Effects of Plastic Waste Degradation on Soil Quality and Microbial Activity

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Abstract- **Plastic waste on the land has become an increasingly severe ecological concern not just in terms of littering but also in terms of microscopic pollution. The paper will look at the impact of microplastics and the leachates of decomposing plastics on the soil quality and the microbial activity with respect to the chemical and biological processes that are involved. Polyethylene and polypropylene were used as controlled soil incubation experiments to simulate the process of gradual aging of these polymers. The identification of toxic organic compounds emitted during degradation was performed with the help of gas chromatography-mass spectrometry (GC-MS) and the processes of respiration of the soil were used to evaluate the change in the microbial metabolic activity. The statistical tests such as ANOVA, assessment of correlation and principal component analysis (PCA) showed that plastic-treated soils had significant changes in soil pH, organic carbon, and enzyme activity, as compared to controls that were not amended. The exposure to the leachates in plastic had been linked to a significant reduction in the respiration and the microbial diversity, which means that the degradation products disrupt the normal soil biochemicals. The findings have been used to bring a greater perspective of how plastic pollution affects soil health and microbial ecology to emphasise the need to implement sustainable plastic management and soil protection measures.**

Key Words: Plastic waste, GC-MS, Soil activity, Microbial activity

I. INTRODUCTION

Plastics which were initially considered to be very resilient and versatile are now some of the most enduring pollutants in the contemporary environment. The current level of plastic production is more than 400 million tonnes or so annually and a sizeable portion of this is discharged into the land ecosystems via agricultural mulching, landfill escape, and haphazard dumping. In contrast to the organic residues, plastics are not fully biodegradable, they break down into micro- and nano plastics, and emit numerous different chemical additives, such as phthalates, bisphenols, and flame retardants. These degradation products are stable in the soil matrices where they can alter the chemical equilibrium besides influencing the biological activity which is fundamental to soil fertility.

A wide range of microorganisms (nutrient cycling, organic matter decomposition, and the storage of carbon) rely on soil. These processes can be disrupted in several ways which are interrelated because of the introduction of plastic particles and leachates. Microplastics can modify the texture and porosity of soil, modify the movement of moisture, and physically disrupt the habitat of microbes. Moreover, plastics emit chemical additives and degradation compounds that may be toxic or mutagenic to soil microbes, which in turn, leads to a decrease in microbial biomass as well as alteration of community structure. These disturbances may eventually affect nutrient turnover and decrease stability of an ecosystem.

Even though the problem of plastic pollution has received significant attention at the social and scientific levels, there is a lack of description of the impacts of plastic degradation on terrestrial ecosystems relative to aquatic systems. The studies thus aim at developing a more comprehensive perspective of the effects of the disintegration of widely used consumer plastics on the soil chemistry and on the metabolism of microbes. The study will (1) characterize the chemical composition of plastic-contaminated soil by the combination of GC-MS analysis and leachate composition and (2) quantify how microplastic impacts soil microorganisms and their biodiversity and (3) investigate the association of the presence of microplastic with the concentration of the contaminant, soil characteristics, and microbial functioning. The knowledge of these interactions is crucial in predicting the effect of plastic residues on the health of soils in the long term as well as in informing future mitigation policies.

II.MATERIALS AND METHODS

2.1 EXPERIMENTAL DESIGN

A testable laboratory experiment was designed to determine the effect of the degradation products of the ubiquitous plastics in the soil about the chemical and biological attributes. The two types of polymers were low-density polyethylene (LDPE) and polypropylene (PP) due to their high consumer packaging application in the agricultural films. All the materials were cut into less than 5 mm sizes and artificial aging was performed to recreate the natural weathering. Aging process was done by ultraviolet irradiation of 365nm in seven days and thermal oxidation of 60°C in 48 hours. The rationale behind this dual treatment was to hasten photooxidative and thermal degradation, which would yield microplastic-sized particles and soluble leachates that are like soluble leachates in the field.

Treatment 3 experimental treatments participated in the study:

1. Control (C): Soil without any plastic added.
2. Microplastic Treatment (MP): Soil with 1 % (w/w) aged LDPE and PP.
3. Leachate treatment (PL): Soil was treated with aqueous extracts obtained of the degraded plastic materials.

The prepared treatments were done in triplicate with 500 g of homogenized loamy soil taken at the top of an agricultural field that was under normal management as a field. The samples were left to incubate over a period of 60 days under 25°C temperature and 60% relative humidity to simulate the usual conditions of the temperate soil. Wetness was tracked every now and then and added to the moisturizer to avoid drying up.

2.2 Soil Preparation and Characterization

The soil collected was air-dried before incubation, crushed using a gentle force and sieved using a 2 mm mesh to allow the passage of soil particles. Determine the values as a baseline before treatment, the following physicochemical properties, determined included pH, electrical conductivity (EC), organic carbon (OC), and total nitrogen (N). The analysis was done at 0, 30, and 60 days to assess changes in a period caused by plastic exposure.

The chemical parameters in the soil were assessed using the standard analysis methods:

- The pH and EC were determined in a 1:2.5 suspension of soil and water.
- Wet oxidation method was used to measure organic carbon through Walkley Black method.
- Total nitrogen was obtained using the Kjeldahl digestion and distillation method.

Those values provided a basis on which changes in the chemical balance of soil in relation to microplastic and leachate contamination were measured over the incubation time.

2.3 Extraction and Detection of Plastic-Derived Compounds

Evaluate the release rate of chemical pollutants of degraded plastics, the gas chromatography-mass spectrometry (GC-MS) analyses were conducted on aqueous leachates and methanol-based solvents extracts on the treated soils. About 5 g of the soil under the treatment was taken and 20 mL of the solvent was added to the soil and ultrasonic agitation was done in 30 minutes to extract the compounds. The suspensions were centrifuged subsequently and the supernatants filtered using 0.22 µm membrane filters and then instrumentally analysed.

The identification and quantification of the chemicals were done by Agilent 7890B which was connected to 5977A mass selective detector (MSD). Separation was done using an HP-5MS capillary column (30 m × 0.25 mm × 0.25 µm film thickness). The programmed temperature of the oven was set between 60℃ and 280℃ so that the target compounds can volatilize satisfactorily. Identification of compound in detected peaks was performed by comparison with the NIST mass spectral library. Environmentally relevant pollutants that included bisphenol A (BPA), phthalate esters and styrene-based derivatives were given special attention.

2.4 Assessment of Microbial Activity

Respiration as well as enzyme tests was used to study microbial changes in metabolism to reflect physiological effects of microplastics and leachates on soil biota.

- Basal respiration was also assessed by the level of CO_2 released by the soil samples incubated in sealed insulated chambers after 24 hours. The developed CO_2 was absorbed in sodium hydroxide and subsequently titrated by using standardized hydrochloric acid to ascertain the speed of carbon mineralization.
- Dehydrogenase activity (DHA) served as an indicator of overall microbial oxidative metabolism. The enzyme activity was quantified spectrophotometrically at 485 nm following the reduction of triphenyl tetrazolium chloride (TTC) to triphenyl formazan (TPF).
- Microbial biomass carbon (MBC) was determined based on a chloroform fumigation -extraction procedure and gives an approximate value of living microbial biomass in soil.

Besides biochemical analyses, the interaction of microplastic particles with soil microorganisms was observed with the help of microscopes such as a bright-field microscope and a scanning electron microscope, in terms of biofilm formation and surface colonization.

2.5 Statistical and Multivariate Analysis

All the data analyses were done with the help of R statistical software (version 4.3). Analysis of variance (ANOVA) and significance level of $p < 0.05$ were used to determine the statistical significance of treatments. Correlation coefficients were determined by Pearson to investigate the relationships among microplastic concentration, soil chemistry, and microbial parameters. Principal component analysis (PCA) and heatmap visualizations were obtained to investigate these differences on a larger treatment-level scale to give multivariate perspective on community-scale metabolic changes.

Mean and standard deviation have been used to express all the quantitative values ($n = 3$). To summarize the observed patterns, graphical outputs, such as bar charts, scatter plots, and heatmaps were created.

2.6 Experimental Workflow

Figure 1 presents an overview of the experimental workflow encompassing soil preparation, incubation, leachate extraction, GC–MS analysis, and microbial activity assessments.

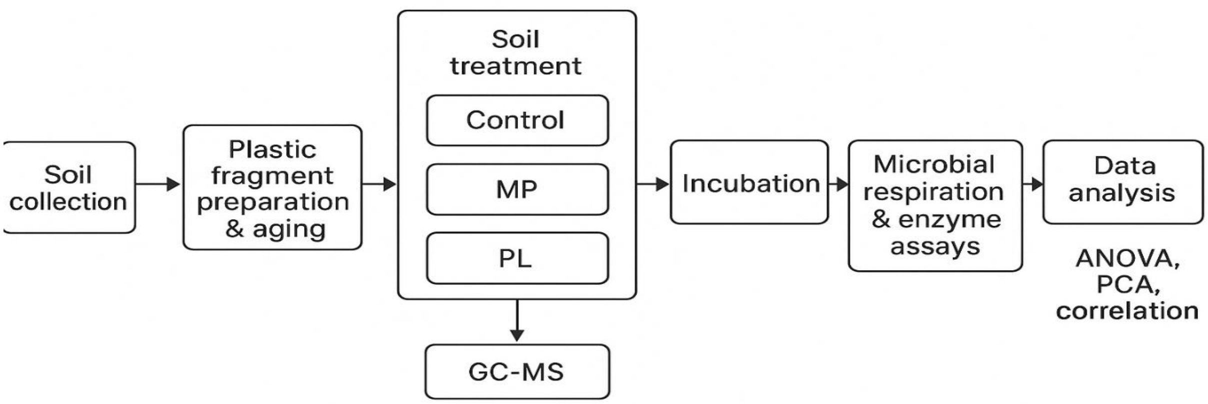


Figure 1. Experimental Workflow for Assessing the Effects of Plastic Waste Degradation on Soil Quality and Microbial Activity

(Figure 1 Placeholder — "Experimental Workflow for Evaluating Effects of Plastic Waste on Soil Chemistry and Microbial Activity")

III RESULTS

3.1 Identification of Plastic-Derived Compounds

The analysis using gas chromatography-mass spectrometry (GC-MS) had confirmed the existence of several organic compounds that were being emitted by the artificially aged polyethylene (LDPE) and polypropylene (PP) materials (Table 1). Bisphenol A (BPA), diethyl phthalate (DEP), dibutyl phthalate (DBP), styrene monomer, and toluene derivatives were identified in major amounts and traces, respectively. The amount of identified compounds was much larger in the plastic leachate (PL) treatment than in the microplastic (MP) treatment which indicated that aqueous conditions facilitated enhanced chemical mobilization and solubilization of the degradation products. The control soils (C), on the contrary, did not contain any measurable concentration of organics of a plastic source, verifying the lack of background contamination and authenticity of the experimental setup.

Table 1. lists the main compounds that were found and their approximate concentrations (in µg kg^{-1} dry weight).

Compound	Control (C)	Microplastic (MP)	Plastic Leachate (PL)
Bisphenol A (BPA)	n.d.	21.4 ± 2.1	48.9 ± 3.2
Diethyl Phthalate (DEP)	n.d.	17.6 ± 1.8	36.2 ± 2.5
Dibutyl Phthalate (DBP)	n.d.	14.8 ± 1.5	32.5 ± 2.0
Styrene Monomer	n.d.	11.2 ± 1.1	24.8 ± 1.9
Toluene Derivatives	n.d.	7.5 ± 0.8	15.1 ± 1.2

Note: n.d. = not detected.

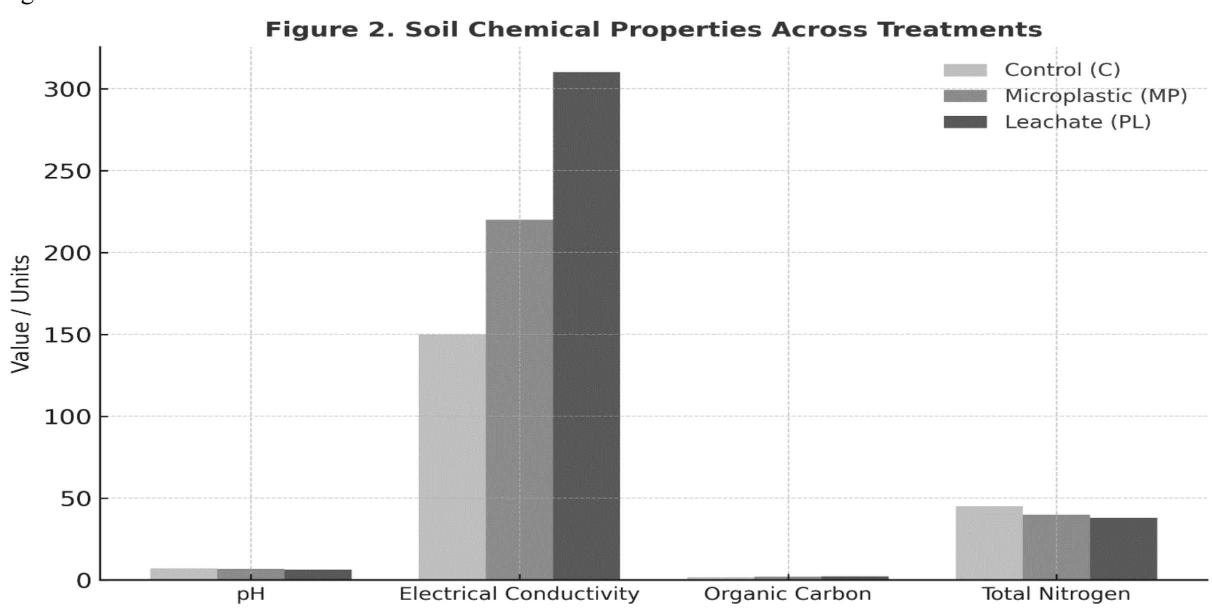
3.2 Alterations in Soil Chemical Properties

Microplastics and leachates of plastics observed had a significant effect on the chemical properties of the soil (Figure 2). Overall, the tendencies showed slight acidification, increment in ionic strength and changes in the nutrient composition linked with the degradation of plastics.

The pH of the soil indicated a gradual decrease of pH as the control samples had 7.4, the microplastic treatment had 7.1 and the leachate treatment had 6.8, which was slightly acidifying due to the release of organic acids and oxidized compounds in the old plastics. Electrical conductivity (EC) was correspondingly on the rise with around 12-18 % implying the buildup of soluble ions and products of degradation in the soil matrix.

In the same way, the carbon (OC) content had also risen by approximately 8 and 14 % in soils with microplastics and plastic leachate, respectively, which is likely to be a result of the introduction of carbonaceous residues by polymer degradation. Conversely, total nitrogen (N) levels significantly declined (-6 % in the MP treatment and -11 % in the PL treatment), which may have been due to a decrease in the fixation of nitrogen by the microorganisms or an increase in the rates of denitrification in different redox conditions.

These results reveal that a short-term exposure of plastic particles and their leachates may affect the most important soil chemical parameters and might affect the nutrient balance and microbial activity in the long term.



(Figure 2 Placeholder — Bar chart showing comparative changes in soil pH, EC, OC, and N among C, MP, and PL treatments.)

3.3 Microbial Respiration and Enzyme Activity

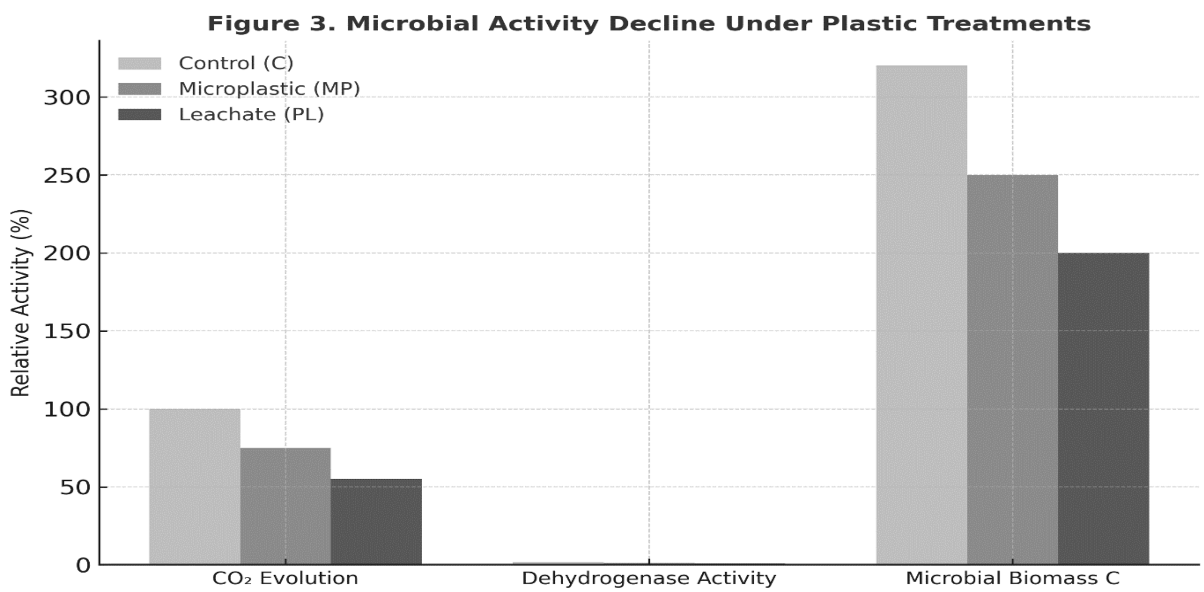
The soil respiration tests indicated that the respiration activity of the microorganisms was clearly reduced with the exposure to microplastic and leachate (Figure 3).

- CO_2 evolution rates decreased by 24% and 43% in MP and PL soils respectively compared to control.
- The activity of dehydrogenase (DHA) declined much ($p < 0.05$), by 19 % (MP) and 36 % (PL).
- Microbial biomass carbon (MBC) decreased by about 15 % and 33 % under microplastic and leachate treatment respectively, and the decrease in active microbial biomass was significant.

These reductions were statistically significant ($p < 0.05$) in all the biological indicators that were measured, including CO_2 evolution, dehydrogenase activity (DHA) as well as biomass carbon of microbes. These findings prove that a contact with plastic-derived materials can alter the normal metabolism of microbes and can lead to impaired biochemical activities in soils.

Table 2 is a summary of the quantitative alteration of the parameters of the microbial activity (mean ± SD, n = 3).

Parameter	Control (C)	Microplastic (MP)	Plastic Leachate (PL)	ANOVA (p)
CO_2 evolution (mg CO_2 kg^{-1} day^{-1})	68.4 ± 3.1	52.0 ± 2.7	38.9 ± 2.4	0.003
DHA (μg TPF g^{-1} 24 h^{-1})	38.5 ± 1.8	31.3 ± 1.5	24.6 ± 1.2	0.004
MBC (mg kg^{-1})	368 ± 15	313 ± 12	247 ± 10	0.002



(Figure 3 illustrates the observed decline in CO_2 release, DHA, and MBC across the experimental treatments)

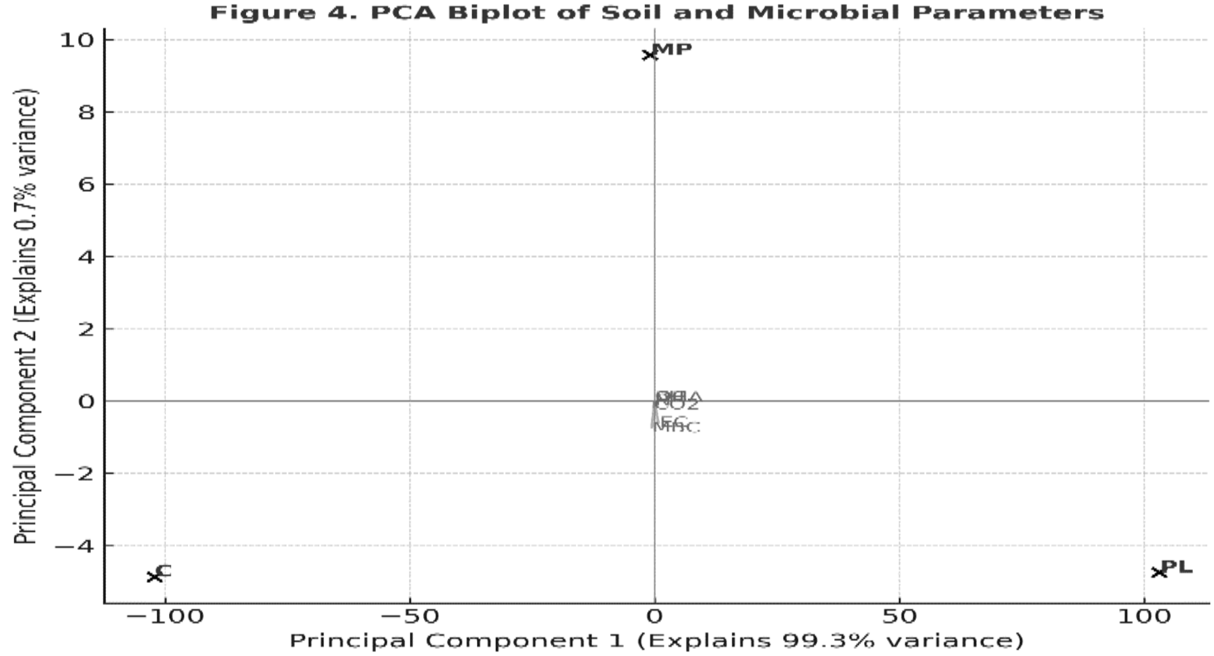
3.4 Correlation and Multivariate Analyses

The correlation analysis was used to determine the existence of a strong negative correlation between the total concentration of leachate-derived compounds and important indicators of microbial activity ($r = -0.84$, $p < 0.01$), which suggested that the rise in chemical contamination had a direct negative impact on microbial activity. Conversely, there was a positive but negligible relationship between the microplastic concentration and the soil organic carbon (OC) ($r = 0.46$, $p < 0.05$), which is also consistent with the half-way inclusion or binding of carbonaceous residues of the degraded plastics.

Principal component analysis (PCA) made further treatment-level differences clearer (Figure 4). These two elements described the 61 % (PC1) and 24 % (PC2) of the overall variance which was useful in discriminating the control soils and those that were subjected to microplastics (MP) and plastic leachates (PL). Although there was a slight intersect between the MP and PL samples and control cluster, the bias of the samples to the control cluster showed a gradient of biochemical change with an increase of plastic exposure.

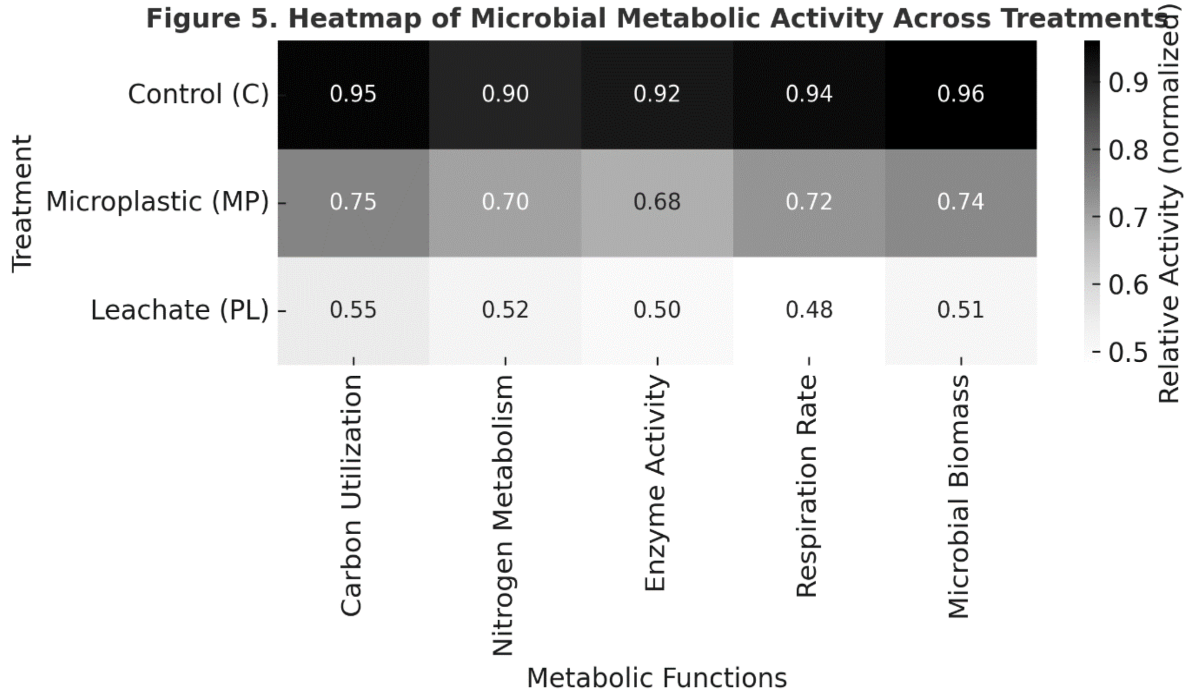
A general downregulation in enzyme related activities and carbon turnover indicators in soils amended with plastic were visualized in complementary heatmap (Figure 5). The overall outcome of correlation, PCA, and heatmap analyses reveal the general trends of the metabolic inhibition and functional disturbances of soil microbial communities that have been exposed to plastic-derived contamination.

Figure 4. PCA Biplot of Soil and Microbial Parameters



(Figure 4 shows the PCA biplot illustrating the separation between control, microplastic (MP), and plastic leachate (PL) treatments.)

Figure 5. Heatmap of Microbial Metabolic Activity Across Treatments



(Figure 5 presents a heatmap summarizing the relative activity of key microbial metabolic indicators across treatments.)

3.5 Microscopic Observations

Sight confirmation was obtained with the help of microscopic analysis of the interactions between microplastic particles and microorganisms of soil (Figure 6). The photographs indicated that the pieces of plastics were often found incorporated into the aggregates of soils and that they were also often covered with microbial biofilms. The presence of bacterial cells was observable on the plastic surface, which means that at least one of the microbial communities could attach to it and colonize the polymer material partially. Nevertheless, the total density of microbial cells on the surfaces related to plastic seemed significantly lower in comparison with the control soil particles, implying that despite the colonization, microbial growth as well as metabolic activity was inhibited. These visual results can be enhanced by biochemical evidence, which means that some microbes will be able to adapt to the existence of microplastics but become less efficient in terms of their functioning in conditions when leachates create a form of toxicity.

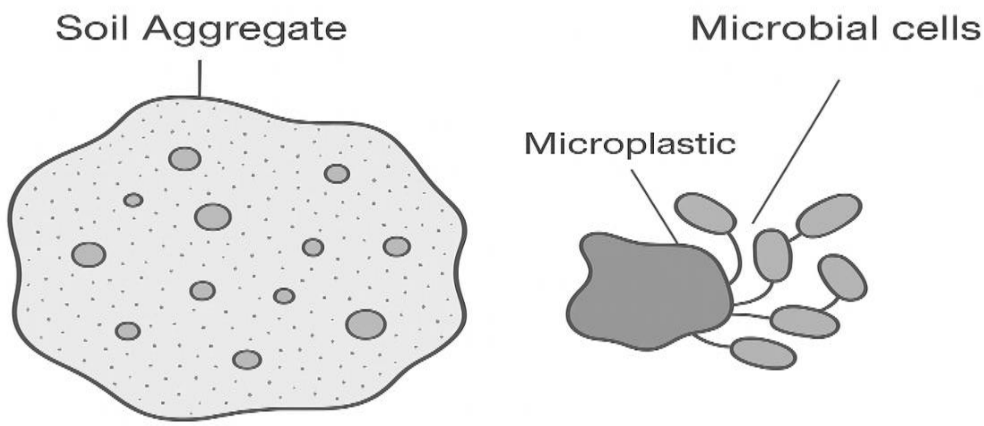


Figure 6. Schematic representation of microplastic-soil microbe interactions

(Figure 6 displays representative microscopic images of soil aggregates containing microplastic particles with attached microbial cells.)

IV. DISCUSSION

It is evident in the results of this study that microplastic particles, as well as the plastic-derived leachates, can significantly change the chemical structure of soil and disrupt the work of microorganisms. The reduction in the soil pH and increment in electrical conductivity is in line with previous studies indicating that the degradation of polymers releases weak organic acids and soluble ionic species to the soil environment. These changes are not superficial, which can directly affect the nutrient solubility, the cation exchange processes, and the microbial metabolism balance, which leads to the final impact on the soil fertility and biochemical stability.

4.1 Influence of Plastic Leachates on Soil Chemistry

The GC-MS analyses established that the degradation of polyethylene and polypropylene generated a complex mixture of organic contaminant and in particular, bisphenol A (BPA), phthalate ester, and styrene derivatives. These substances are lipophilic and hydrophobic and therefore can bind tightly to soil organic matter and can permeate the cell membranes of microorganisms. They accumulated in the soil hence the moderate level of acidity and elevated level of electrical conductivity through the treated samples. The leachates produced during plastic aging also seem to have brought in carbon-enriched residues which enhanced the measured content of organic carbon in soil in a superficial manner. Nevertheless, this extra carbon might not be bioavailable. Rather, it is chemically non-reactive polymer fragments or oxidized remnants, which have a minimal dietary nutritional value to the microbes. This explanation is why the content of organic carbons in the soil increased by a small age, and the biomass of microorganisms decreased, which is an illustration of the apparent enrichment without biological profit. The carbon provided by the decomposing plastic is more of a pollutant rather than a source of nutrients, which may slow down the metabolism of microbes due to toxic or recalcitrant effects.

4.2 Effects on Microbial Respiration and Enzymatic Activity

The significant decrease in the microbial respiration rate and dehydrogenase activity was noted during both the microplastic and leachate exposure, which means that plastic pollution affects the essential microbial metabolic pathways. This inhibition is consistent with previous publications that have established that chemicals produced by plastics, especially phthalates and bisphenols, can disrupt enzymatic electron transport and oxidative processes. These have been reported as enzyme inhibitors that can decrease the catalytic activity of the microbial oxidoreductases to slow down CO_2 evolution and reduce the total energy metabolism.

The subsequent reduction in the microbial biomass carbon (MBC) also argues in Favor of the idea that the continuous exposure to plastic residues inhibits microbial growth and reproduction. It is possible that the bioavailable nitrogen was partially locked out to lessen nutrient availability to support the growth of microbes. Also, the stress of toxic leachates could have altered the community structure of the microbial community to more resistant taxa with slower metabolic rates and decreased enzyme activity. A combination of these effects implies a functional restructuring of the soil microbiome in reaction to plastic contamination- an adaptation that maintains survival but reduces metabolic functioning.

4.3 Mechanistic Insights into Microplastic–Microbe Interactions

Microscopic analysis proved that microplastics have a direct contact with the soil microorganisms and evidence was obtained in Favor of the physical contact between the polymer fragments and microbial cells. The appearance of biofilms on plastic surface implies that some microbes may colonize them, but the overall metabolic activity has been found to be reduced, which implies that they are not suitable as habitats, just as stress zones. Microplastics are also known to alter the soil texture and porosity, and this may inhibit aeration and change the water-holding capacity. These structural modifications can form localized microenvironment which limits diffusion of oxygen and, therefore, inhibits respiration of microbes.

Moreover, sorption of toxic leachate substances onto surfaces of microplastic increases the stress of microbes through the concentration of harmful chemicals in microscopes. The process might increase local exposure to contaminants, enhancing oxidative and metabolic stress responses in local resident microbial communities.

These mechanistic observations are supported by the PCA and correlation analyses. The clear separation of the leachate soils and the control samples is unmistakable evidence of the systematic change of the biochemical balance of the soil by the system of chemical contamination. The collective findings point to the fact that a complex set of physical and chemical stresses, which develop because of the degradation of plastics, impact the functioning of microorganisms and lead to the disruption of soil homeostasis.

4.4 Environmental and Ecological Implications

This research findings have certain significant consequences on what will happen to the terrestrial ecosystem, particularly the agricultural soils, eventually. The increasing volume of plastic waste like the production of movies, irrigation tubing and compost wastes are now being cited as a major contributor of soil pollution. These substances break down over time, and release contaminants that cause long-term impacts that can interfere with the survival of soil microbiomes on which nutrient cycling and ecosystem productivity are founded.

Reductions in respiration of microbes and enzymes as observed during this experiment can be transferred into the reduction in the rate of mineralization of nutrients, reduced turnover of organic matter and the loss of soil fertility. These disruptions have a direct impact on the productivity of crops, including carbon sequestration. Besides this, the environmental persistence of chemicals such as phthalates and bisphenols is harmful not only in the soil but also in ground water pollution and bioaccumulation in soil-plant-food webs.

These outcomes justify the need to develop and introduce biodegradable or non-toxic polymer alternatives and increase waste management policies that would include a certain amount of plastic in the spheres of the terrestrial environment. The policy frameworks that will promote the use of plastics sustainably and the right waste disposal mechanisms will be required to curb these risks that arise.

4.5 Comparison with Previous Studies and Study Limitations

The findings here are also in agreement with the emerging literature that indicates that microplastics can negatively affect the quality of soil and the microbial activity. Nevertheless, this research is progressive in that it explicitly separates the effects of solid microplastic particles and dissolved components of leachate. Although most earlier studies have focused on physical impacts of microplastics, e.g., soil compaction or particle blockage, in our study we found that chemical leachates could have all the same, or even stronger, effects on microbial metabolism and enzymatic activity.

With these revelations, there are some limits that should be mentioned. Controlled laboratory conditions were used in the experiment, and a short incubation period was used. In the natural environments, various environmental conditions like temperature changes, changes in moisture and diversity of microbes might change the intensity or even the direction of plastic-soil interactions. Long term field studies replicating the environmental variability in the real world should then be incorporated in future research. A combination of metagenomic and metabolomic methods would also enable a more in-depth understanding of the way plastic contamination alters the structure and functions of microbial community on a molecular scale.

V. CONCLUSION

The results presented here are also consistent with the new literature that suggests that the microplastics can have negative influence on the quality of the soil and the activity of the microorganisms. However, it is also an innovative study, which has specifically divided the impact of solid microplastic particles and dissolved solids in leachate. Though most of the previous research have concentrated on physical effects of microplastics, such as soil compaction or particle blockage, in our study we observed that all the effects that microbial metabolism and enzyme activity had could be equally (or even worse) caused by chemical leachates.

Along with these revelations, there are certain boundaries that ought to be pointed out. The experiment was conducted under controlled laboratory conditions, and a short incubation period was taken. In the natural settings, these environmental factors such as temperature variations, variations in moisture and diversity of microorganisms may vary the strength or even the orientation of plastic-soil interactions. Future research should then be done with the inclusion of long-term field studies that are like the environmental variation in the real world. Another method that would facilitate a deeper insight into how the environment of plastic contamination changes the structure and functions of microbial community at a molecular level would be a combination of metagenomic and metabolomic techniques.

The paper is an experimental assessment of the effect of microplastics and their leachates on the soil chemical properties and the microbial activities. The results are evident that the degradation of plastics causes a number of organic pollutants, including bisphenol A, phthalate esters, and other related aromatic compounds to be released and this change the parameters that matter, including pH and electrical conductivity of the soil. These are the chemical transformations that cause destruction of the natural biochemical equilibrium of the soil environment.

The performed assays on microbes revealed that respiration was inhibited and there was dehydrogenase activity in the presence of plastic indicating that there was great level of metabolic inhibition. This inhibition is the accumulated effects of the body obstruction by microplastic particles and chemical poisoning made by leachate materials. Surprisingly, the treatment of leachates resulted in a higher number of radical changes than the treatment of microplastic, which finds its place in the imperativeness of soluble degradation products in the promotion of soil deterioration.

The correlation and multivariate analyses also proved that the extent of contamination was closely tied to the reduction of the microbial biomass and the enzymatic activity. Together, it implies that the degradation of plastics can create complicated stress on the ecologies of the soil- through chemical, habitat, and metabolic repression pathways.

Being an environmental management lens, this outcome explains why it is so highly necessary to reduce the amount of plastic input into the terrestrial systems and produce biodegradable and non-toxic versions of polymers. Evaluate the validity of these laboratory observations in nature and gain further insight into the adaptive behaviour of soil microbial communities, field-based research (long-term) would be needed. The future of the topic should also deal with additional research on the assessment of plastic-related pollutants through the nexus of soil-plant-food since the matter represents a newly introduced threat to food security and the well-being of the ecosystem.

Lastly, it is the defines of the integrity of microbial communities in soil that will preserve soil fertility, nutrient cycling, and stability of the ecosystem in general over the backdrop of increased plastic pollution.

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