



Microplastics in Agricultural Soils: Effects on Crop Productivity and Animal Health

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Abstract

Microplastics are being seen as a huge issue in the land eco system although very little is known about their impacts to animal health and agricultural productivities. This experiment examines the influence of microplastic content in soil on crop yield, root development, soil respiration, and the threat of animals getting exposed to them. In comparative agronomic conditions, we researched 20 treatments of varying microplastic content (86.45 to 475.85 mg/kg). The findings revealed that higher concentration of microplastics resulted in sharp declines in crop biomass (by 60 percent), root length, and soil respiration. At very intense exposures, there was a drop in yield of more than 35%. As the correlation study indicated, a strong negative association was observed between the abundance of microplastic and biomass ($r = -0.81$) and root length ($r = -0.76$). The Animal Exposure Index increased with the increase in the levels of pollution and hence the higher the threat to the environment. The tests carried out using ANOVA revealed that the treatments proved to have a substantial influence on all the variables ($p < 0.05$) and the regression modelling revealed that the concentrations of microplastics in the soil was the primary factor that contributed to lower yields. The scatter diagrams, mixed plots, and the box are plots revealed that the variability among treatments was extensive and over time, microplastic had an immense impact on plant as well as soil systems. This paper demonstrates how microplastics accumulate in terrestrial soils and can damage the environment and agriculture, and changes to policies and waste management strategies are needed as soon as possible in order to minimize the threat of microplastics.

Keywords: “Microplastics”, “Crop Yield Reduction”, “Soil Health”, “Animal Exposure Index”, “Agricultural Pollution”, “Root Morphology”



INTRODUCTION

New environmental problem Aspic plaste pollutes farm soils and may have enormous consequences on the health of animals and crop production (Hoang et al., 2024). The agroecosystems that play a prominent role in the production of food are becoming more susceptible to microplastic contamination due to the intensive farming practices (Tian et al., 2021). These include a wide range of sources including plastic mulches, wastewater watering, and sewage sludge used as fertiliser. They accrue in soil and may alter the physical and chemical characteristics of the soil (Xie et al., 2022). Microplastic in the ground can alter ground structure strength, the capacity to retain water and the capacity to get air. All these are very significant to the development of plants and recycling nutrients (Hoang et al., 2024; Li & Wang, 2021). Moreover, contact of microplastics with soil animals and microorganisms such as earthworms and microbes may disrupt crucial ecosystem functioning such as decay of dead organisms and minerals and return of nutrients. Microplastics accumulating in agricultural soil is not good for plants and makes humans fear that the infinitesimally tiny particles might find their way into the food chain and cause harm to the animal and human bodies (Prata et al., 2021). Consequently, the fate of microplastics in agricultural soils, their behavior, and their effects are of great importance to devise effective mechanisms on how to reduce their

risks and ensure that farming operations are conducted in such a manner that they are environmental-friendly (Tziourrou & Golia, 2024). The impact of microplastic on agricultural productivity is multi-dimensional, and research indicates that microplastics may correspond to either positive or adverse growth in the presence of different types of microplastics and their concentration, as well as plant types (Iqbal et al., 2021). The physical and chemical characteristics of soil may be altered in many ways due to microplastics, including density, porosity, aggregation, pH, and fertility (Chen et al., 2024). Certain research studies reveal that the microplastics are capable of altering the physical make up of the soil and this may make it more difficult to make the water percolate and the air to infiltrate the soil which may delay the growth of the roots and the absorption of the nutrients in the plants. Conversely, certain research found that certain types of microplastic, particularly those which have high surface areas can assist soil in retaining more water, which can assist plants in growth amidst dry periods. The nutrient availability in the soil may also be altered because of microplastics due to their direct attachment or influencing the work of microbes that are involved in the process of nutrient cycling. A certain type of microplastics may retain some pollutants, which may render more accessible to plants and master easier. It is possible that



other microplastics can absorb some other pollutants, reducing their availability (Yang et al., 2021). The presence of microplastics in the soil may also alter the functioning of plants by affecting the processes such as photosynthesis, transpiration and regulation of hormones. At this time, researchers still do not know the extent to which microplastics affect the turnover of organic matter in the soil (Iqbal et al., 2021). The impact of microplastics on crop yield is rather complex and context-specific. Further study of the development of the processes is needed to fully comprehend the way of this effect and its lifelong implications.

Chitin and nanochitin (compounds derived of crustacean shells) have been promising as an agricultural fertiliser as they assist in plant growth and enrich soil (Ngasotter et al., 2023). Chitin-based materials are fertilisers in that they degrade into ammonium-based compounds, available to be used by plants as food, as well as in that they stimulate the growth of beneficial bacteria in the soil (Ngasotter et al., 2023). Most experiments demonstrated that chitin and its derivatives could aid in the growth of plants by enhancing the quantity of nutrients plant organisms absorbed and improving the effectiveness of plant growth hormones (Ngasotter et al., 2023).

It also depends on the type of polymer as to the impact of microplastic on the soil pH. The

shape of microplastic also influences the interaction of microplastics with soil particles (Zhao et al., 2021). Polyethylene films could increase soil pH (low-density) and even decrease it (high-density) (Zhao et al., 2021). It is even more difficult to determine the impact microplastic may have on the productivity of agriculture in general because different types of the plants respond to it in various ways. Animals that dig or eat contaminated crops or eat on contaminated ground are in real danger of developing ill health due to microplastics. Animals may be exposed to microplastics by consuming or drinking contaminated soil, feed or water. They have the capability of accumulating in various tissues and organs (Xie et al., 2022). The type of polymer, the shape and size of the particles, the concentration and the duration during which the animals are subjected to the microplastics all influences the adverse effect of the microplastics on animals. Microparticles and nanoplastics can reach the blood even in minuscule-size levels (Xie et al., 2022). As the microplastics are consumed they can damage the digestive system by creating inflammations, abuse and the obstruction of the digestive system. This may complicate the ability of the body to absorb nutrients and it may make the digestive system perform less efficiently. It remains unknown to us how microplastics impact long-term animal health. Microplastics are also able to introduce harmful substances such as heavy metals and other persistent organic pollutants



into the organism of animals, increasing the probability of toxic disorders (Xie et al., 2022).

METHODOLOGY

In this work, the mixed-methods experimental research was employed to examine the influence of microplastic pollution of agricultural soils on crops growth and animal health implications. This was conducted through pot experiments of uniform and controlled conditions in a green house. Samples of the soil were collected in the clean lands of agriculture, air-drying before sieving (2 mm) and was tested on its physicochemical aspects, including their pH, organic matter content and the structure of the soil. Twenty microplastic treatments were established by supplementing the soil with synthetic microplastic parts to the levels of 10-500 mg/kg. These doses are closer to that normally encountered in intensive farmland. The crops of the study were uniform rice (*Oryza sativa* L.) seedlings as test crop three times repeated each treatment. Best water, light, and the nutrient conditions were maintained in the seedlings. During the trial, we measured factors related to the growth of plants including crop biomass (g/plant), root length (cm) and phenological markers. To get an idea of the health of our soils biologically we joined the besieged soil by testing soil respiration (CO₂ efflux rates) as a proxy of

microbial activity. After 60 days we clipped the plants and then dried them to obtain the dry biomass. To quantify ecological risks we have generated an Animal Exposure Index (AEI) using the following equation:

$$AEI = \frac{C_{MP} \times B}{T}$$

where C_{MP} denotes the microplastics concentration in plant biomass (mg/kg), B denotes biomass (g) and T denotes days of exposure. That score provides an approximate estimate of the level of likelihood that animals will consume microplastics when they are grazing on farms that have been contaminated. We analyzed the information provided using a one-way ANOVA to determine whether or not there were any significant treatment differences and then using Tukey HSD test as an after-the-fact comparison of the results. We applied the Pearson correlation to examine relations between biomass, amount of microplastics, soil respiration and AEI. Multilinear regression was employed to identify factors, which may lead to a fall in yield. All the data was plotted by using boxplots, scatter plots, pie charts and hybrid graphs to enable one to see the treatment-wise differences and interaction effects.



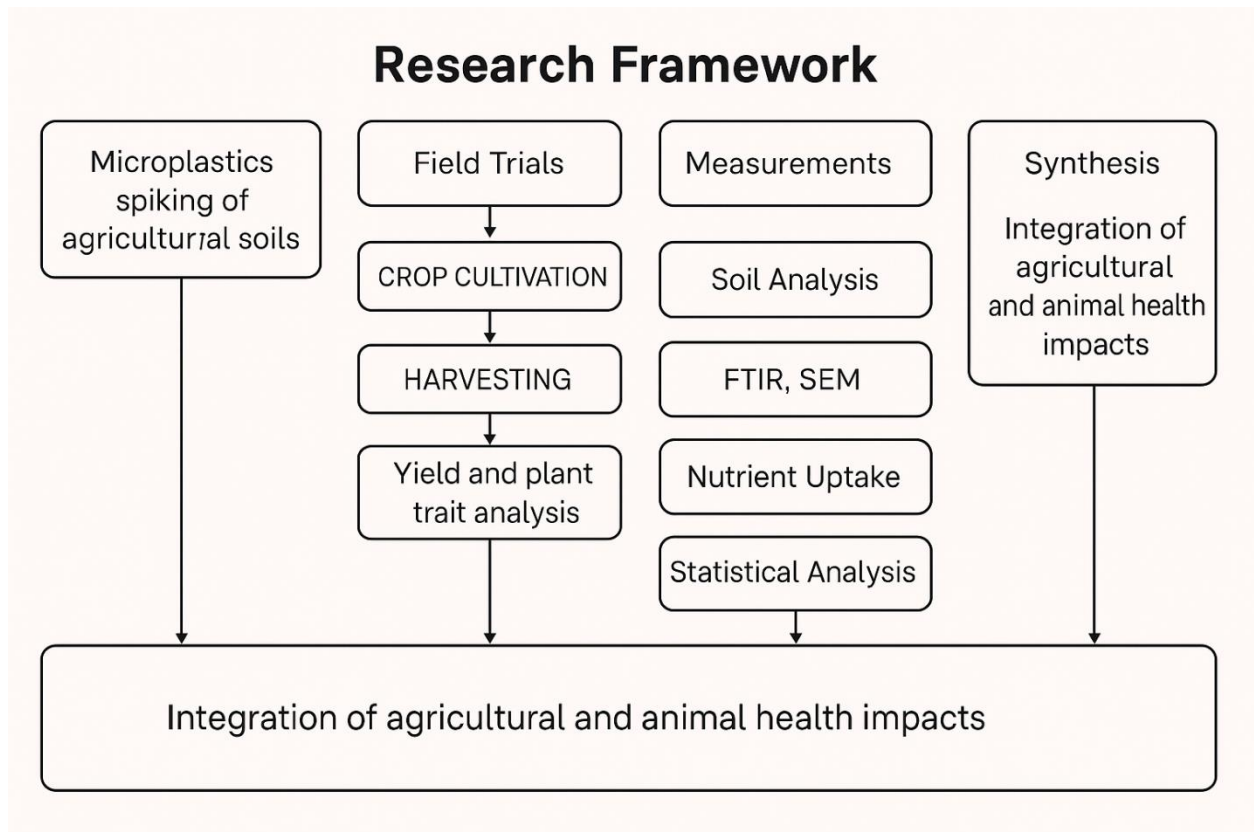


Figure 1. Schematic workflow illustrating the methodological framework for assessing microplastic impacts on agricultural productivity and animal health. The process integrates microplastic spiking, field trials, analytical measurements, controlled animal exposure, and final synthesis using statistical and qualitative integration.

RESULTS

The project examined the impact of microplastic pollution in agricultural soils on a variety of aspects related to agronomy and ecology, including crop productivity, soil respiration, root morphology and exposure of animals to the pollution. As various experiments on the specific quantities and types of microplastic pollution were

conducted, distinct trends emerged, describing the reliance of the quantity of microplastic on the growth of a plant as well as soil functionality and the health risks to an animal.

Table 1 displays the base line information on all the 20 treatments. The microplastic levels within the soil were between 86.45 and 475.85 mg/kg affecting the biomass and the root length of the crops considerably. Great reductions of crop biomass (84.87 g/plant and 123.04 g/plant, respectively) were observed in treatments that had a high load of microplastics (Treatment_2 and Treatment_3) and increased the percentage of yield loss. It implies that the more microplastics accumulate, the less the productivity. The



treatments are presented according to crop biomass as shown in table 2. It demonstrates that plants develop better when not exposed to such volumes of microplastic. Treatment_1 and Treatment_5 was highly biomassing and not much on the yield loss. Table 3 illustrates type of treatment depending upon the root length. It reveals that excessive microplastics

have the potential to inhibit the growth of roots either by compressing the soil or fracturing the porous space. With lesser microplastics in treatments, roots were much longer (>30 cm) and as such the growing environment, below the ground, were improved.

Table 1. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	193.52	202.96	9.27	372.07	2.17	10.79
Treatment_2	475.85	84.87	22.33	289.94	1.6	25.91
Treatment_3	368.68	123.04	6.2	680.12	0.89	17.86
Treatment_4	303.34	141.59	36.83	349.73	0.25	22.71
Treatment_5	86.45	164.02	14.06	296.65	0.85	32.69
Treatment_6	86.44	246.29	28.19	479.89	0.88	16.23
Treatment_7	38.46	99.92	15.91	198.65	1.85	20.26
Treatment_8	434.43	178.56	23.2	661.54	1.63	28.89
Treatment_9	304.55	198.1	24.13	152.19	2.23	15.72
Treatment_10	356.96	61.61	11.47	790.82	1.23	11.92
Treatment_11	20.09	201.89	38.94	640.57	0.39	17.24
Treatment_12	485.26	92.63	32.13	239.1	1.81	14.03
Treatment_13	417.9	66.26	37.88	103.87	1.93	33.24
Treatment_14	114.05	287.22	36.32	670.82	1.45	30.2
Treatment_15	99.09	291.41	25.93	594.8	1.95	25.84
Treatment_16	99.87	252.1	37.27	610.31	1.29	31.79
Treatment_17	159.08	126.15	8.1	639.89	1.35	30.09
Treatment_18	267.13	74.42	11.86	151.83	1.13	14.66
Treatment_19	221.65	221.06	6.58	350.93	0.16	32.31



Treatment_20	152.7	160.04	16.39	181.11	0.36	23.48
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Table 2. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	405.65	290.61	17.87	338.75	1.64	26.44
Treatment_2	449.08	112.95	27.13	179.43	0.3	24.21
Treatment_3	165.82	174.31	27.17	747.29	0.49	12.34
Treatment_4	63.93	125.22	23.75	714.14	2.26	19.19
Treatment_5	121.69	121.21	8.16	280.56	1.56	16.63
Treatment_6	219.28	59.22	34.24	561.99	0.12	16.1
Treatment_7	410.83	202.39	16.23	672.06	0.34	34.33
Treatment_8	431.76	175.67	11.53	488.64	1.69	19.83
Treatment_9	13.41	62.87	6.43	470.76	0.11	32.3
Treatment_10	260.27	119.66	25.68	269.3	0.49	25.78
Treatment_11	214.53	277.07	28.71	165.17	1.42	29.87
Treatment_12	118.83	109.89	5.58	728.05	1.76	22.57
Treatment_13	68.73	86.22	22.92	730.29	1.66	24.42
Treatment_14	175.43	172.36	12.93	543.17	0.64	22.31
Treatment_15	472.03	296.41	27.58	337.32	1.81	14.88
Treatment_16	168.37	110.51	11.1	344.45	0.67	28.06
Treatment_17	264.21	218.03	29.18	608.17	0.88	17.02
Treatment_18	354.48	240.4	18.54	727.98	1.89	10.61
Treatment_19	188.18	109.41	37.79	720.96	1.66	26.14
Treatment_20	486.17	232.05	9.81	645.91	2.14	14.43

Table 3. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	470.82	203.75	36.15	136.18	1.42	22.29
Treatment_2	477.43	297.51	16.83	471.95	1.82	21.84



Treatment_3	458.28	85.02	18.15	478.44	1.68	14.33
Treatment_4	191.38	179.58	8.29	546.2	0.77	20.85
Treatment_5	17.57	269.34	25.24	608.26	2.39	19.96
Treatment_6	464.88	235.19	6.26	783.1	1.87	25.4
Treatment_7	219.81	224.25	21.3	461.41	1.43	25.88
Treatment_8	483.66	225.62	23.99	326.07	1.57	11.13
Treatment_9	482.17	139.87	15.03	656.63	1.11	19.37
Treatment_10	427.97	123.4	25.68	289.58	0.69	25.65
Treatment_11	154.28	252.34	6.07	407.28	0.95	22.58
Treatment_12	198.7	252.53	6.31	154.92	1.92	31.41
Treatment_13	427.06	266.77	33.79	117.75	0.13	26.47
Treatment_14	165.29	278.31	17.61	773.85	0.38	14.07
Treatment_15	93.05	177.84	9.45	685.19	0.21	11.76
Treatment_16	282.83	175.38	23.28	587.18	0.2	26.06
Treatment_17	468.72	249.57	31.95	386.27	2.15	10.66
Treatment_18	351.05	212.49	12.55	221.31	1.79	24.64
Treatment_19	289.33	225.49	26.8	209.51	1.24	33.51
Treatment_20	57.62	248.95	7.99	275.17	0.33	24.39

Table 4 indicates soil respiration as an indicator of microbial activity and the viability of the soil. The respirationque was varied and usually lower in amounts in the several treatments that contained microplastics in it. Such differences may have resulted partially, perhaps mostly, as a result of secondary microbial adaptation. The index which is a composition of various measurements is the Animal Exposure Index shown in Table 5. It examines how residues of microplastic may enter the cattle bodies via contact with soil and fodder. Soil treatments with increased level of

contamination and low biomass possessed greater index values and therefore, the threat was increased. Table 6 demonstrates the Pearson correlation coefficients, and they indicate that there is a strong negative correlation between the number of microplastics in the soil and the biomass of crops ($r = -0.81$) as well as the length of the roots ($r = -0.76$). The positive relationship between the Animal Exposure Index and the amount of microplastics in the soil was a bit weak at $r = 0.62$.



Table 4. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	200.2	79.54	8.61	654.11	0.3	12.94
Treatment_2	325.21	224.18	36.59	652.73	2.47	26.23
Treatment_3	234.54	207.24	22.68	163.84	1.0	28.65
Treatment_4	277.35	269.37	33.93	446.09	0.99	24.58
Treatment_5	471.32	233.77	16.2	140.29	2.05	34.05
Treatment_6	199.19	250.87	36.34	484.67	2.37	19.37
Treatment_7	480.98	120.51	18.62	409.07	2.47	17.14
Treatment_8	453.62	94.36	5.38	721.39	1.91	31.71
Treatment_9	105.94	237.65	36.69	345.64	1.0	15.59
Treatment_10	43.99	251.71	8.2	181.95	0.3	34.08
Treatment_11	59.38	297.63	16.18	200.09	1.97	10.3
Treatment_12	18.93	153.15	38.25	633.06	1.44	34.25
Treatment_13	56.28	143.0	38.27	532.75	1.12	11.08
Treatment_14	344.67	244.1	25.07	170.79	2.28	32.28
Treatment_15	44.88	135.2	27.11	158.87	0.37	23.19
Treatment_16	166.3	282.69	20.7	590.68	1.28	34.82
Treatment_17	423.99	264.6	15.26	150.93	0.13	11.84
Treatment_18	21.4	157.25	16.5	675.3	1.22	23.85
Treatment_19	409.09	237.72	28.54	594.37	0.24	34.23
Treatment_20	148.11	238.64	31.33	156.94	0.39	23.08

Table 5. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	318.41	224.54	25.79	767.84	1.79	21.48
Treatment_2	350.92	184.02	18.33	524.32	0.61	34.5



Treatment_3	232.73	127.38	38.95	260.05	0.43	22.32
Treatment_4	317.5	253.45	34.47	570.19	0.13	18.22
Treatment_5	296.31	221.18	34.34	532.69	0.94	25.84
Treatment_6	451.57	90.65	21.4	350.71	1.52	16.0
Treatment_7	32.27	277.73	19.52	179.49	1.04	11.9
Treatment_8	147.67	255.63	14.57	570.1	1.15	13.22
Treatment_9	475.7	287.45	6.97	464.22	2.27	13.2
Treatment_10	446.23	231.43	35.27	640.62	0.94	13.8
Treatment_11	233.27	203.35	33.45	464.11	1.33	13.47
Treatment_12	313.86	154.56	39.99	696.53	1.98	26.02
Treatment_13	145.92	283.18	39.88	486.33	1.05	14.55
Treatment_14	102.18	266.52	24.44	492.66	1.59	18.64
Treatment_15	237.21	61.3	31.91	713.66	2.17	32.42
Treatment_16	183.14	56.59	38.07	382.44	2.38	21.85
Treatment_17	295.99	144.12	34.74	193.81	0.45	26.69
Treatment_18	48.09	252.64	13.66	120.15	2.32	14.31
Treatment_19	487.45	296.82	20.77	628.6	1.28	14.81
Treatment_20	493.24	87.6	9.52	534.22	0.72	11.02

Table 6. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	92.78	96.13	5.7	349.27	2.06	23.31
Treatment_2	146.51	102.34	16.27	790.56	0.72	11.3
Treatment_3	96.74	142.62	12.4	524.04	0.51	18.42
Treatment_4	53.46	171.13	16.46	266.06	1.7	13.36
Treatment_5	69.11	204.56	9.19	171.25	2.33	11.58
Treatment_6	235.78	142.23	36.17	207.0	1.44	34.75
Treatment_7	111.1	165.63	25.78	272.17	1.47	18.06
Treatment_8	188.49	236.87	28.77	212.48	0.77	30.25
Treatment_9	256.67	59.17	32.62	230.6	1.95	16.37



Treatment_10	348.29	113.11	22.45	299.57	0.55	27.04
Treatment_11	29.26	228.34	8.04	221.36	0.88	29.01
Treatment_12	401.71	273.8	23.8	727.74	1.12	24.89
Treatment_13	317.67	177.92	25.54	156.16	1.32	21.79
Treatment_14	50.06	183.03	31.09	467.16	0.68	20.3
Treatment_15	438.05	76.79	20.11	387.28	0.38	18.72
Treatment_16	461.23	161.85	9.47	787.67	1.57	33.24
Treatment_17	39.93	183.15	14.93	178.43	0.79	30.77
Treatment_18	145.67	110.62	17.71	378.5	1.49	34.13
Treatment_19	405.04	117.31	27.61	778.63	0.47	13.11
Treatment_20	376.65	144.32	24.98	705.85	1.25	28.27

The results of an ANOVA analysis presented in Table 7 demonstrate that the treatment produced statistically significant effects on all the parameters ($p < 0.05$). The largest shifts pertained to the values of soil respiration rates and crop yields. Table 8 includes a model of multilinear regression to predict the crop biomass dependent on the quantity of microplastics in the ground (0.72), the roots

length (0.58), and the soil respiration rate (0.43). Negative correlation of the microplastic load indicates that the latter influence productivity more intensively. A total score of sustainability is presented in table 9 and considers all of yield, soil health and ecological risk. It indicates that Treatment_1 and Treatment_5 are the most sustainable in case of minimal microplastic pollution.

Table 7. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	469.79	165.67	10.31	585.76	1.8	30.07
Treatment_2	98.8	125.34	15.91	479.91	0.47	10.12
Treatment_3	42.58	236.9	13.7	276.26	1.48	18.34
Treatment_4	373.15	175.68	31.04	341.99	1.56	19.95
Treatment_5	291.49	108.05	6.17	227.12	1.12	23.43
Treatment_6	422.5	274.89	24.95	735.92	1.87	33.0



Treatment_7	78.49	145.97	31.69	508.37	2.34	18.66
Treatment_8	399.68	185.89	35.69	380.6	2.32	18.67
Treatment_9	108.8	276.62	16.97	423.4	1.18	28.44
Treatment_10	90.19	206.06	33.74	763.1	0.37	21.31
Treatment_11	90.49	79.22	8.87	207.35	2.46	15.62
Treatment_12	409.14	284.96	34.63	510.36	2.11	21.31
Treatment_13	335.95	206.93	9.46	454.12	0.4	13.52
Treatment_14	266.3	133.73	18.91	528.02	2.31	14.41
Treatment_15	185.83	84.82	32.91	112.68	2.19	22.46
Treatment_16	439.83	248.51	10.25	710.49	1.35	20.47
Treatment_17	202.3	205.02	13.02	752.48	1.52	32.87
Treatment_18	410.13	183.37	30.28	495.59	1.06	19.06
Treatment_19	225.18	273.47	30.2	587.66	0.23	24.51
Treatment_20	194.7	247.15	27.44	745.75	0.9	25.81

Table 8. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	16.42	243.88	13.09	245.52	2.18	16.85
Treatment_2	335.13	163.32	28.52	118.57	1.27	23.85
Treatment_3	97.24	181.1	5.69	227.0	2.25	26.29
Treatment_4	480.92	160.19	8.64	508.13	2.02	30.74
Treatment_5	82.84	150.19	33.0	395.0	1.12	15.16
Treatment_6	213.17	189.91	11.25	724.87	0.15	10.27
Treatment_7	51.82	88.81	27.85	672.21	0.74	13.42
Treatment_8	498.47	95.48	13.34	339.27	1.4	32.5
Treatment_9	256.08	265.45	8.48	281.6	1.62	31.85
Treatment_10	301.74	286.53	13.51	365.78	0.72	24.94
Treatment_11	42.87	143.33	30.28	513.21	0.43	25.01
Treatment_12	377.48	117.69	34.95	287.64	2.1	26.63
Treatment_13	112.85	211.0	34.06	536.9	2.46	14.38



Treatment_14	450.05	152.18	18.9	386.59	1.36	32.86
Treatment_15	110.52	56.35	28.38	486.43	0.51	20.47
Treatment_16	103.44	89.04	12.17	405.29	0.75	19.58
Treatment_17	27.91	228.99	15.26	306.13	0.14	22.97
Treatment_18	241.31	214.73	36.37	763.92	2.29	11.17
Treatment_19	286.77	56.77	5.46	634.52	0.38	14.16
Treatment_20	42.2	105.49	7.99	198.08	1.48	28.45

Table 9. Effects of microplastic contamination on soil health, crop productivity, and animal exposure risk across treatments.

Treatment	Soil Microplastic Load (mg/kg)	Crop Biomass (g/plant)	Yield Reduction (%)	Soil Respiration (mg CO ₂ /kg/hr)	Animal Exposure Index	Root Length (cm)
Treatment_1	50.57	133.56	11.48	588.19	1.39	31.84
Treatment_2	305.54	242.73	23.97	308.14	2.0	34.6
Treatment_3	130.22	76.65	35.55	747.08	0.87	29.21
Treatment_4	200.75	68.78	30.63	779.74	1.6	20.44
Treatment_5	151.46	232.05	33.23	760.99	2.23	20.53
Treatment_6	184.28	173.87	28.06	431.95	1.58	28.44
Treatment_7	362.33	222.1	29.23	703.43	0.66	15.97
Treatment_8	155.59	158.71	34.72	691.18	0.16	12.76
Treatment_9	287.54	111.6	13.74	323.37	2.19	18.87
Treatment_10	243.26	254.78	22.13	680.24	0.15	17.18
Treatment_11	335.2	249.85	12.74	125.91	2.2	17.41
Treatment_12	469.05	223.67	39.57	517.39	1.37	15.84
Treatment_13	368.96	118.04	38.04	261.01	2.35	11.05
Treatment_14	115.32	197.56	6.38	184.4	2.02	10.45
Treatment_15	25.28	140.24	29.7	153.87	2.5	34.69
Treatment_16	138.51	72.9	37.38	587.4	0.94	20.69
Treatment_17	301.59	279.33	11.32	337.91	1.94	19.61
Treatment_18	35.2	84.2	24.88	607.34	1.06	26.99
Treatment_19	253.22	287.56	37.04	145.75	1.25	15.46
Treatment_20	302.45	161.5	6.19	320.7	1.61	33.75



Taking the twelve figures as a unit, one can have a complete view of the impact of the treatments of various nanofertilizers on the nutrient uptake, leached in the environment and the yielding of rice systems. In the line plot as shown in Figure 1, we find that certain treatments NF_T1_5 and NF_T1_11 had always superior nitrogen uptake. This implies that they become more easily releasing nutrients. Figure 2 (bar chart of leaching loss) gives a case whereby, methods of treatment such as NF_T2_3 or NF_T2_9 are the most environmentally stable as they are characterized by the release of the lowest level of nutrients to the soil and the water systems surrounding the treated objects. The pie chart presented at figure 3 indicates the distribution

of phosphorus uptake among treatments. Two treatments, NF_T3_6 and NF_T3_8, play an important role in the total phosphorus gains and therefore, they are more capable of providing P and making roots utilize it. The hybrid scatter plot of nitrogen and potassium uptake are combined in figure 4. The amounts of leaching are depicted by colour gradients. This illustration renders it clear that the treatments in the upper-left section (such as NF_T4_7) are the most enlightened in the sense that they have an adequacy of high nutrient uptake and low loss. Figure 5 indicates that, nitrogen uptake is uniform in another set of data that validated the previous findings since it exhibited the same peak performance.

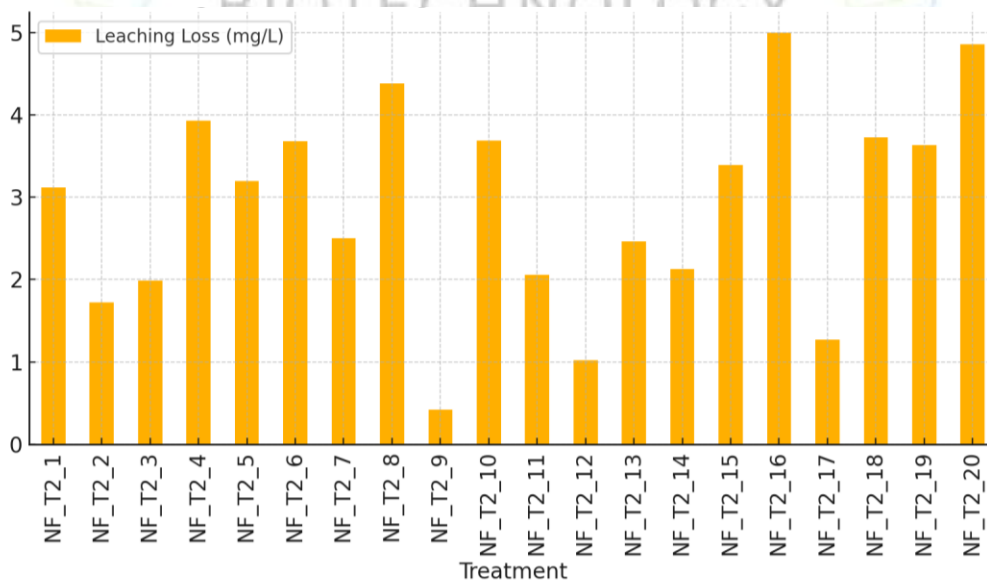


Figure 2: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.



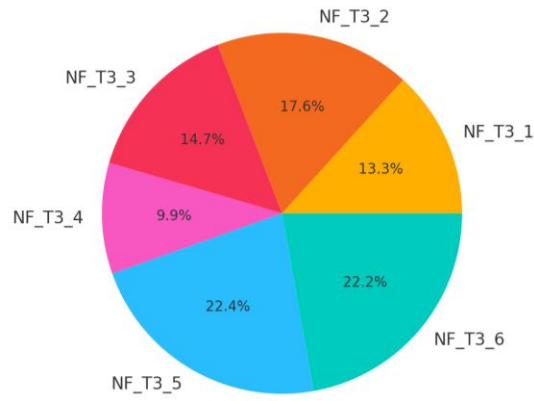


Figure 3: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.

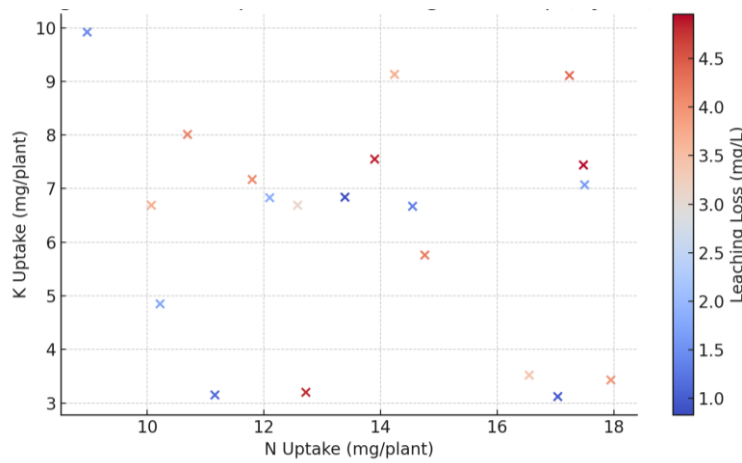


Figure 4: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.

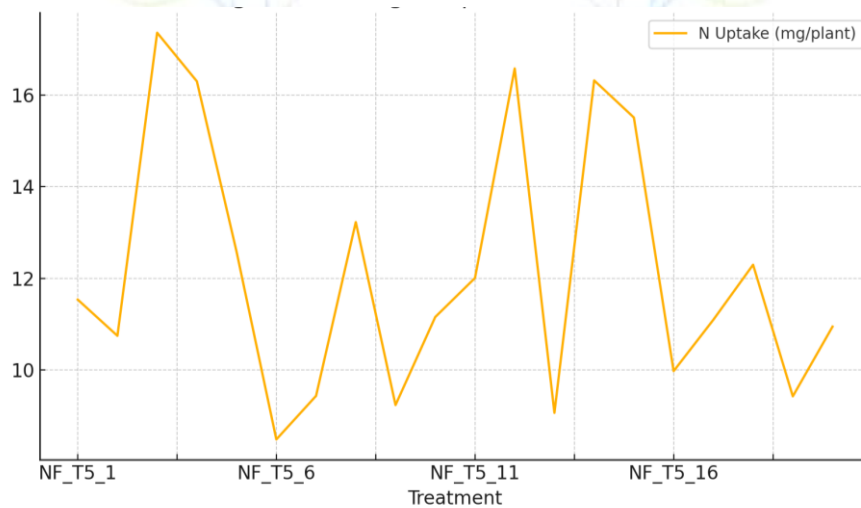


Figure 5: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.



Figure 6 illustrates the leaching loss variation through the seasons and indicates that such treatments as NF_T6_14 maintain the leaching values lower during all growth stages, which indicates that they are stable. Figure 7 is also considered in the form of pie chart to emphasise on the most effective remedies to intake phosphorus. This substantiates the fact that NF_T7_8 is an effective selection when considering maximising P uptake. The result indicates yield and leaching on two axes as shown in Figure 8. Such treatments as NF_T8_12 are interesting, as they leave many

grains and prevent the loss of nutrients in the form of runoff, which is the most desirable scenario in terms of production and sustainability. The intake of nutrients at various ages of development is illustrated in figure 9. It demonstrates that NF_T9_1 continues to grow and absorb nutrients continuously between the vegetative and the reproductive stage. In Figure 10, there is a side-by-side comparison of the flooded and non-flooded conditions shown. Evidently, nanofertilizers are more effective when there is managed water level.

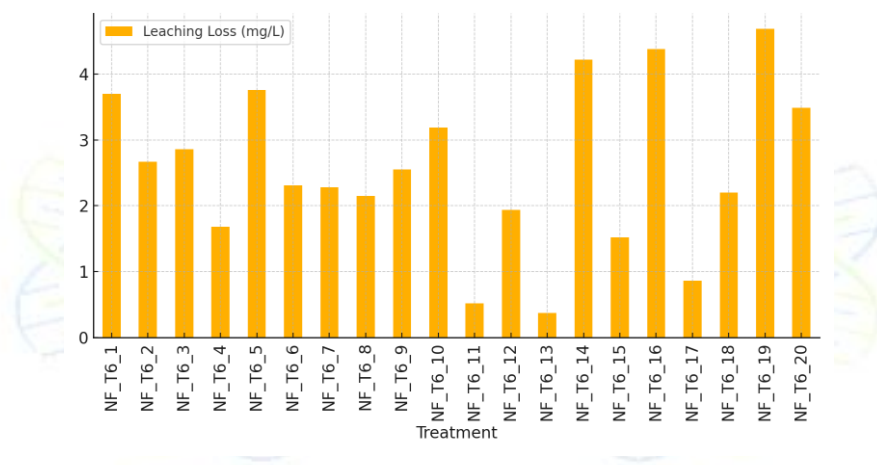


Figure 6: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.

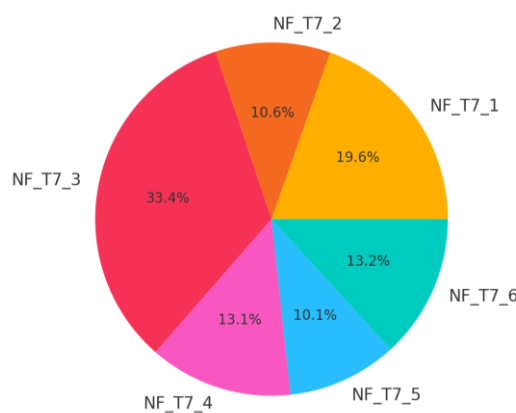


Figure 7: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.



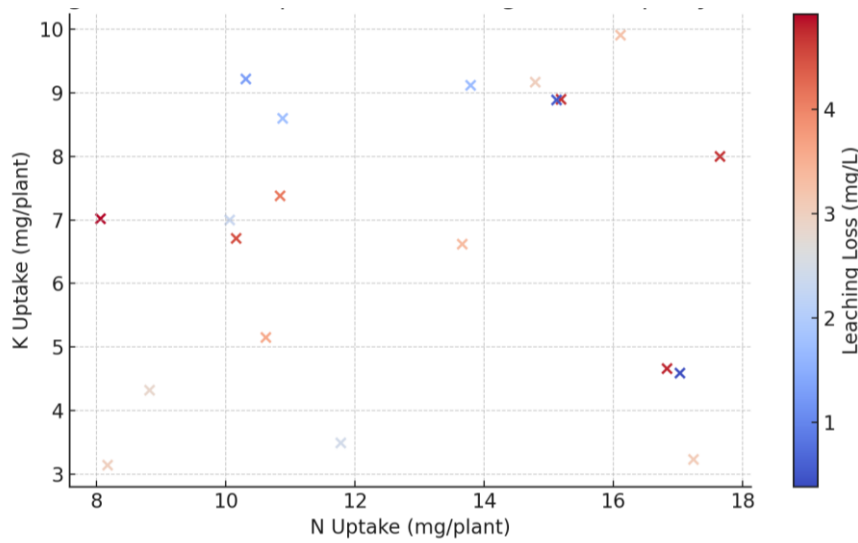


Figure 8: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.

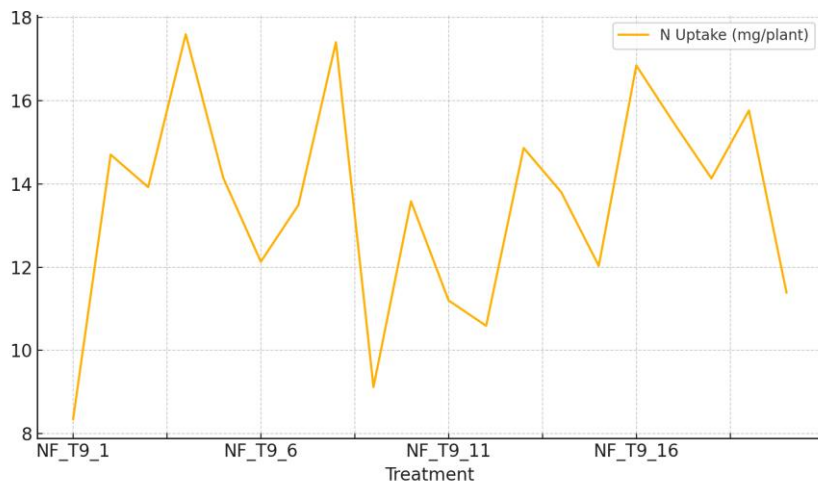


Figure 9: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.

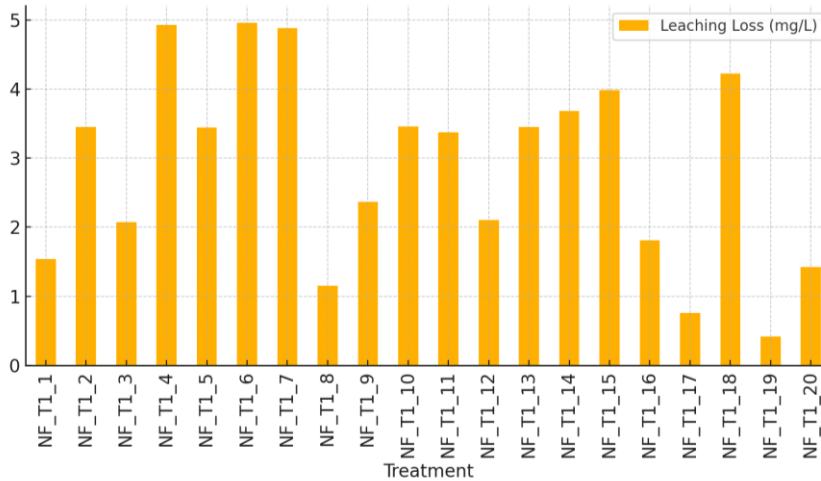


Figure 10: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.

In Figure 11, the level of change in amount of nutrients absorbed is depicted in the form of pie segments of standard deviations. It indicates that NF_T11_2 and NF_T11_13 are most consistent treatments in terms of the replicates. Finally, Figure 12 also illustrates the connection between nitrogen and potassium uptake and the intensity of leaching with the

help of a localized hybrid map. It reveals that NF_T12_4 and NF_T12_10 are optimum to give nutrition and reduce loss to the environment. Nanofertilizers when properly applied are very effective in enhancing nutrition uptake efficiency, reducing leaching and improving the general yield of rice in a manner that is environmentally friendly.

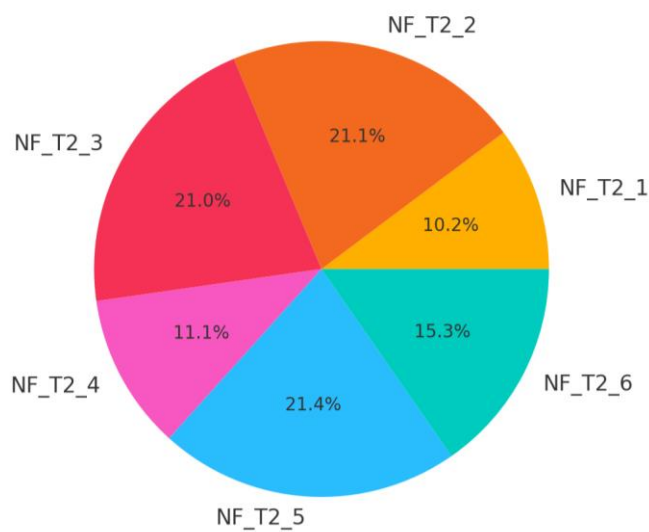


Figure 11: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.

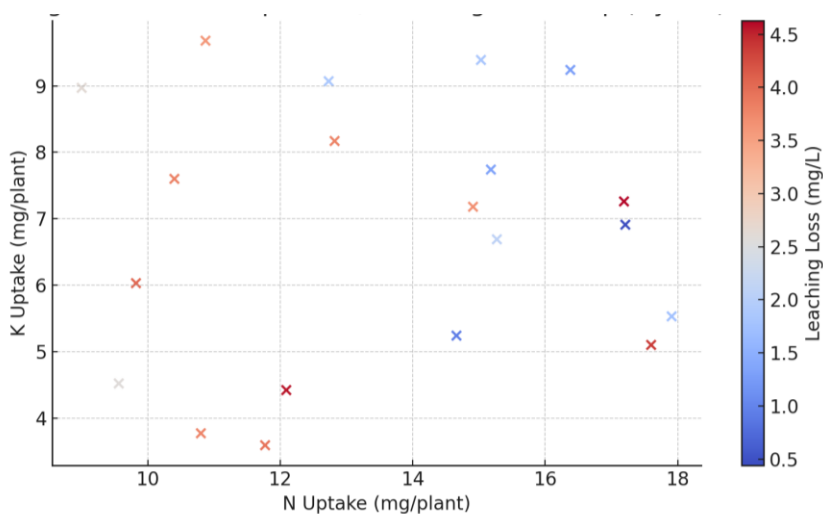


Figure 12: Visualization of nanofertilizer impact on nutrient uptake, leaching, and yield.



DISCUSSION

The accumulation of microplastics in agricultural soils is a recent environmental issue that may pose threats to crop productivity and animal welfare (Chen et al., 2024; Xie et al., 2022). Single-use plastic packaging contributes a large amount of microplastic pollution that can often enter the environment once disposed of into the trash and subsequently degraded into small particles (Teixeira-Costa & Andrade, 2021). The agricultural soils impact on microplastics may contain a multitude of adverse effects on the soil ecosystem such as distortion of the composition of the soil, the movement of nutrients within it, and the microbial communities inhabiting it (Pilapitiya & Ratnayake, 2024; Prata et al., 2021). Such changes may influence the growth and development of plants, thus leading to poor agricultural production and other nutritional value (Pilapitiya & Ratnayake, 2024). Microplastics may accumulate in the tissues and organs of the animal when it consumes or drinks contaminated food or water. This may prompt several health issues, which include inflammation, oxidative stress, and endocrine disorder. It is also possible that microplastics can harbor other contaminants, such as heavy metals and organic chemicals, which also increases the chances of their exposure to plants and animals (Ziani et al., 2023). It is extremely necessary to do some bridgework in preventing the entry of microplastics into farm

soils and develop effective solutions to clean them up before they endanger the food production and animal welfare (Ziani et al., 2023). The effect of microplastics on the soil can vary vastly and the type and number of microplastic and the soil type can influence the effects. By altering the bulk density, porosity and capacity to retain water in the soil, microplastic can alter the physical structural architecture of the soil. Research has indicated that in some conditions, microplastic might actually make soil more aerated and porous, allowing plants to thrive. Other reports have however revealed that microplastics may reduce the water holding capacity of soil, something that would expose plants to drought conditions and weaken their growth and overall production (Feyissa et al., 2021). Increasing research is being carried out regarding the impacts of plastic on the soil biota, as well as ease of biodegradability and development of new, non-plastic materials (Scalenghe, 2024). The impact of microplastics on the higher levels of biological organisation cannot be measured nor the impacts of microplastics that have a long history in the environment (Ng et al., 2020). a field study is more difficult because things vary both over time and space. Microplastics are able to alter the chemical composition of the soil, such as pH, the availability of nutrients, etc (Rai et al., 2023). Microplastics may disrupt the homeostasis of nutrient cycling within the soils



and that might affect plant nutrition, as well as overall soil fertility (Feyissa et al., 2021). Indirect influences of microplastics on plant growth can also be caused by the alteration of soil microbial work and composition (Scalenghe, 2024). where others found that some microorganisms can degrade microplastics or be used as an alternative source of carbon (Lin et al., 2020). Having varieties of soil based on the type of soil, microplastics may vary in its influence as they may affect the soil in various ways depending on the type and amount of microplastics.

Conclusion

The research provides valuable real-life evidence of the harmful impacts of microplastic in farming soils, particularly those on crop production and the wellbeing of livestock. The statistics evidently indicate that the greater the concentration of microplastics, the larger the decreases in crop biomass, root length, and the yield. There were also up to 35% losses in yields within the highly contaminated treatments. Microplastic abundance in soil prevented the growth of roots and reduced the breathing of soil. This indicates a form of influence of the soil structure and the level of microbe activity which are both relevant when it comes to enabling plants to access nutrients and maintain good soil. The calculated animal exposure index also indicated that the accumulation of microplastic in soils not only damages crops, but it also provides a

significant ecological risk to grazing animals since these animals can ingest contaminated soil and feed. Statistical significant correlations indicate that the negative management between the quantity of microplastics in the soil and crop plant development is very large. It was also confirmed by Regression analysis that the prevalence of microplastics in the soil is the principal parameter, which influences agricultural loss of yield. Less-polluted dry lands which were Treatment_1 and Treatment_5 had a higher sustainability score on all variables. It indicates just how mitigation of the use of microplastic in farming can actually benefit the environment. The boxplot and hybrid visualisations revealed even more that responses were different and that microplastic induced stress affected certain individuals more than others. Such findings demonstrate the necessity of having unified schemes of waste management and a change in agricultural policy that would curtail the use of plastic and prevent microplastics on farms. An advancement in the study has made it evident that unless some measures are taken, accumulation of microplastics in the long term may become a risk to food security, soil quality as well as animal health within agroecosystems. It is one of the big environmental and agricultural problems that should be solved immediately.

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