Research Article

Bioremediation Using Microorganisms and Earthworms in Reducing the Impact of Microplastics in Potato Cultivation

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Abstract | Microplastic (MPs), a new pollutant, has been indicated to be contaminant in agricultural soils that affects plant growth. Despite the fact, studies on interaction between MPs-contaminated soils and potato growth involving bioremediation agents are limited. This study investigated the effectiveness of microorganisms ("Mn" brand), earthworms ("Ef"), and two types of organic fertilizers ("SG" – conventional organic fertilizers and "Pa" – natural mineral organic) as an effort to provide healthy potatoes, especially minimal MPs, in achieving the Sustainable Development Goals (SDGs). Seven different treatments were applied: (P0) control – chemicals fertilizer, (P1) chemicals fertilizer + MPs, (P2) chemicals fertilizer + MPs + "Mn," (P3) chemicals fertilizer +MPs + "Ef," (P4) chemicals fertilizer + MPs + "Mn" + "SG" fertilizer, (P5) chemicals fertilizer + MPs + "Ef" + "SG" fertilizer, and (P6) soil with "Pa" brand – natural mineral organic fertilizer. "Pa" is used to find alternatives to replace conventional organic fertilizers contaminated with MPs. This research has limitations because MPs are only in millimeter (mm) size. The observation 100 d after planting showed: (i) a combination treatment of conventional organic fertilizer and earthworm (P5) have improved potato biomass, total chlorophyll, tuber weight, tuber count, and three classes of tuber size significantly compared to other treatments, (ii) organic mineral fertilizer (P6) was unable to support organic potato cultivation, and (iii) MPs in mm size have disrupted potato production. It is recommended for future research as follows: (i) increasing the dose and frequency of application of earthworms and microorganisms, (ii) a combination of earthworms and microorganisms to increase synergy for minimizing the negative impacts of MPs.

Received | June 05, 2025; **Accepted** | July 07, 2025; **Published** | September 12, 2025
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Citation | Setyobudi, R.H., D. Hermayanti, S. Husen, M.P. Garfansa, T.D.N. Subchi, S. Suherman, S. Anwar, I. Iswahyudi, Y. Sincihu, A. Anekawati, M.S. Susanti, M. Anwar, T.A. Pakarti and S.A.A. Putra. 2025. Bioremediation using microorganisms and earthworms in reducing the impact of microplastics in potato cultivation. *Sarhad Journal of Agriculture*, 39 (Special issue 1): 171-184.
DOI | https://dx.doi.org/10.17582/journal.sja/2023/39/s1.171.184
Keywords | Angleworm, Decontamination., *Eisenia fetida*, Emerging pollutants, *Solanum tuberosum*, Sustainable development goals

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Introduction

Microplastics defined as polymer particles smaller than 5 mm have become a global concern due to their significant impacts on the environment and health (Hermayanti *et al*., 2024; Garfansa *et al*., 2024b). They belong to a new group of pollutants resulting from the vast use of plastic due to its durability, flexibility, and low production cost, and its increasing global production has raised significant environmental concerns. The study shows that plastic waste production has increased since the 1950s and is projected to reach 12 000 × 10^6 t by 2050 in the surrounding environment (Yu *et al*., 2023). Being light weight, resistant to chemicals, and able to act as thermal and electrical insulators makes it an indispensable material in various fields. In agriculture, however, plastic remains in the form of microplastics (from this point forward is referred to as MPs) not only disrupt soil structure but also potentially carry harmful chemicals that affect plant health and agricultural productivity (Hasan and Tarannum, 2025).

One of the main challenges regarding MPs is the fragmentation of this material into small particles that now contaminate various ecosystems, including terrestrial, aquatic, and atmospheric environments. In soil, MPs can disrupt physical functions such as soil porosity and water retention capacity critical for plant growth (Lee *et al*., 2022; Wang *et al*., 2020). These disruptions lead to reduced soil quality, hindering plants to access essential resources like water and nutrients (Shi *et al*., 2024). For instance, studies have shown that the presence of MPs can negatively alter soil microbial activity, which in turn affects the microbial communities that support important nutrient cycles, such as nitrogen fixation and carbon cycling (Ma *et al*., 2024). MPs also have the ability to absorb and transport hazardous compounds, including heavy metals, pesticides, and various chemical additives such as antioxidants, plasticizers, and pigments (Zhu *et al*., 2023; Zimmermann *et al*., 2021). When these toxic compounds are released back into the environment or absorbed by plant roots, they can ultimately accumulate in plant tissues and reduce crop productivity. Furthermore, MPs' hydrophobic properties and high surface area allow them to act as a carrier for pathogenic microorganisms, such as *Vibrio* spp., which can further exacerbate plant stress (Li *et al*., 2022). Previous studies have demonstrated that MPs, when contaminated with pathogens, can serve as vectors for disease transmission through soil or irrigation systems, potentially posing a risk to human health through the food chain (Tariq *et al*., 2024). In addition to their toxic effects, MPs can also cause physiological disruptions in plants, such as reduced photosynthetic efficiency and increased oxidative stress, leading to changes in leaf and root morphology (Colzi *et al*., 2022; Kadac-Czapska *et al*., 2024; Pignattelli *et al*., 2020). These disruptions hinder the plant's ability to absorb vital nutrients like nitrogen and phosphorus, further compromising its growth and overall health. Recent studies on the effects of MPs have also explored their impact on animal health, particularly in mammals. Experiments involving rodents have shown that ingestion of MPs can lead to the accumulation of these particles in various organs, including liver and intestines, causing inflammation and oxidative stress (Hermayanti *et al*., 2024; Setyobudi *et al*., 2025; Wang *et al*., 2023). The fact raises further concerns about the potential presence of MPs in crops. Studies have identified MPs particles in potato tubers, which suggest that these particles might also accumulate in edible plant tissues, posing potential risks to human health through consumption (Aydin *et al*., 2023; Ganfansa *et al*., 2024b; Saati *et al*., 2025). This connection between animal and plant contamination highlights the broader implications of microplastics entering the food chain. Just as MPs can transport hazardous substances in mammals, they may similarly act as carriers for toxic compounds in plants, which could be transferred to humans through the consumption of contaminated crops (Ganfansa *et al*., 2024b; Gea *et al*., 2020; Hermayanti *et al*., 2024).

The presence of MPs specifically in potato crops (*Solanum tuberosum* L.) has become a growing concern, as these particles can enter the agricultural system at various stages. From seedling production where plastic containers or bags are often used (Setyobudi and Shazma, 2024) to the cultivation process where MPs can be introduced through plastic-based mulching materials (Brodhagen *et al*., 2017; Huang *et al*., 2020; Luo *et al*., 2024) or contaminated organic fertilizers (Iswahyudi *et al*., 2023; Setyobudi *et al*., 2024a, b), these particles accumulate in the soil. Additionally, post-harvest activities such as the handling and packaging of potatoes using plastic materials may further contribute to the contamination of the crop. Moreover, rainwater and irrigation water in potato cultivation have been contaminated with

MPs (Garfansa *et al*., 2024a; Setyobudi *et al*., 2024a, b). Therefore, research aimed at understanding the impacts of MPs on soil and plants, particularly in contaminated agricultural systems, has become a critical priority in the development of strategies for global food production sustainability in order to achieve the Sustainable Development Goals (SDGs), namely the Goal 2: Zero hunger; the Goal 3: Good health and well-being, and the Goal 12: Responsible consumption and production (UNDP, 2025).

While extensive research has documented the detrimental effects of microplastics on both ecosystems and human health, critical gaps remain in understanding their interactions within agricultural systems, particularly regarding effective remediation strategies. Several key studies have illuminated this issue: (i) Experimental trials exposing rodents to MPs demonstrated significant negative impacts, including reduced survival rates and increased oxidative stress in vital organs (Ganfansa *et al*., 2024b; Hermayanti *et al*., 2024; Setyobudi *et al*., 2025); (ii) Comprehensive identification of microplastic particles in potato tubers has raised serious concerns about their entry into the human food chain (Aydin *et al*., 2023; Setyobudi *et al*., 2024a, b, c); and (iii) Investigations revealing the pervasive presence of microplastics in water, soil, organic fertilizers, potato plants, and potato byproduct within potato cultivation systems (Setyobudi *et al*., 2024a, b, c). Despite these important findings, effective management strategies for microplastic-contaminated agricultural environments remain elusive. Current research has predominantly focused on toxicological assessments and contaminant transport mechanisms, while sustainable remediation approaches have received comparatively limited attention.

Amobonye *et al*. (2021), Iswahyudi *et al*. (2025a), Li *et al*. (2023), Meng *et al*. (2023), Shi *et al*. (2024), Yang *et al*. (2023b) have reported their research on MPs bioremediation efforts with earthworms (*Eisenia fetida* Savigny, 1826). However, previous research has not been directed at potato cultivation, which is relatively easily exposed to MPs because potatoes are buried in the soil. Likewise, it has not been done with a combination of organic fertilizers, even though organic materials are needed for earthworm feed. Nevertheless, organic fertilizers are one of the sources of MPs pollution (Iswahyudi *et al*., 2024, 2025b; Setyobudi *et al*., 2024b, c; Wahyudi *et al*., 2025).

Thapliyal *et al*. (2024) stated that the potential for bioremediation of MPs is also in mixed/cocktail organisms, including rhizosphere microorganisms. Playing an essential role in the MPs degradation process, it is potential to utilize them as a carbon source as MPs are synthetic polymers consisting of carbon and hydrogen. Various studies have reported the colonization of microbial communities such as bacteria, archaea, fungi, algae, diatoms, viruses, and protozoa in the form of biofilms on the surface of MPs known as the "plastisphere" (Yang *et al*., 2023a). The microbial community sequentially degrades MPs through enzymatic hydrolysis– breaking down the polymer into oligomers, dimers, and monomers which are then assimilated as the sole source of carbon and energy, and eventually undergoes complete mineralization into carbon dioxide and water (Thapliyal *et al*., 2024). "Mn", a microbial culture produced by CV. Agro Gemilang, Malang, East Java, consisting of minerals N, P, K, Mg, and Fe as well as lignolytic, cellulolytic, methanogenic, and pectinovora bacteria (Krismawati and Sugiono, 2019), has been recommended as an "pesticide remover" (destroy agricultural chemical residues) in Indonesian soil farm.

Based on the aforementioned details, the author team conducted this bioremediation research employing earthworms, organisms, and a mixture of various materials as organic fertilizers to minimize the negative impacts of MPs in potato cultivation. The study aims to increase the productivity of "healthy" potatoes, particularly ones with minimal MPs content, to support food availability and the Sustainability Goals (SDGs).

Materials and Methods

This study used Granola Kembang potato seedlings obtained from tissue culture at the University of Muhammadiyah Malang – Central of Potato Seeds (7°54'55.3824" S, 112°35'20.0724" E). The topsoil of regosol type (Prasetyo *et al*., 2022; Subardja *et al*., 2014) also recognized as entisol (USDA – NRCS, 2014) was collected from a depth of 30 cm from potato cultivation fields in Maron village, Pujon, Malang, East Java, Indonesia (7°50'22.3"S, 112°28'16.4"E) for pots experiment. The reason for using Maron village's soil is that this farm has been identified as an MPs-contaminated site, and their potato products have been used as *in vivo* test materials, with an impact on the mortality of experimental animals (Ganfansa *et al*., 2024b; Hermayanti *et al*., 2024).

Chemical fertilizers (Urea = 46 % N, SP-36 = 36 % P_2O_5, and KCl = 60 % K_20), insecticide ("Mi" brand) 25 DS (carbosulfan 25 %), and insecticide ("Ma" brand) 50 WP (Isoprocarb 50 %) were purchased at Ortani Agricultural Store, Pujon (7°54'46.7892" S, 112°34'54.156" E). Organic fertilizers were mixed as per recommendation of SenviGrow ("SG") brand a potato seed breeder in Pujon (7°51'29.5884" S, 112°27'51.6132" E) consisting of coco peat (50 %), rice husk charcoal (40 %), goat manure (5 %), and fermented urban waste fertilizer (5 %). The nutrient contents of the product are: N of 0.67 % to 0.77 %, P_2O_5 of 0.67 to 1.01, K_2O of 0.93 % to 0.95 %, C of 14.20 % to 22.34 %, and C/N ratio of 18.44 % to 33.34 %. The natural mineral P-K ("Pa" brand) fertilizer containing N of 0 %, P_2O_5 of 10 %, and K_2O of 10 % was obtained from Petro Kimia, Gresik, Indonesia (7°8'55.428" S, 112°38'26.8872" E). Earthworms (*E. fetida* "Ef") Figure 1B were obtained from "RAJ Organik", Malang (S7°59'45.708" S, 112°37'20.802"E), while microbes ("Mn" brand) were obtained from CV. Agro Gemilang, Malang, Indonesia (7°54'46.7892" S, 112°34'54.156"E).

Figure 1: *Material research on the bioremediation of soil contamination MPs in potato cultivation. (A) 42 pot experiments (potato plant on 1 wk); (B) Earthworms; (C) Potato plant on 40 d.*

Experimental setup

A total of 42 pot experiments (Figure 1A) determined based on Federer's formula (Bakri *et al*., 2025) were conducted to evaluate the effects of MPs contamination on potato growth, and "Mn" and "Ef" were inserted as bioremediation agents for MPs in the soil. Each pot contained 18 kg of soil – 15 kg of soil was prepared at the beginning of planting, and 3 kg of soil was added when the plant was 70 days after planting (dap). The pot experiments were arranged in "SG" open yard Figure 1A (7°51'29.5884" S, 112°27'51.6132" E) with sufficient sunlight exposure where mountain spring water was irrigated daily by spraying.

Employing "duplo" (duplicate) treatments, the pots were arranged in a randomized block design with three replication (Arifin and Zahiruddin, 2017; Bakri *et al*., 2025). Seven treatments were of: (P0) control chemicals fertilizer, (P1) chemicals fertilizer + MPs, (P2) chemicals fertilizer + MPs + "Mn" microbial, (P3) chemicals fertilizer +MPs + "Ef" (P4) chemicals fertilizer + MPs + "Mn" microbial + "SG" fertilizer, (P5) chemicals fertilizer + MPs + "Ef" + "SG" fertilizer, and (P6) soil with "Pa" brand – natural mineral organic fertilizer.

The seeds were soaked in "Mi" and "Ma" insecticides (1:1, an amount of 30 g for 50 potato seed) for 30 min prior to planting. After air-drying, one seed was planted in each pot and given chemicals fertilizer (except for treatment P6) in the form of Urea, SP-36, and KCl as per "SG" recommendation – 400 kg Urea ha^{-1}, 300 kg SP-36 ha^{-1}, and 200 kg KCl ha^{-1}. Urea as the basic fertilizer was of 21 dap and 45 dap, while TSP at basic fertilizer, and 21 dap; KCl at 21 dap and 45 dap. "Pa" fertilizer in P6 was given as basic fertilizer in the amount of 1.5 t ha^{-1} as recommended by Petro Kimia, while "SG" was of 15 t $ha^{-1.}$ All doses of chemical fertilizers and organic fertilizers ("SG" and "Pa") were converted to pot experiments with a total of 40 000 ha^{-1} of potato plants.

Polyethylene terephthalate (PET) was the MPs used in this study. Used PET bottles were cut into pieces in Research and Community Service Institute – Universitas Islam Madura (7°9'20.1708" S, 113°27'27.9504" E), combined with PET pellet, ground in a rice mill, and sieved through a 3 mm filter. The result was then mixed with agricultural soil in a 1 % (w w^{-1}) ratio to simulate MPs contamination (Li *et al*., 2021; Meng *et al*., 2023).

While procuring MPs is a weakness, it is a novelty of this research at the same time. The authors had limitations in making MPs in micron/micrometer (μm) size like several previous MPs researches due to limited equipment. However, obtaining data on the impact of MPs in millimeter (mm) size on the

Links Researchers

potato cultivation environment is a new invention as it naturally takes years for plastic to degrade into µm size. This research should be able to determine whether MPs of approximately 3 mm in size negatively affects potato cultivation.

"Mn" microbial was sprayed onto the soil at a dose of 40 mL L^{-1} (0.04 v v^{-1}) at intervals of 7 d, 14 d, 28 d, 56 d, and 70 d in the morning as advised by CV Agro Gemilang. Subsequently, a total of 20 "Ef", each of approximately 5 cm long (Damayanti *et al.*, 2023; Indriani, *et al.*, 2024; Saputra *et al.*, 2022) Figure 1B were taken from the RAJ's organic vermiculture and distributed into pots on the first day of planting.

Potato growth and chlorophyll determination

Potato growth (Figure 1C) was monitored by chlorophyll content at 80 dap, comprising chlorophyll a (Chl. a), chlorophyll b (Chl. b), and total chlorophyll (tot. Chl.) at Biotechnology Laboratorium, University of Muhammadiyah Malang, Campus III (S 7°55'14.1636", E 112°35'51.126"). The chlorophyll content analysis refers to Yangyang *et al.* (2022), *i.e.*, 1 g of randomly selected leaves was extracted with 96 % ethanol (Merck) and sieved (Whatman grade 1). The filtrate was diluted to 10 mL and measured using a spectrophotometer (Shimadzu UV-Vis 1800) at wavelengths of λ = 649 nm and λ = 665 nm. The absorbance value was measured, and the chlorophyll content was calculated using Equations 1a, 1b, 1c):

$$Chl.\ a = (13.7 \times A\lambda\ 665) - (5.76 \times A\lambda\ 649) \quad ....(1a)$$
$$Chl.\ b = (25.8 \times A\lambda\ 649) - (7.60 \times A\lambda\ 665) \quad .... (1b)$$
$$Tot.\ Chl. = (20.0 \times A\lambda\ 649) - (6.10 \times A\lambda\ 665) \quad .... (1c)$$

To measure potato growth, the fresh weight of the above-ground parts of the potato plant (excluding the tubers) was weighed using an electronic balance (AUX 320, Shimadzu).

Harvest component

Potatoes were carefully harvested at 100 dap by hand to avoid mechanical damage. All tubers were thoroughly cleaned from any remaining soil and then sorted according to the standards set by the United States Department of Agriculture (Li *et al.*, 2024). The tubers was weighed using an electronic balance (AND compact balances EK-I, Series EK-1200i).

The variables observed in this study included tuber weight per plant and the number of tubers per plant. Additionally, the distribution percentage of tuber grades was determined by sorting and weighing the tubers based on the pre-defined size categories: Grade L (60 g to 90 g), Grade M (30 g to 60 g), and Grade S (< 10 g). All the data obtained were analyzed to evaluate the effects of the treatments on potato yield quantity and quality.

Statistical analysis

The results of each double sample were presented as the mean. Statistical analysis was preceded in accordance with Shapiro Wilk test for data normality and Levene test for data homogeneity (Praptiningsih, *et al.* 2015). Significant differences between the treatments and control were determined by one-way analysis of variance (ANOVA, $p < 0.05$), followed by LSD test (least significant difference), using SPSS 20.0. Origin 9.5 was used to create and modify all the graph (Damat *et al.*, 2021).

Results and Discussion

Plant growth

The result of treatments on potato biomass is presented in Figure 2. It is apparent that P5 has produced the highest yield quantity although not significantly different from P4 with an increase of 46.1 % compared to the control (P0), indicating that the combination of earthworms ("Ef") and organic fertilizer ("SG" brand) positively affects plant growth.

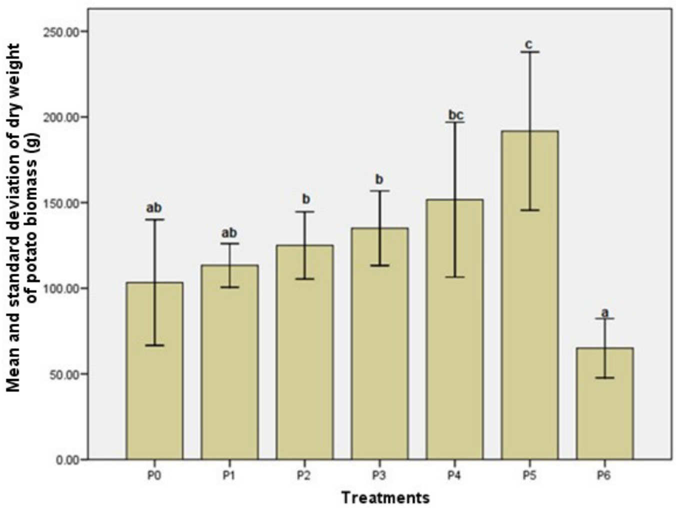

Figure 2: *Effect of treatment on potato biomass.*

"Ef" require organic materials for living and reproducing (Bellitürk and Sundari, 2024; Yatoo *et al.*, 2022), which are supplied by organic fertilizer ("SG" brand). The mutual symbiosis is formed as "Ef" then discharge decomposed "SG", essential nutrients beneficial for potato plant (Li *et al*., 2023). When "Ef" move underground, they leave small tunnels that boost soil aeration (Li *et al*., 2023), allowing roots to grow well and absorb more water as well as nutrients (Chakraborty *et al*., 2022).

In regards of bioremediation, "Ef" digest introduced PET-MPs, reducing the amount of MPs absorbed by the plant (Amobonye *et al*., 2021; Cui *et al*., 2022; Lwanga *et al*., 2018; Meng *et al*., 2023; Shi *et al*. 2024). Amobonye *et al*. (2021), Lwanga *et al*. (2018), Meng *et al*. (2023), Thapliyal *et al*. (2014), and Yang *et al*. (2023b), also reported on MPs degradation, fragmentation, and depolymerisation (for certain polymers) in the intestine of "Ef". This finding on biomass enhancement through "Ef" bioremediation is supportive towards previous studies, among them are Amobonye *et al*. (2021), Iswahyudi *et al*. (2025), Li *et al*. (2023), Meng *et al*. (2023), and Shi *et al*. (2024).

On the contrary, significant biomass diminution has appeared in treatments P1, P2, and P3 compared to P5 at 40 %, 29.5 %, and 34.7 %, respectively. P1 is of the least yield as biomass formation is hindered by PET-MPs, and it is in sync with prior findings (Garfansa *et al*., 2024c; Iswahyudi *et al*., 2024). Such hindrance is evidently lessened in P2 ("Mn" brand) and P3 ("Ef").

Figure 2 also highlights that the biomass in P4 is higher than in P1, P2, and P3 although not significantly different, and that the biomass in P4 is lower than in P5 although not significantly different. Thus, further questions raised are whether the dosage of "Mn" microbial is not sufficiently high and whether the combination of "Ef" and "Mn" is called for.

A drastic decline can also be seen in P6 at 51.8 %, 48 %, 56.9 %, and 66 % compared to P2, P3, P4, and P5, respectively. It can therefore be inferred that natural mineral fertilizer ("Pa" brand) is not adequate in enhancing soil quality and providing nutrients essential for potato growth and productivity, particularly in regosol. Organic fertilizer ("SG" brand) in P4 and P5 is proven to be more effective to increase biomass than in P2 and P3. "Pa" brand used in this research was absent from N, but the current product has contained 5 % nitrogen (https://petrokimia-gresik.com/product/phonska-alam).

Figure 2 further underlines that P0 and P1 are statistically not significantly different– P1 even seems higher than P0 in the graphic. It is surmised that the induced PET-MP particles are not small enough to be absorbed by potato plant, resulting in insignificant MP intrusion. However, previous studies have reported an assortment of impacts regarding the presence of MPs, whether they were negative (Qi *et al*., 2020; Wang *et al*., 2020c; Qi *et al*., 2018) or neutral (Judy *et al*., 2019), even positive (Machado *et al*., 2019).

Contradictions regarding MPs have been summed up by Zhou *et al*. (2023) as that polyester microplastic fibers (PES-MPs) were notably embedded in corn (*Zea mays* L.) biomass before the mature stage whereas it increased at the mature stage, and that polypropylene microplastic fibers (PP-MPs) and PES-MPs positively increased the culm diameter of corn at the flowering, grain-filling, and mature stages ($p < 0.05$) as well as the culm diameter of soybean (*Glycinemax* (L.) Merr.) at the flowering and grain-filling stages ($p < 0.05$). Li *et al*. (2023) stated that the total biomass of spring onion (*Allium fistulosum* L.) increased when exposed to primary polyamide (PA) and polyethylene terephthalate (PET), but these two microplastics had opposite impacts on the dry biomass and water content of onion bulbs. Brodhagen *et al* (2019) found out that contacts with PP-MPs and PES-MPs increased the chlorophyll content in peanut (*Arachis hypogaea* L.) as well as specific leaf width and soluble sugar in soybean.

Chlorophyll content

The treatments have shown significant effects on the total chlorophyll (chlorophyll a and chlorophyll b) content in potatoes (Figure 3). The highest total chlorophyll content was observed in P5 (213.08 mg L^{-1}). This finding confirms the data in Figure 2 regarding the highest biomass in P5. It is scientifically due to the role of "Ef" in (i) enhancing soil physics (Shi *et al*., 2024) by creating tunnels advantageous for soil aeration and optimal root growth as nutrients and water are easily absorbed, (ii) improving soil chemistry (Li *et al*., 2023; Shi *et al*., 2024) by degrading organic fertilizer ("SG" brand) through digestion system, and (iii) minimizing the effect of PET-MPs by means of fragmentation and depolymerisation in the intestine (Amobonye *et al*., 2021; Li *et al*., 2023; Meng *et al*, 2023; Shi *et al*., 2024).

In contrast, the low chlorophyll content in P6 is deduced to be the result of limited nutrient availability in the soil, and the condition can inhibit chlorophyll synthesis. As aforementioned, P6 is only administered with "Pa", an organic mineral fertilizer product containing P and K, without N. A number of researchers (Amin, 2022; Arta, 2023; Muhammad, 2022) confirmed the importance of N in chlorophyll formation. Purbajanti *et al.* (2019) and Widyati *et al.* (2016) even emphasized that organic fertilizer (plant remains and manure) was key in chlorophyll development by binding soil grains in sandy soil (such as regosol employed in this research), avoiding N to get washed away.

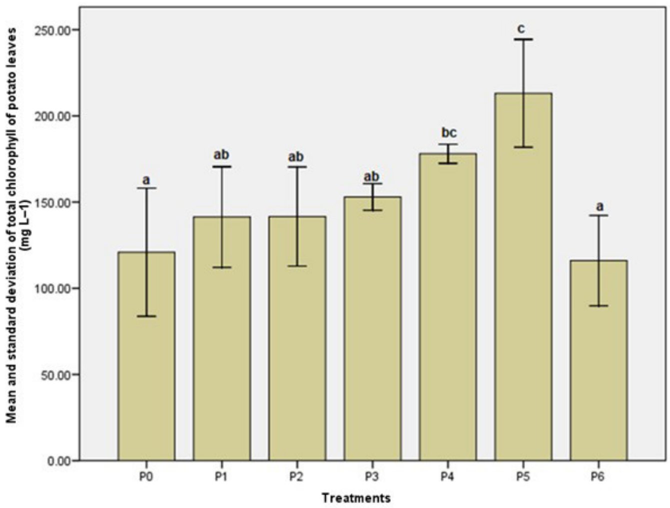

Figure 3: *Effect of treatment on chlorophyll.*

Harvest component

Number of tubes: The effects on tuber quantity in all treatments are recorded in Figure 4. While P6 contains the fewest tubers of all, no significant differences appear in P0, P1, P2, P3, and P4. The only significant progress exists in P5 compared to P6 at 50 %, whereas the treatment is not significantly different from P0, P1, P2, P3, and P4. MP hindrance is construed to happen in the early stage of tuber forming, resulting in slight discrepancy.

Potato weight

The effects on tuber weight in all treatments are cited in Figure 5. P6 has significantly the lowest rate than other treatments, verifying that natural mineral fertilizer needs further support for optimal potato tuber growth as pointed in Figures 1 and 2. P6 also demonstrates a weight decrease at 24 % compared to control. This finding validates that "Pa" is deficient for potato growth. On the other hand, P5 produces the highest yield with an increase of 49 % compared to P6, proving that "Ef" and "SG" combination is constructive towards potato growth.

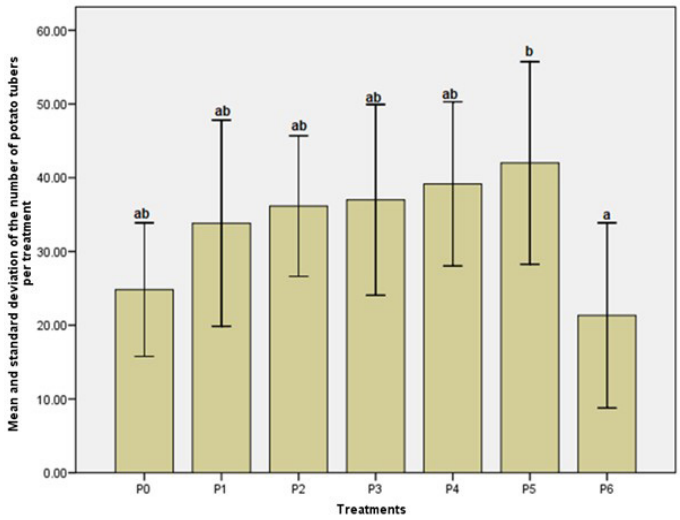

Figure 4: *Effect of treatment on number of tubers.*

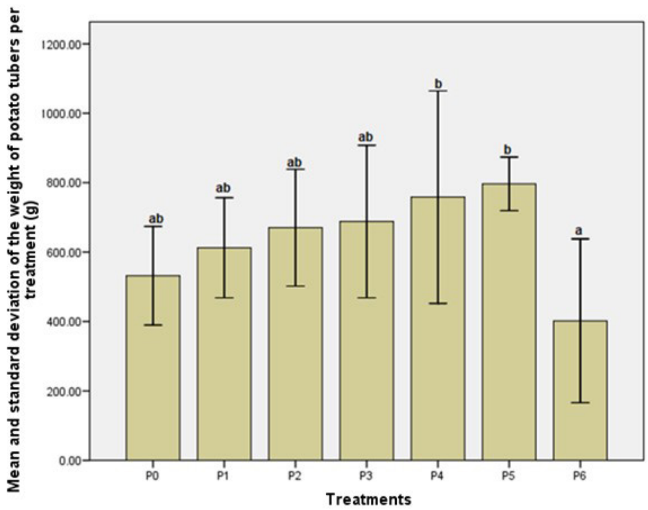

Figure 5: *Effect of treatment on potato weight.*

Another drawback of "Pa" is its inability to optimize water holding capacity in regosol soil. A study by Ierna and Distefano (2024) underlined the fact that soil with low water retention capacity is prone to water deficiency. Its coarse grains let water vaporize more quickly or flow out of the pot. Made of plant remains and manure, "SG" is alternately able to bind soil grains and improve soil's water holding capacity, allowing tubers to grow favourably.

The significant weight differences, especially in P5, corroborate the hypothesis that any disturbance may occur in the early stages of growth affecting tuber forming can be eliminated by "Ef" and "SG" combination – tubers should be able to grow optimally and gain the most weight. However, Figure 4 also reveals that higher amounts of "Ef" and "Mn" are called for "Ef", specifically, should be administered not only in the beginning of planting period but also in the middle of it (at approximately 50 dap). Future research should also employ P4 ("Mn") and P5 ("Ef") combination to find their synergy, as reported by McIntyre and Li (2024) and Othman *et al*. (2021).

Potato grade

The treatments significantly affected the distribution of potato grades (Figure 6). Treatment P5 resulted in the highest percentages of Grade L (60 g to 90 g), M (10 g to 60 g), and S (< 10 g) compared to the other treatments, with 8 %, 32 %, and 65.85 %, respectively. Meanwhile, P6 produced a smaller percentage of Grade L but of insignificant difference compared to P0. The high percentage of Grades L and M in P5 indicates that the combination of "SG" and "Ef" creates optimal soil conditions that support tuber growth and filling, resulting in higher-quality potatoes.

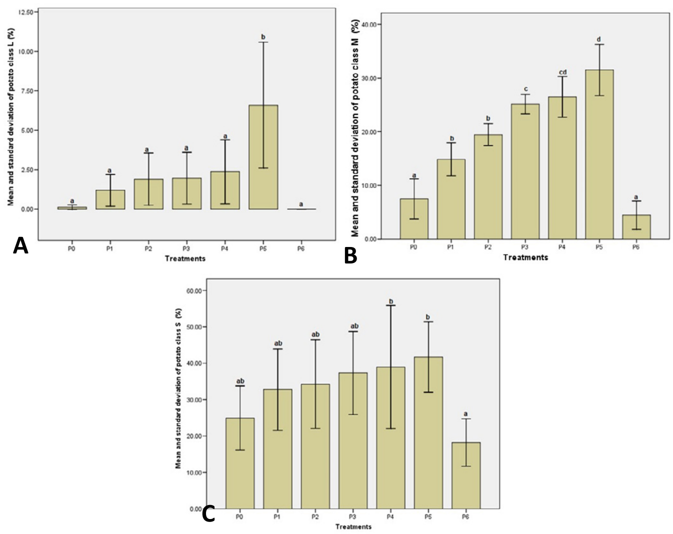

Figure 6: *Effect of treatment on percentage potato grade. (A) Grade L, (B) Grade M, and (C) Grade S.*

"Ef" improves soil structure through bioturbation, which enhances soil aeration and water movement, thereby supporting root growth and the formation of larger tubers (Reyes *et al*., 2023). "SG', on the other hand, provides key nutrients such as nitrogen and phosphorus that supports plant physiological processes, including photosynthesis and the formation of storage tissues (Liu *et al*., 2024; Purbajanti *et al*., 2019; Widyati *et al*., 2016). In contrast, in P4 and P2, although microorganisms helped in the degradation of MPs. This explains why the Grade L percentage in P4 and P2 remains lower than in P5. The decline in potato quality in P0 and P6 can also be attributed to the lack of biological supporting factors such as earthworms or microorganisms. In P6, despite the presence of "Pa" mineral organic fertilizer, it is unable to support the potato productivity. Overall, these data suggest that the combination of "SG" fertilizer and "Ef", as in P5, is the most effective strategy to improve potato quality, especially in soils contaminated with MPs.

Conclusions and Recommendations

This study aimed to evaluate the effectiveness of bioremediation using a combination of microorganisms ("Mn"), earthworms ("Ef"), and organic fertilizers ("SG") in reducing the impact of MPs on the growth, yield, and quality of potato plants. The results indicate that treatments involving "Ef" and "SG" provided the best outcomes in increasing biomass, tuber number, tuber weight, and potato grade distribution compared to other treatments. This combination has proven to create optimal soil conditions through enhanced aeration, nutrient distribution, and biological activity, thereby minimizing the negative effects of MPs.

This study has significant implications by providing a biology-based solution for mitigating the impact of MPs pollution in agricultural systems, while also supporting the sustainability of food production. Future researches are recommended to focus on (i) improving "Ef" and "SG" dosage with an "Ef" administration additional to the beginning of planting period, (ii) intensifying synergy through earthworm ("Ef"), microorganism ("Mn"), and organic fertilizer ("SG") combination treatments, and (iii) improving plant remain, urban waste, charcoal, and manure processing for MP-free organic fertilizers.

Acknowledgements

The authors express their gratitude to the Directorate of Research and Community Service, University of Muhammadiyah Malang (DPPM- UMM), which has funded this research under the letter of consent No. E.2a/811/BAA-UMM/viii/2023. Heartful thanks are also extended to Intan Andini and Nabilla Rahmah Malihah, students of the Agrotechnology Department, University of Muhammadiyah Malang; Muhammad Efendi Zarkasi and Bambang Suhermanto, CV. SenviGrow for assistance in maintaining potatoes in experimental pots; PT. Petro Kimia, CV. Agro Gemilang, and CV. RAJ Organik for providing research materials, *i.e.,* "Pa" - organic

minerals fertilizer, "Mn" - mixed organisms, and "Ef"- earthworms.

Novelty Statement

The novelty of this research covers these findings: (i) PET-MPs pose harm for potato production even in millimetre size (ii) with improved dosages and frequencies, earthworm ("Ef") and mixed organism ("Mn") are potential for bioremediation, (iii) organic mineral fertilizer ("Pa" brand containing P and K) is insignificant in organic potato farming in regosol soil, (iv) organic fertilizer ingredients – among them are fermented urban waste, manure, and charcoal – contain MP pollutants, (v) potato seed (G0 to G2) employed in this research has been polluted by MPs, (vi) spring water in Pujon, Malang, Indonesia as well as rainwater irrigating treatments in this research has been polluted by MPs.

Author's Contribution

Roy Hendroko Setyobudi: Conceptualized and designed the study, elaborated the intellectual content, performed literature search, manuscript preparation, and manuscript revision.
Syarif Husen: Research supervision, materials research, and grant funding.
Marcel Putra Garfansa: Performed literature search and manuscript preparation
Diah Hermayanti, Shazma Anwar, Iswahyudi Iswahyudi, Yudhiakuari Sincihu, Thontowi Djauhari Nur Subchi, Suherman Suherman and Muslih Anwar: Manuscript review.
Anik Anekawati and Mardiana Sri Susanti: Statistical analysis
Trias Agung Pakarti: English scientific writing and layout editing
Surya Andhi Angga Putra: Administration
All authors have read and approved the final manuscript.

Generative AI and AI-assisted technology statement
The authors stated that they didn't use generative AI and AI-assisted technology in preparing this manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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