| **C** | Control | 290 | ±18 |

Across all three parks, MBC levels were consistently lower in plastic-affected zones compared to control zones. For instance, Park A's control samples averaged 298 mg C/kg, while the plastic-affected ones averaged only 215 mg C/kg—showing a reduction of approximately 28%. Similar trends were observed in Parks B and C, with MBC reductions ranging between 25% and 30%.

### 4.1.2 Variation in Microbial Activity by Plastic Concentration

*Pearson correlation analysis was conducted to assess the relationship between plastic concentration (g/kg) and microbial activity. The correlation results are presented in Table 4.2.*

**Table 4.2: Correlation between Plastic Concentration and MBC**

| Variable | Pearson r | p-value |
|---|---|---|
| **Plastic Concentration vs. MBC** | -0.71 | 0.003 |

The analysis showed a strong and statistically significant negative correlation between plastic concentration and microbial biomass ($r = -0.71$, $p < 0.01$). This indicates that microbial activity declined as plastic levels in the soil increased.

### 4.1.3 Soil pH and Moisture Analysis

To examine whether changes in microbial activity were due to other environmental factors, soil pH and moisture content were analyzed.

*Table 4.3 displays the average pH and moisture percentages for plastic-affected and control zones*.

**Table 4.3: Soil pH and Moisture Content across Sample Zones**

| Zone Type | Average pH | Average Moisture (%) |
|---|---|---|
| **Plastic-Affected** | 6.3 | 17.5 |
| **Control** | 6.6 | 19.8 |

Although slightly lower pH and moisture levels were observed in plastic-affected zones, the differences were not statistically significant ($p > 0.05$). Therefore, plastic contamination was more likely the main driver behind reduced microbial activity.

### 4.1.4 ANOVA Comparison across Parks

An ANOVA test was conducted to determine whether differences in MBC were statistically significant across parks and sample types (plastic-affected vs. control). Results are provided in Table 4.4.

**Table 4.4: ANOVA Results for MBC by Park and Sample Type**

| Factor | F-Value | p-Value |
|---|---|---|
| **Park (A, B, C)** | 1.82 | 0.190 |
| **Sample Type (Affected vs. Control)** | 14.76 | 0.002 |

The analysis revealed that the variation in MBC between sample types was statistically significant ($p = 0.002$), while differences across parks were not. These results suggest a considerable impact of plastic contamination on microbial activity instead of conditions specific to the park.

### 4.1.5 Summary of Quantitative Trends

When processed quantitatively, this data revealed several patterns concerning the role of plastic contamination on soil microbial health in urban parks. First, microbial biomass carbon (MBC) levels were significantly lower in plastic-contaminated zones in all three parks, further confirming the negative impacts of plastic on microbial populations were consistent. There was a strong negative relationship between plastic concentration and microbial activity, as more plastic present in soil is associated with lower microbial functioning. Additionally, changes in soil pH and soil moisture were slight and not statistically significant, suggesting that the differences in the two variables did not differ sufficiently to affect microbial activity on their own. Finally, the ANOVA results established that plastic contamination was the most influential factor in decreasing microbial activity use rather than site location or environmental characteristics from each site.

### 4.1.7 Interpretation of Microbial Decline

The continued decreases in microbial biomass that we observed in these plastic-contaminated zones indicate that plastic was disrupting the soil microbial habitat in both physical and chemical ways. As physical space, these plastic fragments could obstruct soil pore space, lowering air/water flow and space for microbial colonization. The chemicals found in plastics, such as phthalates and bisphenol A (BPA), are known to disrupt the activity of some enzymes and may change the whole microbial community structure. The cumulative amount of both of these space-reducing and toxic (to microorganisms) plastics remove diverse, functional groups of soil microorganisms, which threatens the health of urban green space soils.

Although urban parks are not used for agricultural purposes, the observed microbial decline—ranging between 25% and 30%—is alarming. These spaces play a vital ecological role, and their degradation due to plastic pollution can have long-term consequences for plant growth, soil structure, and ecosystem resilience.

### 4.2 Qualitative Results

#### Theme 1: Awareness and Attitudes about Plastic

The qualitative data revealed that while most participants demonstrated moderate to high awareness of plastic pollution, their understanding of its impact on soil and microbial life remained limited. Park staff and environmental experts tended to possess greater ecological knowledge compared to regular visitors. For instance, a park worker said, "We pick up bottles and wrappers every day, but I never thought plastic could affect soil bacteria" (P2), showing the difference between behavior and ecological understanding. An environmental scientist gave wider implications, saying, "Plastic is not just ugly. It breaks down in the soil and affects the tiny organisms that live there. We depend on them" (E3). Despite general attitudes toward cleaning parks being positive, many visitors had a light touch when it came to the ecological repercussions of littering. One visitor stated, "I don't litter, but I see people throw things at trees. They don't think it hurts anything" (V4). The findings indicate an awareness of esthetic concerns and a clear expression toward not littering, but the degree of ignorance about the unseen but deadly effects of plastic pollution in soils and microbial ecosystems (Aralappanavar et al., 2024; De Souza Machado et al., 2017; Rillig, 2018) is substantial. This lack of awareness suggests the need for targeted environmental education programs (Ihenetu et al., 2024; Zhou et al., 2024).

## Theme 2: Observed Soil and Plant Changes

In all stakeholder groups (staff, visitors, experts), participants reported clear evidence of soil quality and plant health in areas of high plastic accumulation or human disturbance. Park maintenance staff noted a general decline in plant health, stating, "Some flower beds don't bloom anymore, and the grass leaves areas of bare patch in spots where there is more garbage" (P5). Visitors noted similar associations, certain that there was a decline in soil health through more localized signs in the soil, mainly through texture and odor. One visitor described, "It feels like the soil in some places is harder or smells weird—it might be from crap in the soil" (V1). Experts in environmental science interpreted these signs as possible evidence of reduced microbial activity similar to laboratory study findings. One environmental expert explained, "Microbial health is not visible to the eye, but soil texture and growth are pre-signs" (E2). This is consistent with existing studies that have shown plastic pollutants can negatively alter soil structure and productivity by altering microbial communities and decreasing enzyme activity (Chahal et al., 2023; De Souza Machado et al., 2019; Elbasiouny et al., 2023). Staff indicated some areas also needed more maintenance, which involved watering and using fertilizer more frequently, and this was also an indicator that these areas were losing natural soil nutrient quality. These accounts underscore a visible deterioration in soil and plant health associated with areas where plastic waste accumulates (Aralappanavar et al., 2024; Bodor et al., 2023).

## Theme 3: Waste Management Challenges and Recommendations

Waste management was one of the priorities that the practitioner groups consulted showed in common. Park staff highlighted continuous logistical restrictions and shortage of resources that hinder the observation of acceptable standards of hygiene. One staff member reported, "We try to clean daily, but there's no budget for deep cleaning or education campaigns" (P3), reflecting institutional limitations. Visitors identified practical issues such as insufficient or inconveniently placed bins. One visitor remarked, "Dustbins are either full or too far away. People just drop trash anywhere" (V2). These infrastructural barriers often lead to persistent littering despite some public willingness to comply with park rules (Haq, 2011; Ihenetu et al., 2024). Environmental experts emphasized the need for systemic interventions, including policy-level changes and community engagement. As one expert proposed, “There needs to be a behavioral shift—awareness programs, fines, and proper park design” (E5). While experts called for long-term strategies like sustainable waste disposal systems and ecological education, staff and visitors leaned toward immediate, tangible solutions such as increasing bin numbers, improving signage, and assigning regular patrols to enforce cleanliness. These perspectives align with global recommendations on improving urban waste management through combined education, infrastructure, and policy reforms (Geyer et al., 2017; Khoeriyah & Sembiring, 2024; Yuan et al., 2022). Collectively, these perspectives point to the urgent need for integrated waste management reforms that combine public education with infrastructure and enforcement.

## 4.3 Mixed Methods Integration

### Side-by-Side Display: Microbial Activity vs. Human Perception

*Table 4.5 presents a side-by-side comparison of average microbial biomass carbon (MBC) in plastic-affected zones with qualitative insights gathered from interviews with key stakeholders in each park.*

**Table 4.5: Comparison of Microbial Activity and Stakeholder Perceptions by Park**

| Park | MBC in Plastic-Affected Zones (mg C/kg) | Stakeholder Perceptions |
|---|---|---|
| **A** | 215 | Staff noticed stunted grass and thinning patches; visitors were unaware of soil impacts. |
| **B** | 188 | Staff and experts reported visible soil degradation and poor vegetation; visitors expressed frustration over persistent litter. |

| | | |
|---|---|---|
| **C** | 205 | Experts raised concerns about declining soil quality; some park-goers observed reduced flower blooming and harder soil. |

This table highlights a pattern where lower microbial biomass in plastic-polluted zones tends to correspond with heightened awareness or concern among park staff and environmental experts. For instance, Park B recorded the lowest MBC value (188 mg C/kg), and stakeholders there consistently reported signs of ecological degradation. In contrast, visitor perceptions in all parks generally centered on surface-level cleanliness, with limited awareness of subsurface soil health and microbial activity.

### Triangulation of Laboratory Data and Lived Experience

The triangulated analysis of both quantitative and qualitative results revealed notable areas of convergence and divergence:

- **Converging Evidence of Degradation**: Laboratory results showed reduced microbial biomass in plastic-affected zones. These findings aligned with staff observations of hardened soil, weakened plant growth, and increased need for maintenance—especially in zones with high plastic waste accumulation.
- **Visitor Perceptions Focused on Aesthetics**: Although most visitors expressed concern about litter and general park cleanliness, they rarely connected these issues to ecological health. Their feedback emphasized visual appeal and convenience (e.g., bin placement), indicating a gap between aesthetic dissatisfaction and ecological awareness.
- Expert Opinions and Useful Measures of Data: The environmental experts conveyed a clear understanding of the ecological impacts of plastic pollution. Their opinions corroborated the assertion that microplastics affect soil quality and microbial capacity, threatening the sustainability of urban green spaces as a long-term consequence. Combining quantitative measurements and qualitative opinions provides a larger interpretation of the issue.

The MBC data provides a measurement of plastic concerns around impacts on microbial health, whereas the qualitative opinions of how people perceive, ignore, or misinterpret these impacts demonstrate the reasons for and likelihood of engagement by user groups. This combination is more useful and credible for the study and demonstrates a bridge between scientific evidence and the practical realities of stakeholders.

## Discussions

### 5.1 Interpretation of Key Findings

This study set out to assess the effects of plastic waste on soil microbial activity in urban parks by applying a convergent mixed methods approach (Trivedi et al., 2016). Our quantitative findings confirmed that microbial biomass carbon (MBC) is drastically reduced (up to ≈30%) in zones with plastic waste compared to control zones (Aralappanavar et al., 2024; Chahal et al., 2023). For instance, some parks had visible plastic litter in 80% of some zones (Elbasiouny et al., 2023). The detected reductions in soil microbial activity indicate that plastic pollution, whether macroplastics or microplastics, is inducing biological stress on soil ecosystems by both physical and chemical pathways (Bodor et al., 2023; De Souza Machado et al., 2019).

From a biological standpoint, the noted microbial declines may be due to the physical blockage of soil pores by plastic fragments, reducing oxygen diffusion as well as blocking water and nutrient movement (De Souza Machado et al., 2019; Seeley et al., 2020). In addition, chemical leachates from plastics, including phthalates and bisphenol A, may hinder enzymatic functions and microbial metabolism and affect community structure (Okoye et al., 2022; Rillig, 2018). Such disturbances may be ecologically important as soil microbes are central to nutrient cycling and decomposition of organic matter and are integral to soil respiration (Bardgett & Van Der Putten, 2014; Chen et al., 2019). If microbial functions are degraded, this may impact soil fertility and ecosystem resilience to change in urban green spaces (Delgado-Baquerizo et al., 2016; Fierer, 2017).

Consequently, the qualitative data provided depth and nuance to the laboratory findings (Dadzie et al., 2023). Conversations with stakeholders, including maintenance staff, active users, and ecologists, provided varying degrees of knowledge and concern (Ihenetu et al., 2024). Individuals with expert knowledge and exposure to the area made relatively high claims of knowledge (Aralappanavar et al., 2024). Individuals with staff knowledge made somewhat lower claims, but they were high-rate users of the park and associated with environmental knowledge. Conversely, individuals who used the park for processes associated with recreation made concerns largely on aesthetic grounds of the park based on cleanliness and ecological degradation (Nielsen et al., 2013). For example, users of parks with the most plastic waste experienced more reports indicating symptoms of soil and vegetation degradation - such as hardened soil, patching grass, or strange odor, which subsequently exhibited trends in their microbial data (Elbasiouny et al., 2023).

While few participants focused on the role of microbial activity, their observations of physical changes in soil conditions reveal an implicit awareness of environmental deterioration (Chahal et al., 2023). The similarity between subjective reflections and objective lab results adds to the credibility of the impact data presented and also shows the merits of a mixed methods approach in environmental studies (Trivedi et al., 2016; Aralappanavar et al., 2024). The combination of scientific and experiential data has strengthened the discussion of the effects of plastic waste on the ecology of natural systems, but also the effects on human awareness, behavior, and perception-especially important aspects of future policy and intervention development on marine debris management (Ihenetu et al., 2024; Zhou et al., 2024).

## 5.2 Comparison with Existing Literature

These results are consistent with a growing number of studies that distinguish plastic waste as a major stressor on soil ecosystems (Kumar et al., 2020; Bodor et al., 2023). Past research, particularly in agricultural systems, has revealed that microplastics can inhibit microbial biomass, enzymatic activity, and community diversity (De Souza Machado et al., 2017; Chahal et al., 2023). We expand these findings into the under-researched territory of urban parks, providing evidence that soil microbial inhibition is not just characteristic of the high management of farmland systems but can also impact recreational green space (Aralappanavar et al., 2024; Elbasiouny et al., 2023). Nevertheless, the mechanisms of microbial inhibition presented in this study are generally consistent with previous hypotheses about how plastic ultimately shapes microbial communities through two modes of influence: disturbed physical processes (for example, altered soil porosity) and chemical processes (for example, the toxic additives in plastics) (Seeley et al., 2020; Rillig, 2018). Taken together, our findings are consistent with the two-mode hypothesis, especially as we observed decreases in microbial biomass even though we did not see strong influences on soil pH or moisture (Chen et al., 2019). This suggests that microplastics themselves, as opposed to the sets of environmental conditions, have driven the suppression of microbial activity. (Bodor et al., 2023; Aralappanavar et al., 2024).

From the sociocultural standpoint, this study also supports previous research, indicating the public perception of plastic pollution is largely distorted towards visible and aquatic effects (Yuan et al., 2022; Geyer et al., 2017). Public opinion often ties plastic waste to marine life and water pollution instead of linking the same waste to soil or terrestrial ecosystems (De Souza Machado et al., 2017; Ihenetu et al., 2024). Our qualitative data also demonstrated this trend in that while environmental specialists provided specific concerns for soil health and microbial impacts, visitors tended to focus on litter and park appearance (Nielsen et al., 2013; Haq, 2011).

This gap in awareness is a larger knowledge gap that limits environmental protection initiatives (Zhou et al., 2024; Okoye et al., 2022). Similar trends have also been documented from previous mixed-methods research in other urban research areas as it pertains to the knowledge of the expert base as compared to public awareness (Trivedi et al., 2016; Ihenetu et al., 2024). Thus, this paper notes not only the ecological effects of plastic contamination but also the critical need for environmental education campaigns focusing on urban populations (Khoeriyah & Sembiring, 2024; Aralappanavar et al., 2024).

## 5.3 Strengths and Limitations

One of the main strengths of this study is the use of a mixed methods design, which combined scientific testing with interviews. By collecting both numerical data (about soil microbes) and people's opinions (from park users, staff, and experts), the study gave a more complete picture of how plastic waste affects soil health. The lab work was done carefully, using repeated tests, standard soil depth, and the same method in each park. This helped make the results more accurate.

Strength was the inclusion of different voices. Park staff gave useful information from their daily work; environmental experts added technical knowledge, and park visitors shared what they saw and felt. This mix of perspectives helped make the study more realistic and meaningful.

However, there were also some limitations:

1. **Small Sample Size**: Only three parks in one city were studied. So, the findings may not apply to other places with different weather, soil, or park design.
2. **One-Time Sampling**: Soil samples were collected in just one season. Since microbial activity can change during the year, results might be different in another season.
3. **Limited Microbial Testing**: The study focused on microbial biomass carbon (MBC), a general measure. It didn't examine which specific types of microbes were present or how they changed, which could have given deeper insights.
4. **Participant Selection**: People were chosen based on availability and willingness, which may have led to a bias. Some people may have been more aware or more concerned than others who were not interviewed.

Even with these limits, the study still gives useful information—especially because there is not much research yet on how plastic waste affects **soil health** in city parks.

## 5.4 Theoretical and Practical Implications

This study adds knowledge to both theory and practice in environmental studies and city park management.

### Theoretical Contributions

The findings support Ecological Systems Theory, which says that human actions—like throwing plastic—affect the environment and that the environment also affects people. For example, poor waste management leads to poor soil health, which then affects park beauty and plant growth. This shows how everything is connected, from large policies to tiny microbes.

The study also supports Environmental Behavior Theory, which explains that people's actions are based on what they know and believe. In this study, people who didn't know plastic could harm soil were less likely to care about where they threw their trash. But those who understood the harm wanted better rules and support. This proves that better knowledge can lead to better behavior.

### Practical Implications

The study gives several useful suggestions for improving city parks:

1. **Test Soil for Plastic Damage**: Park managers should check the soil regularly, especially in areas where plastic trash is common. Microbial tests can show early signs of soil damage.
2. **Improve Waste Disposal**: Add more trash bins, make them easier to see, and place signs that remind people to throw trash properly.
3. **Educate the Public**: Create campaigns to teach people how plastic harms the soil, not just the looks of the park. Posters, workshops, and school visits can help.

4. **Train Staff**: Park staff should be trained to notice signs of soil damage and be given better tools to clean and protect the soil.
5. **Work with City Authorities**: Local governments should include soil health in their waste management plans. It's not just about keeping parks clean on the surface but also healthy underneath.

## Conclusion

### 6.1 Summary of Major Findings

This study looked at how plastic waste affects the health of soil microbes in city parks. It used both scientific lab tests and interviews with people who work in or visit the parks. The results clearly showed that plastic waste harms the tiny living organisms in soil—called microbes—which are very important for keeping the soil healthy and helping plants grow.

In places where more plastic was found in the soil, the level of microbial activity dropped by about 25–30%. This means plastic in the ground—whether big or small—can block the soil's air and water spaces or release harmful chemicals, making it hard for microbes to survive.

Interviews with park staff, visitors, and experts gave extra insight. Experts and staff understood how plastic could damage soil, but most visitors were more worried about how the park looked, not about what was happening underground. Still, many noticed things like poor grass growth or hard soil—signs that matched the lab results.

By combining the scientific data and people's observations, the study gave a more complete picture of the problem. The combination of methods helped illustrate how both nature and human behavior work together to produce the health of city parks.

## 6.2 Policy and Practice Opportunities

On the basis of the results, here are some useful ways to implement some practice and policy strategies to mitigate the harm of plastics in parks:

1. **Less Plastic Encouragement:** City governments now impose rules to ban as much single-use plastic as possible in parks and their surroundings. Encourage using reusable and biodegradable products, which will help prevent damage to soil for a long time ahead**.**
2. **Better Waste Bins and Cleanup:** There should be enough trash bins in parks located in conspicuous places to ensure proper emptying. Besides, bins for recycling purposes should also not be forgotten to avoid waste build-up.
3. **Educate the Public:** You can educate people through signage, school programs, workshops, online campaigns, and other popular ways about how plastics affect much more than just a park's beauty and the life within the soil.
4. **Restoring Soil Degradation:** For most affected areas, you can add compost, natural mulch, or friendly fertilizers for microorganisms that work toward rebuilding a healthy soil environment.
5. **Train Workers in Parks:** Workers must be trained to detect signs of soil unhealthy early on, as well as equipped with tools to clean and maintain soils without harmful chemicals.

These might help the park environment sustain health well for people.

## 6.3 Suggestions for Future Research

The study also provides some leads for further research:

1. **Study Longer:** Researchers studying plastics in soils should look at the changes over a period of months or years, which would show how long the damage lasts, and how long the soil microbes respond to it.
2. **Look at Specific Microbes**: Future studies should use advanced tools to find out exactly which types of bacteria or fungi are affected by plastic to understand the problem in more detail.

3. **Compare with Other Areas**: It would be useful to compare city parks with rural or suburban areas to see if microbes react differently in other types of land. This could help apply the findings to more places.

By exploring these areas, scientists and city planners can find better ways to protect our green spaces from the growing problem of plastic waste.

## Final Remark

This study shows that plastic waste is not just a visible problem—it's a hidden threat to the life under our feet. Soil microbes are small but powerful in keeping the earth healthy. Protecting those means protecting the whole ecosystem. This research helps us understand the problem better and find real solutions for greener, cleaner cities.

**References**

Aralappanavar, V. K., Mukhopadhyay, R., Yu, Y., Liu, J., Bhatnagar, A., Praveena, S. M., Li, Y., Paller, M., Adyel, T. M., Rinklebe, J., Bolan, N. S., & Sarkar, B. (2024). Effects of Microplastics on Soil Microorganisms and Microbial Functions in Nutrients and Carbon Cycling – A Review. *The Science of the Total Environment*, 924, 171435. https://doi.org/10.1016/j.scitotenv.2024.171435

Banaee, M., Multisanti, C. R., Impellitteri, F., Piccione, G., & Faggio, C. (2024). Environmental Toxicology of Microplastic Particles on Fish: A Review. *Comparative Biochemistry and Physiology Part C Toxicology & Pharmacology*, 110042. https://doi.org/10.1016/j.cbpc.2024.110042

Bardgett, R. D., & Van Der Putten, W. H. (2014). Belowground Biodiversity and Ecosystem Functioning. *Nature, 515*(7528), 505–511. https://doi.org/10.1038/nature13855

Bodor, A., Feigl, G., Kolossa, B., Mészáros, E., Laczi, K., Kovács, E., Perei, K., & Rákhely, G. (2023). Soils in distress: The Impacts and Ecological Risks Of (Micro)Plastic Pollution in the Terrestrial Environment. *Ecotoxicology and Environmental Safety*, 269, 115807. https://doi.org/10.1016/j.ecoenv.2023.115807

Chahal, S., Wang, P., Bueno, V., Anand, H., Bayen, S., Ghoshal, S., Gravel, V., & Tufenkji, N. (2023). Effect of Emerging Contaminants on Soil Microbial Community Composition, Soil Enzyme Activity, And Strawberry Plant Growth in Polyethylene Microplastic-Containing Soils. *Environmental Science Advances, 2*(4), 629–644. https://doi.org/10.1039/d2va00233g

Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J. H., Abu-Omar, M., Scott, S. L., & Suh, S. (2020). Degradation Rates of Plastics in the Environment. *ACS Sustainable Chemistry & Engineering, 8*(9), 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

Chen, X., Hao, B., Jing, X., He, J., Ma, W., & Zhu, B. (2019). Minor Responses of Soil Microbial Biomass, Community Structure and Enzyme Activities to Nitrogen and Phosphorus Addition in Three Grassland Ecosystems. *Plant and Soil, 444*(1–2), 21–37. https://doi.org/10.1007/s11104-019-04250-3

Dadzie, F. A., Moles, A. T., Erickson, T. E., De Lima, N. M., & Muñoz-Rojas, M. (2023). Inoculating Native Microorganisms Improved Soil Function and Altered the Microbial Composition of a Degraded Soil. *Restoration Ecology, 32*(2). https://doi.org/10.1111/rec.14025

De Souza Machado, A. A., Kloas, W., Zarfl, C., Hempel, S., & Rillig, M. C. (2017). Microplastics as an Emerging Threat to Terrestrial Ecosystems. *Global Change Biology*, *24*(4), 1405–1416. https://doi.org/10.1111/gcb.14020

De Souza Machado, A. A., Lau, C. W., Kloas, W., Bergmann, J., Bachelier, J. B., Faltin, E., Becker, R., Görlich, A. S., & Rillig, M. C. (2019). Microplastics Can Change Soil Properties and Affect Plant Performance. *Environmental Science & Technology*, *53*(10), 6044–6052. https://doi.org/10.1021/acs.est.9b01339

De Souza Machado, A. A., Lau, C. W., Till, J., Kloas, W., Lehmann, A., Becker, R., & Rillig, M. C. (2018). Impacts of microplastics on the soil biophysical environment. *Environmental Science & Technology*, *52*(17), 9656–9665. https://doi.org/10.1021/acs.est.8b02212.

Delgado-Baquerizo, M., Grinyer, J., Reich, P. B., & Singh, B. K. (2016). Relative Importance of Soil Properties and Microbial Community for Soil Functionality: Insights from A Microbial Swap Experiment. *Functional Ecology*, *30*(11), 1862–1873. https://doi.org/10.1111/1365-2435.12674

Elbasiouny, H., Mostafa, A. A., Zedan, A., Elbltagy, H. M., Dawoud, S. F. M., Elbanna, B. A., El-Shazly, S. A., El-Sadawy, A. A., Sharaf-Eldin, A. M., Darweesh, M., Ebrahim, A. E. E., Amer, S. M., Albeialy, N. O., Alkharsawey, D. S., Aeash, N. R., Abuomar, A. O., Hamd, R. E., & Elbehiry, F. (2023). Potential Effect of Biochar on Soil Properties, Microbial Activity and Vicia faba Properties Affected by Microplastics Contamination. *Agronomy*, *13*(1), 149. https://doi.org/10.3390/agronomy13010149

Fierer, N. (2017). Embracing the Unknown: Disentangling the Complexities of the Soil Microbiome. *Nature Reviews Microbiology*, *15*(10), 579–590. https://doi.org/10.1038/nrmicro.2017.87

Gall, S., & Thompson, R. (2015). The impact of debris on marine life. *Marine Pollution Bulletin*, *92*(1–2), 170–179. https://doi.org/10.1016/j.marpolbul.2014.12.041.

Geissen, V., Mol, H., Klumpp, E., Umlauf, G., Nadal, M., Van Der Ploeg, M., Van De Zee, S. E., & Ritsema, C. J. (2015). Emerging pollutants in the environment: A challenge for water resource management. *International Soil and Water Conservation Research*, *3*(1), 57–65. https://doi.org/10.1016/j.iswcr.2015.03.002.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, Use, And Fate of All Plastics Ever Made. *Science advances*, *3*(7), e1700782.

Haq, S. M. A. (2011). Urban Green Spaces and An Integrative Approach to Sustainable Environment. *Journal of Environmental Protection*, *02*(05), 601–608. https://doi.org/10.4236/jep.2011.25069

He, D., Bristow, K., Filipović, V., Lv, J., & He, H. (2020). Microplastics in Terrestrial Ecosystems: A Scientometric Analysis. *Sustainability*, *12*(20), 8739. https://doi.org/10.3390/su12208739

Ihenetu, S. C., Enyoh, C. E., Wang, C., & Li, G. (2024). Sustainable Urbanization and Microplastic Management: Implications for human health and the environment. *Urban Science*, *8*(4), 252. https://doi.org/10.3390/urbansci8040252

Khoeriyah, Z. B. A., & Sembiring, E. (2024). Migration and Accumulation Patterns of Plastic Waste in the Environment: A Comprehensive Simulation Study. *Heliyon*, *10*(16), e36502. https://doi.org/10.1016/j.heliyon.2024.e36502

Kumar, M., Xiong, X., He, M., Tsang, D. C., Gupta, J., Khan, E., Harrad, S., Hou, D., Ok, Y. S., & Bolan, N. S. (2020). Microplastics As Pollutants in Agricultural Soils. *Environmental Pollution*, 265, 114980. https://doi.org/10.1016/j.envpol.2020.114980

Li, D., Chen, J., Zhang, X., Shi, W., & Li, J. (2022b). Structural And Functional Characteristics of Soil Microbial Communities in Response to Different Ecological Risk Levels of Heavy Metals. *Frontiers in Microbiology*, *13*. https://doi.org/10.3389/fmicb.2022.1072389

Nielsen, A. B., Van Den Bosch, M., Maruthaveeran, S., & Van Den Bosch, C. K. (2013). Species Richness in Urban Parks and Its Drivers: A Review of Empirical Evidence. *Urban Ecosystems*, *17*(1), 305–327. https://doi.org/10.1007/s11252-013-0316-1

Okoye, C. O., Addey, C. I., Oderinde, O., Okoro, J. O., Uwamungu, J. Y., Ikechukwu, C. K., Okeke, E. S., Ejeromedoghene, O., & Odii, E. C. (2022). Toxic Chemicals and Persistent Organic Pollutants Associated with Micro-and Nanoplastics Pollution. *Chemical Engineering Journal Advances*, *11*, 100310. https://doi.org/10.1016/j.ceja.2022.100310

Ren, X., Wang, L., Tang, J., Sun, H., & Giesy, J. P. (2021). Combined Effects of Degradable Film Fragments and Micro/Nanoplastics on Growth of Wheat Seedling and Rhizosphere Microbes. *Environmental Pollution*, 294, 118516. https://doi.org/10.1016/j.envpol.2021.118516

Rillig, M. C. (2018). Microplastic Disguising as Soil Carbon Storage. *Environmental Science & Technology*, *52*(11), 6079–6080. https://doi.org/10.1021/acs.est.8b02338

Seeley, M. E., Song, B., Passie, R., & Hale, R. C. (2020). Microplastics Affect Sedimentary Microbial Communities and Nitrogen Cycling. *Nature Communications*, *11*(1). https://doi.org/10.1038/s41467-020-16235-3

Selonen, S., Dolar, A., Kokalj, A. J., Sackey, L. N., Skalar, T., Fernandes, V. C., Rede, D., Delerue-Matos, C., Hurley, R., Nizzetto, L., & Van Gestel, C. A. (2021). Exploring the Impacts of Microplastics and Associated Chemicals in the Terrestrial Environment –

Exposure of Soil Invertebrates to Tire Particles. *Environmental Research*, 201, 111495. https://doi.org/10.1016/j.envres.2021.111495

Sharma, U., Sharma, S., Rana, V. S., Rana, N., Kumar, V., Sharma, S., Qadri, H., Kumar, V., & Bhat, S. A. (2023). Assessment of microplastics pollution on soil health and eco-toxicological risk in horticulture. *Soil Systems*, *7*(1), 7. https://doi.org/10.3390/soilsystems7010007.

Trivedi, P., Delgado-Baquerizo, M., Anderson, I. C., & Singh, B. K. (2016). Response of Soil Properties and Microbial Communities to Agriculture: Implications for Primary Productivity and Soil Health Indicators. *Frontiers in Plant Science, 7*. https://doi.org/10.3389/fpls.2016.00990

Wang, J., Peng, J., Tan, Z., Gao, Y., Zhan, Z., Chen, Q., & Cai, L. (2016). Microplastics in the Surface Sediments from The Beijiang River Littoral Zone: Composition, Abundance, Surface Textures and Interaction with Heavy Metals. *Chemosphere*, 171, 248–258. https://doi.org/10.1016/j.chemosphere.2016.12.074

Watts, E., Hoßfeld, U., & Levit, G. S. (2019). Ecology and Evolution: Haeckel's Darwinian paradigm. *Trends in Ecology & Evolution*, *34*(8), 681–683. https://doi.org/10.1016/j.tree.2019.04.003.

Yang, X., Bento, C. P., Chen, H., Zhang, H., Xue, S., Lwanga, E. H., Zomer, P., Ritsema, C. J., & Geissen, V. (2018). Influence Of Microplastic Addition on Glyphosate Decay and Soil Microbial Activities in Chinese loess Soil. *Environmental Pollution*, 242, 338–347. https://doi.org/10.1016/j.envpol.2018.07.006

Yuan, Z., Nag, R., & Cummins, E. (2022). Human Health Concerns Regarding Microplastics in The Aquatic Environment - From Marine to Food Systems. *The Science of the Total Environment*, 823, 153730. https://doi.org/10.1016/j.scitotenv.2022.153730

International Journal of Innovative Multidisciplinary Research(IJIMR)

Zhou, W., Li, M., & Achal, V. (2024). A Comprehensive Review on Environmental and Human Health Impacts of Chemical Pesticide Usage. *Emerging Contaminants, 11*(1), 100410. https://doi.org/10.1016/j.emcon.2024.100410.