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Impact Of Polyethylene Terephthalate Microplastic Contamination On Andosol Soil Quality

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Abstract

The increasing volume of single-use plastic bottle waste, particularly that made from Polyethylene Terephthalate (PET), has become a serious environmental issue due to its non-biodegradable nature and potential degradation into microplastics, which pollute and affect the soil's physical and chemical properties as well as plant growth. This study aims to determine the effect of Polyethylene Terephthalate (PET) microplastic contamination on andosol soil quality and spinach (Amaranthus sp.) plant growth. The research was conducted using an experimental method under the framework of a control group and a treatment group. Using 4 reactors, namely one control reactor and 3 treatment reactors with microplastic variations of 10 grams, 15 grams, and 20 grams, where each reactor is given daily watering of 200ml. The results showed that exposure to PET microplastics decreased soil pH and moisture, but increased c-organic and bulk density.

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Introduction

Single-use plastic waste has become a pressing global environmental concern, largely due to the increasing consumption of beverages packaged in *Polyethylene Terephthalate* (PET) bottles. PET, a polyester-based plastic, is widely utilized for its lightweight, strength, and durability, but it has an extremely low biodegradation rate (Kibria et al., 2023). In Indonesia, a significant proportion of ready-to-drink beverages are packaged in PET bottles, contributing substantially to the growing volume of plastic waste (Pandey, 2023).

Environmental degradation of PET results in the formation of microplastics (<5 mm), which can persist in soils and potentially alter their physical, chemical, and biological characteristics (Niyomukiza et al., 2021). Previous studies have reported that microplastics can affect soil structure, porosity, water-holding capacity, and nutrient cycling (Lambert & Wagner, 2017). Such modifications to soil properties may in turn influence plant productivity, including that of important agricultural crops (Chae & An, 2018).

While much of the existing literature has focused on microplastic pollution in aquatic environments and marine ecosystems (Smodlaka Tanković et al., 2015; Wang et al., 2021), relatively few studies have explored their effects on agricultural soils and the implications for crop growth. This knowledge gap is particularly relevant to andosol soils, which are characterized by high porosity, abundant organic matter, and a high cation exchange capacity (Sutiyono et al., 2022). Andosols are among the most fertile soils and are widely used for horticultural production in volcanic regions of Indonesia, yet the potential risks posed by PET microplastic contamination to their quality and agricultural productivity remain poorly understood.

Therefore, the present study aims to evaluate the effects of PET microplastic contamination on the quality of andosol soils and the growth of spinach (*Amaranthus sp.*), focusing on soil physical and chemical parameters as well as key plant growth indicators.

Methods

The research was conducted using an experimental method under the framework of a control group and a treatment group, with the following steps:

2.1. Preparation

The equipment used in this study included pipettes, 100 ml measuring flasks, 3-in-1 soil sensors, ovens, porcelain dishes, dish clamps, analytical scales, sample rings, desiccators, spectrophotometers, 5-liter used gallons, pot stands, plastic measuring cups, and scissors. The materials used in this study were Andosol soil, single-use plastic bottles, spinach seeds, distilled water, 1 N potassium dichromate ($K_2Cr_2O_7$ 1 N), H_2SO_4, and concentrated sulfuric acid.

2.2. Soil Incubation

In the initial stage, disposable plastic bottles that had been manually cut into microplastics measuring <5 mm were mixed into the soil and left in pots for 30 days. Each pot contained 3 kg of andosol soil mixed with PET microplastics in amounts of P1 (10 grams), P2 (15 grams), and P3 (20 grams).

2.3 Spinach Planting

After 30 days of incubation, spinach seeds are planted in the soil, 15 seeds per pot, and left to grow for 30 days (harvest period). Watering is carried out every day at the same time (in the morning) with 200 ml/pot.

2.4 Measurement of Height, Number of Leaves, and Root Length

During the growth period of spinach plants, measurements of plant height and number of leaves were taken every 5, 10, 15, 20, 25, and 30 days, with one representative plant selected from each pot so that measurements from day 5 onwards used the same plant sample. Then, during the harvest period, root length measurements were taken on the same samples as before. Height and root length measurements were taken using a ruler.

2.5 Fresh Weight & Dry Weight Testing of Plants

Fresh weight and dry weight testing of spinach plants was conducted during the harvest period. Fifteen plants per pot were used as samples. Measurements began with weighing the fresh weight of the spinach using digital scales. Record the weighing results before placing the samples in the oven. Dry the material in the oven at a temperature of 100-105 degrees Celsius for 3 to 5 hours. Heat again in the oven for 30 minutes, then let cool in a desiccator and weigh again.

2.6 Soil pH and Moisture Testing

Insert the 3-in-1 instrument into the soil sample (pot) until the silver electrode is completely covered with soil. Wait until the soil pH and moisture readings are stable.

2.7 C-organic testing

Weigh 0.500 grams of soil (with particle size less than 0.5 mm) and pour it into a 100 mL measuring flask. Then, add 5 mL of 1 N K2Cr2O7, followed by shaking, then add 7.5 mL of concentrated H2SO4, shake again, and let it stand for 30 minutes. After that, dilute with distilled water to the 100 mL mark on the volumetric flask and mix the solution thoroughly once more. Let it stand overnight. Measure the absorbance of the clear solution for organic carbon determination using a UV-Vis spectrophotometer calibrated at a wavelength of 561 nm. For comparison purposes, standard solutions of 0 and 250 ppm were prepared by transferring 0 and 5 mL of the 5,000 ppm standard solution into a 100 mL volumetric flask, following the same procedure. Before measuring the sample, the standard solution and blank were measured first.

Organic C calculation was performed:

$$\text{Initial Organic C (\%)} = \text{ppm curve } x \ \frac{\text{extraction mL}}{\text{1000 mL}} \ x \ \frac{\text{sample 100 mg}}{\text{mg}}$$

Test results based on dry weight:

$$\text{Organic C (\%)} = \text{Initial Organic C } x \ \frac{100\%}{(100-\text{ moisture conten})}$$

Where ppm curve is concentration of the sample obtained , and extraction mL as a volume of the flask.

2.8 Bulk Density Testing

Open the ring lid and place the ring containing the soil into the dish. Dry the sample in an oven at 105 degrees Celsius for 24 hours until it reaches a stable weight. To increase the accuracy of the measurement, the dry soil should be placed in a desiccator for about 10 minutes before weighing. Measure the dry weight of the soil (Ms) along with the weight of the ring (Mr) and the dish (Mc).

Next, determine the internal volume of the ring (Vt) and perform the necessary calculations:

$$Db = \frac{Ms}{Vt} = \frac{(Ms + Mr + Mc) - (Mr + Mc)}{Vt}$$

$$Vt = Vs + Vw + Va = \pi r^2 t$$

Where Vs is volume of soil solids, Vw is volume of liquid, Va is volume of soil air. Because a ring is used, Vt is easier to calculate using πr2. Where: r is inner radius of the ring and t is height of the ring.

Results

Andosol soil is a type of soil formed from volcanic ash and often found in mountainous areas. Andosol soil is characterized by its reddish-brown to pitch-black color (Figure 1).

Figure 1. Microplastic Mixing in Andosol Soil

Table 1. Andosol Soil Characteristics Data

Soil Parameters	Method	Result
pH	Elektrokimia	6,9
C-Organic	Walkley & Black	3,34
Specific gravity (grams/cm^3)	Piknometer	1,94
Weight Volume (g/cm^3)	Ring	0,85
Porosity (%)	Calculation	56,18
Water Content (%)	Gravimetry	14,17

Table 2. Results of Andosol Soil Quality Analysis

Soil Parameters	K (Control)	P1 (MP 10 gram)	P2 (MP 15 gram)	P3 (MP 20 gram)
pH	7,5	7	6,5	6
C-Organic	5,49	5,94	6,04	6,3
Soil moisture (%)	60	55	50	43
Bulk Density (gram/cm3)	0,71	0,72	0,73	0,73

Table 3. Plant Weight Measurement Result

Sample	Fresh Weight (grams)	Dry Weight (grams)
K (Control)	2,524	1,401
P1 (MP 10 gram)	2,640	1,537
P2 (MP 15 gram)	2,097	1,211
P3 (MP 20 gram)	2,116	1,189

Table 4. Growth in the number of leaves

Sample	Growth in the number of leaves (sheet) on day:						p-value
	5	10	15	20	25	30	
K (control)	2	3	4	5	7	9	0.911*
P1 (MP 10 gram)	2	3	4	5	8	9	
P2 (MP 15 gram)	2	3	5	6	9	11	
P3 (MP 20 gram)	2	3	5	6	9	11	

*one-way ANOVA test

Table 5. Plant Height Measurement Results

Sample	Plant height growth (cm) on day :						p-value
	5	10	15	20	25	30	
K (control)	2	3.5	5	7	9	14	0,952 *
P1 (MP 10 gram)	2	4	6	7	8	13.5	
P2 (MP 15 gram)	2	4	6	8	11	16.5	
P3 (MP 20 gram)	2	4.3	6	8	10	16.5	

*one-way ANOVA test

Table 6. Root Length Measurement Result

Sample	Root length (cm)
K (control)	8.5
P1 (MP 10 gram)	5
P2 (MP 15 gram)	7
P3 (MP 20 gram)	13

Discussion

Microplastic exposure affects soil pH (Xiang Y et al., 2023). The pH in the treatment reactor after 60 days was lower than that in the control reactor. The higher the concentration of microplastics added, the lower the soil pH value. However, based on soil pH measurements in andosol, all reactors still met the ideal soil pH standards. Ideal soil pH ranges from 6 to 7.8 (SS kekane et al., 2015). Microplastics also have the potential to affect soil organic carbon (Jia K et al 2024). The organic carbon content in the treatment reactor after 60 days was higher than that in the control reactor. The higher the concentration of microplastics applied, the higher the organic carbon value. The moisture content in the treated reactors after 60 days was lower than in the control reactors. The higher the concentration of microplastics applied, the lower the soil moisture content. Meanwhile, bulk density increased by 0.01–0.02 from the control reactors to the treated reactors.

Microplastic contamination can affect changes in soil quality, including pH, organic carbon, moisture, and bulk density. Soil pH is very important to study because pH affects various soil properties, including nutrient availability and microbial activity, which are important for organic matter decomposition, nutrient release, and overall soil health (Mosley et al., 2024). Soil pH also affects plant performance in root growth and nutrient availability (Yalan et al., 2024). Results show that the higher the concentration of microplastics applied, the lower the soil pH (Table 2). This is due to microplastics containing additives that can dissolve into the soil, thereby altering its chemical composition and potentially increasing H+ ion concentration (Nasrin et al., 2022). Low soil pH conditions lead to reduced nutrient availability and hinder the breakdown of organic matter, ultimately resulting in decreased soil fertility. Nutrient ion transport is disrupted, affecting plant absorption and growth (Radulov I et al., 2024). Previous research ((Yibo L et al.,2024) aligns with the results of this study. However, exposure to low-concentration (0.01%) and high-concentration (0.50%) polybutylene adipate terephthalate (PBAT) microplastics actually increased soil pH in Chinese agricultural fields (Liu X et al., 2024).

Microplastics at higher concentrations affect greater organic carbon content (Table 2). This is because microplastics derived from polymeric materials contain carbon, and microplastics in soil can manipulate the natural organic carbon content of the soil, leading to an increase in soil organic carbon levels (Sha Chang et al., 2024). Previous similar studies, consistent with the results of this study, found that polypropylene (PP) microplastics from disposable masks increased organic carbon in peat soil (Mentari AE et al., 2022). However, different soil types yielded different results, with PP microplastics decreasing organic carbon in loamy soil (Khoironi A et al., 2024).

Soil moisture also needs to be considered as it affects plant growth. Inadequate soil moisture can cause stress and reduced productivity (Cahyono BE et al., 2022). The results show that the higher the concentration of microplastics added, the lower the soil moisture (Table 2). These findings are inconsistent with existing theory. PET microplastics have hydrophilic properties that should increase soil moisture. This is further supported by the increasing content of organic carbon, which should make the soil more moist. Similar studies, consistent with the results of this study, show that higher concentrations (1% and 2%) of polypropylene (PP) microplastics result in lower moisture values compared to polyvinyl chloride (PVC) and polyethylene (PE) (Zhi-Chao et al., 2022).

Bulk density affects the ability of soil to retain nutrients that are important for plant health and productivity (Geiss L., 2024). Low soil density allows for greater plant root penetration, thereby enabling better access to water and nutrients (Sharma S et al.,2023). In this study, microplastics increased soil density. The results of this study are not in line with existing theory. The presence of microplastics actually reduced porosity, which in turn reduced bulk density. This is supported by the increased c-organic content, which should result in a decrease in bulk density. A similar study where polyester (PES) microfibers at concentrations of 0.1% and 0.3% did not affect bulk density (Zhang GS et al., 2019). The soil parameters measured in this study are interrelated and interconnected. Based on theory, when organic carbon is high, soil moisture increases but bulk density decreases.

The weight of the plants was measured comprehensively, including the leaves, stems, and roots. Reactors P2 and P3 had lower fresh and dry weights than the control reactor. P1 experienced an increase in both fresh and dry weight compared to the control reactor. Microplastics not only affect the quality of andosol soil but also affect the quality and growth of plants. The results of dry weight and fresh weight of plants in (Table 3) show no root aggressiveness. This is because the characteristic of root aggressiveness is that the fresh weight (total weight) is greater with increasing microplastics, but after drying, the dry weight is smaller than the control. Similar studies have shown different results from this study, where exposure to polystyrene (PS) microplastics resulted in smaller dry weight and fresh weight of plants with increasing concentrations (3% and 5%) in wheat plants (Triticum aestivum L) (Riaz K et al., 2025). For the same type of microplastic, PS 5 and 0.1 μm treatments significantly increased the fresh and dry weights of the above-ground and below-ground parts of cucumber plants, indicating that cucumber plants can withstand stress caused by microplastic pollution by increasing the accumulation of metabolites such as flavonoids and phenolic acids (Liu B et al., 2024).

Measurements from day 5 to day 30 showed a continuous increase in plant height. However, there was no significant difference between treatment groups as the concentration of microplastics increased. Based on the ANOVA test results, a P-value greater than 0.05 indicated that there was no significant difference between the treatment groups and the control group. There were no significant differences in the number of leaves and plant height. This was due to the high plant density in a small container, which resulted in competition for sunlight, water, and essential nutrients. If plants are too densely packed, lower leaves may be shaded by other plants, preventing them from receiving sufficient sunlight for photosynthesis, thereby affecting leaf production. If too many plant roots absorb water and nutrients from the same source, some plants may lack essential nutrients needed for proper growth (Dong T et al., 2016). Previous similar studies, consistent with this research, found that exposure to Low-Density Polyethylene (LDPE) microplastics with an average size of 250 μm at approximately 3% exposure did not affect the number of leaves grown or plant height in kelabat plants on days 40 and 60. However, by day 80, plant height increased in the treatment group compared to the control group after the plants entered the flowering stage (Singh B et al., 2022).

Root length showed that P3 experienced an increase in root length compared to the control. However, there was no effect of microplastic presence on root length for P1 and P2. Microplastics (MPs) also significantly affect plant root growth, with varying effects depending on the type, size, and concentration of microplastics. The response of root characteristics to MPs also varies according to plant species (Cui L et al., 2024). In reactor P3, there was an increase in root length, but the presence of microplastics had no effect on root length for reactors P1 and P2. The impact of microplastics on plants varies depending on the properties of the microplastics and the type of plant. A similar study, consistent with this research, found that higher additions (1% and 2%) of polypropylene (PP) significantly increased root length in Phalaris arundinacea (a perennial grass species) (Xu H et al., 2024). However, with the same type of microplastics as in this study, different results were observed. A 1% concentration of PET inhibited root elongation in rice plants over 15 days (Iswahyudi I et al., 2024).

When plants, especially vegetables, are exposed to microplastics, which are then absorbed by the plants and eventually accumulate in the human body, it can affect human health, such as metabolic disorders, neurotoxicity, and an increased risk of cancer (Rahman A et al., 2021). To minimize the impact of microplastics on human health, the public is advised to properly manage plastic waste, particularly single-use plastic bottles, and reduce their use to decrease the amount of single-use plastic waste generated daily, while adopting an environmentally friendly lifestyle.

Conclusion

Based on the research results and discussion, the authors conclude that exposure to polyethylene terephthalate affects changes in the physical and chemical parameters of andosol soil, specifically lower pH and soil moisture values at higher concentrations, greater bulk density compared to the control, and higher organic carbon content at higher concentrations. Then, the exposure to Polyethylene Terephthalate affects the fresh weight and dry weight of spinach plants. For fresh weight, P2 and P3 are lower than the control, but P1 is higher. The same applies to dry weight. Lastly, the exposure to Polyethylene Terephthalate does not affect the growth of the number of leaves and plant height. Root length is also affected, but only in P3.

Author Contributions

Conceptualization, Dilean Zeva Balistyadhana (DZB), and Eko Hartini (EH); methodology, DZB and EH; validation, DZB; laboratory analysis, DZB; resources, DZB and EH; writing—original draft preparation, DZB; writing—review and editing, EH; visualization, DZB; project administration, EH. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest:

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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