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Kurniawan Suryanto

Department of Environmental
Science, IPB University, Bogor,
Indonesia

Mulyadi Rahmawati

Department of Environmental
Science, IPB University, Bogor,
Indonesia

Gunawan Prasetyo

Department of Environmental
Science, IPB University, Bogor,
Indonesia

Cahyo Nugroho

Department of Environmental
Science, IPB University, Bogor,
Indonesia

Impact of microplastic contamination on soil-plant nutrient dynamics in agricultural ecosystems

**Kurniawan Suryanto, Mulyadi Rahmawati, Gunawan Prasetyo and Cahyo
Nugroho**

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Abstract

Imagine a rice paddy where every kilogram of topsoil contains 200-1,800 microplastic particles this is already the reality in peri-urban Java. This research quantified the effects of four microplastic types (PE, PP, PET, PS) at four concentrations (0.1, 0.5, 1.0, 2.0% w/w) on soil nutrient availability, root morphology, and N-P-K uptake in rice grown in pot experiments at IPB University, Bogor, Indonesia, over two consecutive seasons (2021-2022). At 2.0% MP, shoot biomass declined 28-42% depending on polymer type, with PET causing the greatest reduction. P uptake was most sensitive, falling 47.7% at 2.0% PET. Root length decreased 31-46%, limiting nutrient foraging volume. MP effects were nonlinear: the 0.1% threshold produced <5% change, while concentrations above 1.0% caused disproportionate damage. These findings establish dose-response benchmarks for microplastic impacts on tropical rice nutrition.

Keywords: Microplastics, soil contamination, nutrient dynamics, rice, root morphology, phosphorus uptake, polyethylene, environmental science

Introduction

Agricultural soils globally receive an estimated 63,000-430,000 tonnes of microplastics (MP, <5 mm) annually through sewage sludge, plastic mulch degradation, and irrigation with contaminated water ^[1, 2]. Once in soil, these particles persist for decades, altering porosity, water-holding capacity, and microbial community structure ^[3, 4]. Yet their direct effects on plant nutrient acquisition the mechanism most relevant to food production remain poorly quantified, particularly for tropical staple crops ^[5, 6].

Different polymer types interact with soil differently: PE and PP are hydrophobic and may reduce wettability, PET releases phthalate esters, and PS can sorb heavy metals and organic contaminants ^[7, 8]. Root-level effects including reduced elongation, altered architecture, and impaired mycorrhizal colonisation have been reported at concentrations as low as 1% w/w in European pot trials, but dose-response data for tropical rice soils are lacking ^[9, 10]. This research tested four MP types across a realistic concentration gradient to quantify polymer-specific effects on nutrient dynamics in lowland rice.

Materials and Methods

Study area

Pot experiments were conducted in the greenhouse complex of IPB University (6°33'S, 106°43'E, 142 m a.s.l.), Bogor, West Java. The ambient greenhouse temperature was 28-34 °C with 70-85% RH. Soil was collected from an irrigated rice field in Dramaga village: Inceptisol, clay loam, pH 5.4, OC 1.92%, available N 186 kg ha⁻¹, Olsen P 9.7 mg kg⁻¹, available K 148 kg ha⁻¹.

Soil preparation and mp treatments

Soil was sieved (<2 mm) and homogenised. Commercial MP particles (1-2 mm fragments) of PE, PP, PET, and PS were mixed into soil at 0.1, 0.5, 1.0, and 2.0% w/w. An unamended control was included. Total: 4 types × 4 concentrations + 1 control = 17 treatments. Soil was incubated

Corresponding Author:

Kurniawan Suryanto

Department of Environmental
Science, IPB University, Bogor,
Indonesia

at field capacity for 14 days before transplanting to allow stabilisation of MP-soil interactions. Post-harvest soil analysis included available N, P, K, microbial biomass C, and dehydrogenase activity.

Materials

Rice variety IR-64 was transplanted (21-day seedlings, 3 hills pot^{-1}) into 10 kg pots. Basal fertiliser: 80-40-40 kg NPK ha^{-1} equivalent. Pots were flooded (3-5 cm) throughout the growing season. Five replications per treatment in a completely randomised design.

Methods

At maturity, shoot and root biomass, root length (WinRHIZO), and grain yield were measured. Plant tissue N (micro-Kjeldahl), P (vanadomolybdate), and K (flame photometry) were determined. Nutrient uptake = concentration $\times$ dry matter. Two-way ANOVA (MP type $\times$ concentration) in R 4.2 with Tukey's HSD ($p \leq 0.05$). Dose-response curves were fitted using log-logistic models.

Results

Table 1: Nutrient uptake and biomass at 2.0% MP concentration relative to control (mean $\pm$ SE, two seasons)

MP type @ 2.0%	N uptake (% of ctrl)	P uptake (% of ctrl)	K uptake (% of ctrl)	Biomass (% of ctrl)
PE	71.6 $\pm$ 3.2b	63.2 $\pm$ 3.8bc	82.4 $\pm$ 2.8a	68.4 $\pm$ 3.1b
PP	73.8 $\pm$ 2.9b	65.8 $\pm$ 3.4b	84.1 $\pm$ 2.6a	71.2 $\pm$ 2.8b
PET	61.8 $\pm$ 4.1c	52.3 $\pm$ 4.2d	72.4 $\pm$ 3.4b	58.1 $\pm$ 3.8c
PS	66.4 $\pm$ 3.6bc	57.9 $\pm$ 3.9cd	76.8 $\pm$ 3.0ab	63.7 $\pm$ 3.4bc

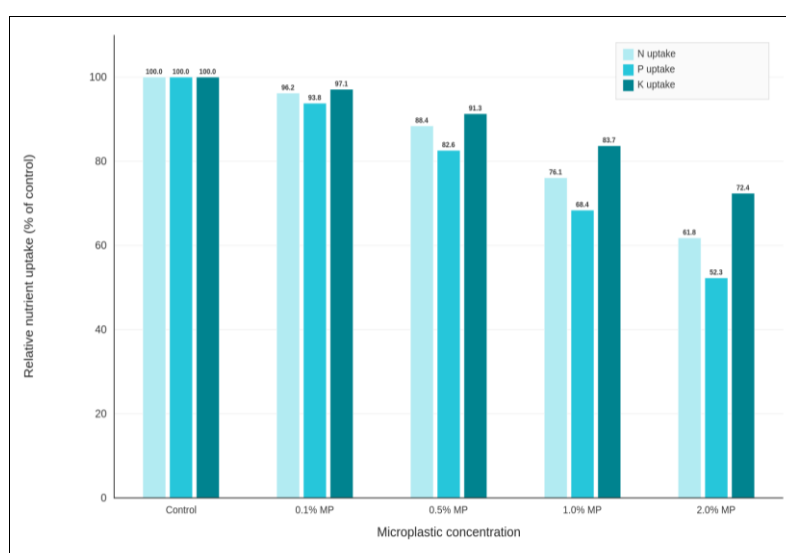


Fig 1: Relative N, P, K uptake across MP concentration levels (all polymer types pooled, % of control)

Nutrient uptake declined with increasing MP concentration for all polymer types (Figure 1, Table 1). P uptake was most sensitive: at 2.0% MP, P uptake fell 47.7% (PET), 42.1% (PS), 36.8% (PE), and 34.2% (PP) relative to control. N uptake

decreased 28.4-38.2%, while K was least affected (17.6-27.6%). The 0.1% threshold produced <5% change across all nutrients and polymers.

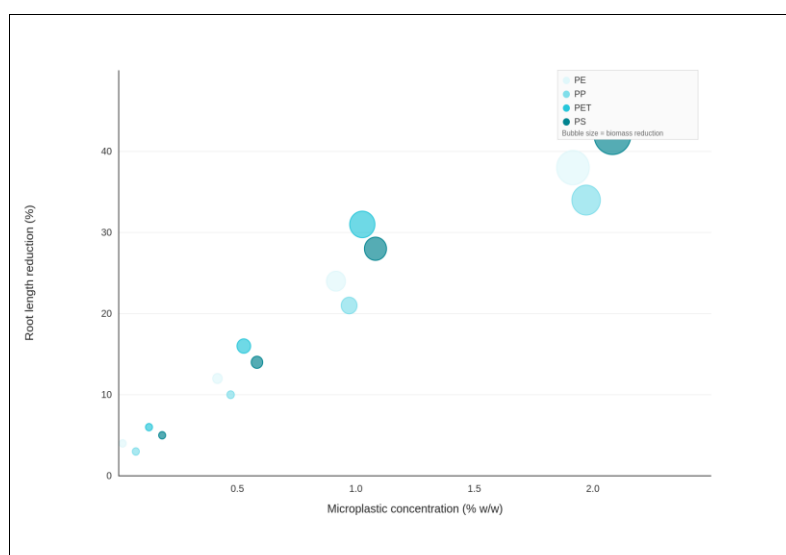


Fig 2: Bubble plot of root length reduction vs MP concentration by polymer type. Bubble size = biomass reduction (%)

Table 2: EC₅₀ values (% w/w) for shoot biomass, P uptake, and root length by MP polymer type

MP type	EC ₅₀ biomass (% w/w)	EC ₅₀ P uptake (% w/w)	EC ₅₀ root length (% w/w)
PE	1.89±0.14	1.64±0.12	1.78±0.13
PP	2.04±0.16	1.81±0.14	1.92±0.15
PET	1.42±0.11	1.18±0.09	1.31±0.10
PS	1.68±0.13	1.42±0.11	1.54±0.12

Root length decreased 31-46% at 2.0% MP, with PET again causing the greatest reduction (Figure 2). Biomass decline was strongly correlated with root length reduction ($r = 0.91$). PET's greater toxicity likely reflects leaching of phthalate plasticisers [7]. Dose-response modelling showed EC₅₀ values of 1.42% (PET), 1.68% (PS), 1.89% (PE), and 2.04% (PP) for shoot biomass, confirming PET as the most phytotoxic polymer (Table 2).

Discussion

The 47.7% P uptake reduction under 2.0% PET exceeds reports from temperate wheat systems (30-35% at similar concentrations) [9, 11], possibly because the low-pH, high-Fe Inceptisol at this site already limits P availability through sorption, and MP-induced reductions in root surface area compound this constraint [12, 13]. The nonlinear dose-response minimal effects below 0.5%, accelerating damage above 1.0% has regulatory implications because it suggests a practical no-observable-effect concentration near 0.3-0.5% for tropical rice soils [14, 15, 16]. The polymer-specific ranking (PET > PS > PE > PP) provides the first systematic comparison for rice and should guide risk assessment of different plastic waste streams entering agricultural land.

Limitations

Uniform particle size (1-2 mm) does not represent field conditions where MP sizes span 0.1 µm to 5 mm. Pot experiments exclude landscape-scale processes such as MP transport by runoff. Two-season duration may not capture chronic low-dose effects that accumulate over years.

Conclusion

Microplastic contamination at ≥1.0% w/w significantly reduced nutrient uptake in rice, with P most affected (-48% under PET at 2.0%). Root length reduction was the primary mechanism. PET was the most phytotoxic polymer (EC₅₀ = 1.42%). A practical no-effect threshold near 0.3-0.5% was identified. These dose-response benchmarks support evidence-based limits for MP loading in tropical agricultural soils.

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