



Soil texture modifies the impact of microplastics on winter wheat growth

Katharina J. Neubert¹ · Nicolas Brüggemann¹

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Abstract

Purpose Research on the impact of microplastics (MPs) on plant performance has primarily focused on MP type or concentration, often neglecting the role of soil texture.

Methods In this study, a 42-day experiment was conducted in which winter wheat was grown in three soils of different textures, contaminated with two types of MPs: low-density polyethylene particles (LDPE) and polyester fibers (PES) at 0.4% concentration. The effects on soil water content, nutrient levels, and plant growth were examined.

Results In silty loam, LDPE reduced root length and biomass, likely due to altered soil texture, which created more macropores and reduced water and nutrient availability. PES fibers had similar effects, indicating that changes in soil porosity impacted root access to resources. In sandy loam, both MP types reduced root growth, with PES fibers causing a significant 85% reduction in root length and decreasing nitrogen content, suggesting impaired nutrient availability due to reduced nitrification. Conversely, in silty clay loam, LDPE increased root length by 4.6 times, likely due to enhanced water movement pathways, although it also increased water loss. PES fibers showed minimal positive effects on root growth but reduced nutrient content.

Conclusion Overall, soil texture had a significant impact on how MP affected plant growth, as the two types of MP had different effects on different soil textures. LDPE increased macroporosity in fine soils, promoting root growth, but reduced nutrient uptake in coarse soils. PES fibers influenced soil structure, affecting water retention and nutrient availability differently in different soil types. The study highlights the complexity of MP–soil–plant interactions. Moreover, it also calls attention to rethinking soil management in the future, such as using biodegradable alternatives, applying biochar or avoiding plastic-coated controlled-release fertilizers.

Keywords Plant performance · Winter wheat · Low-density polyethylene (LDPE) · Polyester fibers (PES)

Abbreviations

AL	Albic Luvisol
CAL	Calcium-Acetate Lactate Solution
Car	Carotenoid
CH	Chernozem
chl _a	Chlorophyll-a

chl _b	Chlorophyll-b
C _{org}	Organic Carbon
HDPE	High-Density Polyethylene
K _{av}	Plant-Available Potassium
LDPE	Low-Density Polyethylene
LU	Luvisol
MP	Microplastic
NH ₄ ⁺	Ammonia
N _{min}	Plant-Available Mineral Nitrogen
NO ₂ ⁻	Nitrite
NO ₃ ⁻	Nitrate
N _t	Total Nitrogen
P _{av}	Plant-Available Phosphate
PES	Polyester
PP	Polypropylene
PS	Polystyrene

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✉ Katharina J. Neubert
k.neubert@fz-juelich.de

Nicolas Brüggemann
n.brueggemann@fz-juelich.de

¹ Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, Agrosphere (IBG-3), Wilhelm-Johnen-Straße, 52428 Jülich, Germany

PVC Polyvinylchloride
 WHC Water-Holding Capacity

1 Introduction

Plastic waste, a ubiquitous characteristic of the Anthropocene, has pervaded natural environments, with microplastic (MP) pollution emerging as a global environmental challenge. MPs, defined as plastic particles or synthetic fibers smaller than 5 millimeters, raise concerns about their long-term impact on ecosystems and associated hydrological and biogeochemical processes (Bian et al. 2022; Wang et al. 2022a). While our understanding of these impacts is evolving, it is clear that MPs are increasingly accumulating in the environment.

Terrestrial ecosystems and soils have become significant reservoirs for MP accumulation, with approximately 80% of marine plastic waste originating from land sources (Andrady 2011; Jambeck et al. 2015). Various activities contribute to MP pollution, including wastewater irrigation, sewage sludge utilization (Corradini et al. 2019), atmospheric deposition (Klein and Fischer 2019), and plastic film mulching (Wang et al. 2022b). In agricultural soils, polyethylene (PE) and polyester fibers (PES) are commonly found plastic types, which is plausible, as the sum of low-density and high-density PE (LDPE and HDPE) accounts for almost 30% of the total plastic production in Germany (Fuhr, 2019). LDPE, for example, is ductile, flexible and transparent, and is therefore used in films. PES fibers, which are synthesized from petrochemical-based polyethylene terephthalate (PET), accounted for the highest share of synthetic fiber production in 2017, at 80% (Fuhr, 2019). They have been detected in the soil of agricultural fields, mostly due to the application of sewage sludge (Büks and Kaupenjohann 2020). Around 80–99% of the microfibers contained in wastewater are retained in sewage treatment plants and end up in sewage sludge, resulting in concentrations ranging from 1,000 to 56,400 particles kg⁻¹ dry sewage sludge (Mahon et al. 2017; Mintenig et al. 2017; Zubris and Richards 2005). Global trends that contribute to plastic contamination, particularly in agriculture, include the use of plastic seedling trays, protective meshes or plastic irrigation tubing, as well as some fertilizers and pesticides which are encapsulated in plastic coatings. According to Meizoso-Regueira et al. (2024), fertilized soils have a 0.47% higher growth rate of MPs.

The concerning prevalence of MPs in agricultural fields has prompted a series of research efforts aimed at understanding and addressing their impact. On the one hand, scientists have focused on mitigation strategies to reduce MP contamination and prevent its accumulation in soil. These

include more targeted use of fertilizers and pesticides with the use of GPS and sensor-based equipment (Nakachew et al. 2024) or the development of biodegradable fertilizer which embeds nutrient granules in naturally generated, biodegradable plastic (Witt et al. 2024). On the other hand, it is equally important to evaluate whether MP exposure has specific effects on plant growth and physiology, particularly in wheat as one of the world's major staple crops (Gkoutselis et al. 2021; Liu et al. 2022; Wang et al. 2020, 2022b; Zang et al. 2020; Zhou et al. 2021). However, results pertaining to the effects of MP contamination in agricultural soil on wheat root and shoot growth have been controversial, reporting increase (Liu et al. 2022), dose-dependent decrease (Zang et al. 2020), or no discernible changes in wheat growth (Lozano et al. 2021a; Mészáros et al. 2023). As an example, one study reported an increase in biomass of both wheat roots and shoots of up to 200% (Liu et al. 2022), while another study claimed a reduction of wheat and shoot biomass by 13–53%, despite using PE and polyvinyl chloride (PVC) in the same concentrations of 1% and 5% in soil (Zang et al. 2020). Liu et al. (2022) assumed that these differences could have been caused by the different soil types used. Likewise, while it was shown that PES in a loamy sand decreased soil bulk density, which affects root growth (de Souza Machado et al. 2019), another study using a clay loam could not confirm these findings although they used the same type and concentration of MP fibers (Zhang et al. 2019). These contradictions underscore the need to study the influence of soil type on MP effects on plant growth, in addition to the type, size, and concentration of MPs used.

Nevertheless, awareness has increased that soil characteristics can have a potential impact on MP effects, thereby influencing root growth indirectly (Krehl et al. 2022). On the one hand, an altered soil structure due to MP contamination can impact soil hydraulic properties, such as water-holding capacity (Guo et al. 2022), water flow in the soil pore space (Hangele et al. 2020) or field capacity (Qi et al. 2020). Especially fibers in soil have been shown to have a more pronounced effect on soil hydraulic properties compared to granular MPs (de Souza Machado et al. 2019; Ingrassia et al. 2022a; Lehmann et al. 2021; Lozano et al. 2021a; Yu and Flury 2022). This is because the fibrous, flexible nature of MP fibers can rearrange soil structure more extensively than particles and can lead to increased or reduced aggregation (Lozano et al. 2021b), depending on soil type. Especially in the presence of soil biota, microfibers reduced soil aggregate stability (Lehmann et al. 2019). However, some studies have found that polyester fibers can actually increase the formation and stability of soil macroaggregates, particularly in clay-rich soils (Ingrassia et al. 2022b; Lehmann et al. 2021). This suggests that the effects of polyester fibers on soil aggregation are complex and depend on factors like

soil texture, mineralogy, and the presence of a microbial community.

On the other hand, the changes in soil properties can also create selection pressure, driving changes in soil microbial communities, their habitats and functions, and further impacting plant performance. For example, the increase in porosity by MP in soil was found to increase air flow and to be beneficial for the growth of aerobic microbes (Wang et al. 2023), but can also affect the performance of wheat seedlings negatively (Zhang et al. 2024). Due to these indirect alterations in microbial communities in soil, nutrient dynamics and enzyme activities are changed or even impaired (Chen et al. 2022; Liu et al. 2023). It has also been reported that the hydrophobic surface of MPs is a suitable niche for a wide variety of microorganisms (Miao et al. 2019). As a result, the definition of the plastisphere, a term which was introduced in the marine literature (Zettler et al. 2013), has been extended to the terrestrial realm and defined as the soil volume immediately influenced by the plastic particles (Rillig et al. 2024).

Another important factor determining plant performance is the unrestricted functioning of the rhizosphere, characterized as the soil region influenced by plant roots, and playing an important role in nutrient dynamics, such as mineralization or denitrification and nutrient acquisition (Pii et al. 2015; Richardson et al. 2009). In this context, an increased ammonium (NH_4^+) and nitrate (NO_3^-) consumption by wheat roots and subsequent disturbance of the rhizospheric microbial community were detected after the addition of PE in soil at 5%, using in situ soil zymography techniques (Liu et al. 2022). Moreover, it was found that the addition of 1%-w LDPE as MP significantly altered the bacterial community composition in the rhizosphere of wheat compared to the control (Qi et al. 2020) by disrupting beneficial plant-microbe interactions in the rhizosphere. The variations in volatile compounds and microbial communities caused by LDPE residues may account for the observed negative effects on wheat growth.

These findings underscore the multifaceted impacts of MPs on soil-plant interactions and highlight the need for further investigation. To this end, we addressed the current knowledge gaps by introducing LDPE particles and PES fibers, varying in their shape (particle vs. fiber), into three different soil types. We hypothesized that the impacts of

MPs on plant performance would vary not only as a function of polymer type and morphology, but would also depend on the respective soil's inherent properties, and primarily on its texture.

2 Materials and methods

2.1 Soils

Three soil types were used in the study: (i) a Luvisol (LU) with a loamy silt texture, (ii) an Albic Luvisol (AL) with a loamy sand texture, and (iii) a Chernozem (CH) with a silty clay loam texture. The basic soil characteristics of the three different soils are listed in Table 1. The two soils CH and LU did not differ largely in soil texture but in their organic carbon (C_{org}) content ($\text{CH}=2.06\%$, $\text{LU}=1.01\%$). The LU soil was taken from arable land at the agricultural research station Campus Klein-Altendorf of the University of Bonn, Germany (50.613614°N , 7.000713°E). The AL soil was taken from an agricultural field of the Albrecht Daniel Thaer Institute for Agriculture and Horticulture Sciences of the Humboldt University of Berlin located in Thyrow, Germany (52.254674°N , 13.236030°E). The third soil type, CH, was collected from the agricultural research station of the Helmholtz Centre for Environmental Sciences (UFZ), located in Bad Lauchstädt, Germany (51.393447°N , 11.875048°E). All soil types were taken from 0 to 20 cm depth, air-dried and sieved to 2 mm.

It must be acknowledged that it was impossible to definitively exclude the presence of MPs and/or nanoplastics in the soil types used, considering that the agricultural areas from which the soil was taken may have been subject to anthropogenic pollution. Nonetheless, these sites had no record of plastic mulching or sewage sludge fertilization. Any larger plastic debris found was removed during sieving. In addition, the inclusion of control samples without added MP and the relatively high MP concentration (0.4% by weight, %-w) mitigated any potential bias from prior contamination.

Table 1 Characteristics of experimental soils including organic carbon (C_{org}) content, plant-available mineral nitrogen content (N_{min}), plant-available phosphate (P_{av}) and potassium (K_{av})

Soil type	Abbr.	Texture	Sand	Silt	Clay	pH ¹	C_{org}	N_{min}	P_{av}	K_{av}
			%	%	%		%	$\mu\text{g g}^{-1}$	$\mu\text{g g}^{-1}$	$\mu\text{g g}^{-1}$
Luvisol	LU	Loamy silt	8	77	15	6.5	1.01	168	20	116
Albic Luvisol	AL	Loamy sand	87	10	3	5.1	0.50	37	22	112
Chernozem	CH	Silty clay loam	11	68	21	7.5	2.06	21	12	51

¹pH determined in 0.01 M calcium chloride solution; particle sizes for sand = 63–2000 μm , silt = 2–63 μm and clay < 2 μm

2.2 Microplastics

Based on results on MP pollution of German agricultural soils from literature (de Souza Machado et al. 2019; Piehl et al. 2018) and on results from previously conducted rhizotron plant experiments, LDPE particles and PES fibers were considered significant for further investigation.

LDPE (Goodfellow GmbH, Hamburg, Germany) was used as powder with a particle size of 300–600 μm . The particle size distribution (Fig. S1) was measured with a laser diffraction particles size analyzer (HORIBA LA-950, Irvine, CA, USA) by dispersing the LDPE powder in ethanol. The LDPE powder had a relatively narrow particle size distribution with a mean particle diameter of $444.6 \pm 1.1 \mu\text{m}$.

The PES fibers used were commercially available pillow filling material (JYSK Nordic A/S, Braband, Denmark) with $2.88 \pm 0.17 \text{ mm}$ in length and $0.74 \pm 0.01 \text{ mm}$ in diameter. The average fiber length was determined by manually measuring individual fibers ($n = 50$), while the diameter was determined by analyzing scans (EPSON, Expression, 12000x1, Meerbusch, Germany) of fibers using the software tool WinRHIZO (Regent Instruments Inc., Québec, Canada). The polymer structure was PET, which was confirmed via Raman spectroscopy (Fig. S2). A piece of a PET plastic bottle was used as a reference material for PET, and its spectrum matched the spectrum of the fibers.

2.3 Experimental design

For the pot experiment, sewage pipes (10 cm diameter, 80 cm length) made of polypropylene (PP) were used. Potential contamination of the soil with PP plastic debris or additives from the PP pipes was considered negligible, as the 42-day exposure period was insufficient for significant weathering processes of the PP plastic due to UV radiation. To allow for optimal drainage and aeration, these pipes were equipped with perforated caps at the bottom, covered inside with a cloth, and supplemented with a layer of 2 cm quartz sand. To ensure stable temperature conditions in the root zone, the pipes were installed in empty lysimeter spaces on the campus of Forschungszentrum Jülich (50.908738°N, 6.403356°E), embedded in a custom-made polystyrene rack with only the top 10 cm of the PP pipes above ground.

Prior to filling the pipes, the air-dried soils were mixed with 0.4%-w of the respective MP type by manually stirring the mixture in a box for 5 min. According to de Souza Machado et al. (2018a), the applied mass concentration of 0.4%-w was the upper limit of MP concentration at which the MP-amended soils show only minor changes in total volume. The control of each soil without the addition of MP followed the same procedure. Subsequently, the sewage pipes were then gradually filled with portions of approximately

300 g of soil, which were carefully compacted by hitting the pipes to the ground, achieving compaction densities of 1.5, 1.7, and 1.3 g cm^{-3} for dry LU, AL, and CH, respectively, which corresponded to the bulk densities of these soils in the field. Final amounts of soil within the columns for LU, AL and CH soil, were $8.7 \pm 0.3 \text{ kg}$, $9.8 \pm 0.2 \text{ kg}$ and $7.9 \pm 0.2 \text{ kg}$, respectively. A total of nine treatments (three soils $\times$ three MP treatments including the control) were prepared, with each treatment replicated in quadruplicate. To minimize bias, one set of replicates was allocated to each of the four lysimeter spaces (Fig. S3), arranged in squares of 1 m $\times$ 1 m, approximately 3 m apart from each other.

After assembling the soil-filled pipes in the lysimeter spaces, they were irrigated from above with irrigation water equivalent to rainwater to reach 60% of the soil type-specific gravimetric water-holding capacity (WHC) for LU and AL soils, corresponding to a total water content of 20%-w and 11%-w of dry soil, respectively. For the CH soil, the target values was 70% WHC, corresponding to a total water content of 27%-w of dry soil. The initial weight of the soil-filled and irrigated tubes served as reference. After a one-week equilibration period outdoors, two pre-germinated winter wheat seeds (*Triticum aestivum*, variety Nordkap, SAATEN-UNION GmbH, Isernhagen, Germany) of similar size were planted 2 cm deep into the soil in the center of each pipe. Germination had occurred in darkness under ambient conditions on moist paper towels for 24 h. After one week, the less developed seedling was removed.

Plant growth continued for a period of 42 days. Each set of replicates was planted at staggered intervals of one week, thus the total growth period ranged from August until October 2023. Plants were exposed to outdoor weather conditions. The mean temperatures of August, September, and October 2023 were $17.97 \pm 4.24 \text{ }^{\circ}\text{C}$, $17.98 \pm 4.75 \text{ }^{\circ}\text{C}$, and $13.07 \pm 4.25 \text{ }^{\circ}\text{C}$, respectively, with total precipitation of 123.4 mm, 75.1 mm, and 95.0 mm during these months. The weather data were obtained from the weather station located on the campus of the Forschungszentrum Jülich, and exact temperature curves and precipitation are depicted in Fig. S4. To ensure well-watered conditions, soil water content was maintained at the initial level by weighing each tube and replacing the water loss by irrigating every 3 to 4 days from above. Stable temperature conditions in the root zone were maintained throughout the experiment by both the insulating polystyrene rack and the positioning of the pipes below ground level in the empty lysimeter spaces (Fig. S3a). A temperature probe positioned at half the depth of each of the lysimeter spaces indicated realistic soil temperature conditions (Fig. S5). Alongside the continuous monitoring of water content and root zone temperature, regular assessments of shoot length were conducted.

It should be noted that the applied MP concentration of 0.4%-w used in our study was much higher than reported for today's agricultural soils, e.g., <0.002%-w for arable land treated with biosolids for 10 years (Corradini et al. 2019). However, the aim of our study was to investigate a future scenario of MP effects in different soils assuming a constant or even increasing MP input to agricultural soils, and to exclude bias from any potential prior MP content of the soils.

2.4 Soil analysis

On the final sampling day, the soil-filled pipes were cut horizontally with a saw into three compartments of approx. 2000 cm³ volume, representing soil depths of 0–25 cm, 25–50 cm, and 50–75 cm. The root-containing soil of the compartments was stored in plastic bags at -20 °C until further analysis. Immediately before root sampling, soil samples were taken, differentiating between the soil attached to individual roots, labelled as “rhizo soil”, and the surrounding soil without roots, referred to as “bulk soil”. The rhizo soil was carefully brushed from individual roots, while for the bulk soil care was taken to ensure that there were no roots in the soil sample.

For each soil sample, two extractions were performed: one extraction with 0.01 M CaCl₂ for mineral nitrogen content (N_{min}) analysis, and with calcium acetate-calcium lactate solution (CAL) for plant-available potassium (K_{av}) and plant-available phosphate (P_{av}) analysis. The preparation of extraction media was based on VDLUFA (VDLUFA 2016). For each extraction method, 5 g (+/- 10%) of frozen soil sample were weight into 50-ml centrifuge vials (made from PP, Eppendorf AG, Hamburg, Germany) mixed with 40 ml of the respective extraction medium and were shaken horizontally for 1 h at 200 rpm. The resulting mass of soil in extraction medium was 0.125 g ml⁻¹. After centrifuging for 15 min at 3500 rpm, a syringe was used to collect 20 ml of the supernatant. The first 5 ml were discarded through a 0.45 µm syringe filter (made from polyethersulfone, Sartorius AG, Göttingen, Germany) and the remaining 15 ml were pushed through the filter into PTFE vials for further analysis. Samples were stored at -20 °C until further analysis.

The respective pH values were measured in the 0.01 M CaCl₂ extracts for 5 min each with a pH meter (Multi 3630 IDS, Xylem Analytics Germany GmbH, Weilheim, Germany). Prior to the measurements, a two-point calibration of the pH meter using buffer solutions of pH 2 and pH 7 was performed (Xylem Analytics Germany GmbH, Weilheim, Germany). The pH of pure 0.01 M CaCl₂ solution at 20 °C was 5.7.

2.5 Root analysis

Roots were cleaned from attached soil with a water showerhead over a 2-mm sieve. Finally, roots were collected from the sieve and were stored in 50%-v ethanol until roots were scanned and quantified with the software WinRHIZO (Regent Instruments Inc., Québec, Canada). The collected roots were placed individually on a scanner (EPSON, Expression, 12000xl, Meerbusch, Germany), while ensuring that the roots did not overlap extensively. Scans were conducted with a resolution of 600 dpi. A batch analysis of all scans was accomplished with the parameters defined in Table S2. From stereomicroscopic pictures of harvested roots (Fig. S6), a diameter range from 0 to 0.4 mm was chosen for lateral roots, and from 0.4 to 1 mm for primary roots. Diameter classes above 1 mm, which were also assigned by WinRHIZO, were neglected.

2.6 Leaf analysis

On the final harvest day, the wheat shoots were cut and dried at 60 °C for 7 days, after which they were ground in a ball mill (MM200, Retsch GmbH, Haan, Germany). 20 mg of the resulting powder was weighed into 5-ml Eppendorf vials. The powder was mixed with 5 ml of an acetone-water mixture (4:1 v/v) (acetone: analysis grade ≥ 99.8%, Honeywell International Inc., Offenbach, Germany), vortexed for 5 s and shaken for 90 min at 200 rpm in the dark. Vials were centrifuged at 2800 rpm for 15 min, after which 2 mL of the supernatant were transferred into cuvettes and measured photometrically (Genesys 50, Thermo Fisher Scientific, Darmstadt, Germany) at 470, 646 and 663 nm against a blank of the prepared extraction medium. Each sample was measured in triplicate.

The following equations were applied to determine the chlorophyll a (*chl_a*), chlorophyll b (*chl_b*) and the carotenoid (*car*) content within the extracts (Eqs. 1–3). The values were further converted to µg g⁻¹ of leaf powder by dividing though the exact mass concentration.

$$chl_a = Abs_{663} \cdot 12.21 - Abs_{646} \cdot 2.81 \frac{\mu g}{ml} \quad (1)$$

$$chl_b = Abs_{646} \cdot 20.13 - Abs_{663} \cdot 5.03 \frac{\mu g}{ml} \quad (2)$$

$$car = \frac{Abs_{470} \cdot 1000 - Chl_a \cdot 3.27 - Chl_b \cdot 104}{229} \frac{\mu g}{ml} \quad (3)$$

3 Results

3.1 Root analysis

3.1.1 Root lengths

The roots harvested from a soil depth of 75 cm in the control soils were generally longest in the loamy sand AL, with on average 270 ± 60 m, slightly shorter in the loamy silt LU with on average 200 ± 70 m, and shortest in the silty clay loam CH with on average 36 ± 8 m (Fig. 1). In the LU (Fig. 1a) and the AL (Fig. 1b), the same trend of significantly lower root growth in the presence of both MP types was observed. In the LU, LDPE reduced the root length by more than half ($-57\% \pm 29\%$, $p=0.04$), and PES even by two thirds ($-65\% \pm 12\%$, $p=0.01$) of the length measured in the LU control soil. In the sandy AL, LDPE also reduced the total length by half ($-49\% \pm 20\%$, $p=0.01$), while PES reduced the root lengths by $85\% \pm 2\%$ ($p=0.003$). The trend was exactly the opposite in the CH (Fig. 1c), with greater root length in MP treatments compared to the control soil. In comparison to the control, LDPE in CH increased root length by $462\% (\pm 100\%, p=0.002)$. The PES fibers, in contrast, led only to a weak increase in root length ($+45\% \pm 38\%$, $p=0.07$).

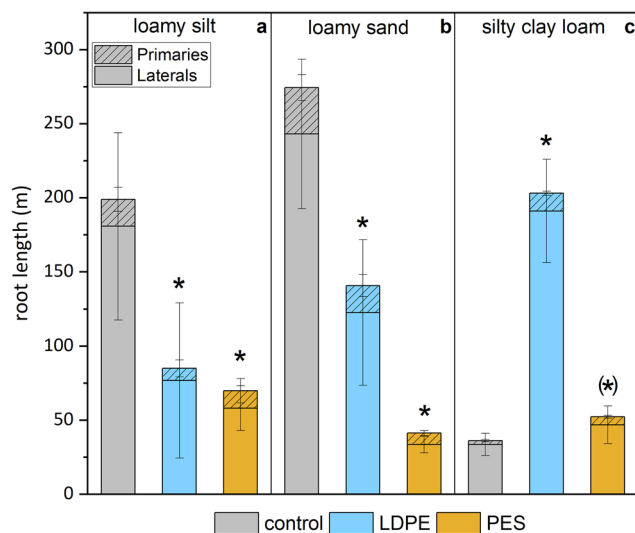


Fig. 1 Mean root lengths (in m) of winter wheat harvested from 75 cm long PVC tubes and grown in (a) the loamy silt Luvisol, (b) the loamy sand Albic Luvisol, and (c) the silty clay loam Chernozem soil for 42 days. Plants were grown with the additions of the microplastic types low-density polyethylene (LDPE) particles and polyester fibers (PES) at 0.4%-w in dry soil. Control is the respective soil type without MP addition. Laterals indicate lateral roots with a width of 0–0.4 mm and Primaries (crosshatched) indicate primary roots with a width of 0.4–1 mm. Bars show the mean values of 4 replicates with whiskers representing the standard deviation. Asterisks show significant difference to the control ($p \leq 0.05$), while asterisks in parentheses show weak significance to the control ($p \leq 0.1$), tested via heteroscedastic, paired t-test

3.1.2 Nutrient content in roots

Analysis of the nutrient content in dried winter wheat roots, including potassium (K), phosphate (P) and total nitrogen (N_t), revealed slight variations for the different soil types (Fig. 2). In particular, the K content in roots grown in all soil types remained below 2.8 mg g^{-1} , and the P content in all root samples was consistently below 1.5 mg g^{-1} . Nevertheless, the N_t content varied in particular between soil types, with the highest values in roots grown in the LU (Fig. 2a) control, ranging from 9 to 13 mg g^{-1} . In contrast, roots grown in AL (Fig. 2b) and CH (Fig. 2c) revealed N_t contents below 7 to 14 mg g^{-1} .

Significant variations in root nutrient content were observed between plants grown in MP-treated soil and control soil across different soil types. Roots in MP-treated LU and AL consistently showed reduced K, P, and N_t contents. The most significant reduction was in N_t uptake, particularly in LU soil amended with LDPE particles and PES fibers ($-92\text{--}93\% \pm 5\%$ less N_t , $p=0.03$). AL soil showed less pronounced but still significant N_t reductions with LDPE ($-36\% \pm 19\%$ less, $p=0.04$) and PES fibers ($-75\% \pm 13\%$ less, $p=0.003$). In CH soil, only PES-treated roots exhibited significantly less N_t ($-64\% \pm 3\%$, $p=0.03$), while LDPE-treated roots were similar to the control. Similarly, the P content of roots in LDPE-treated CH was similar to the CH control, whereas roots in PES-treated CH contained not only significantly less P ($-64\% \pm 12\%$, $p=0.04$) but also less K ($-64\% \pm 17\%$, $p=0.02$). Roots grown in LDPE-treated CH showed significantly higher K content ($+62\% \pm 24\%$, $p=0.02$) compared to the control.

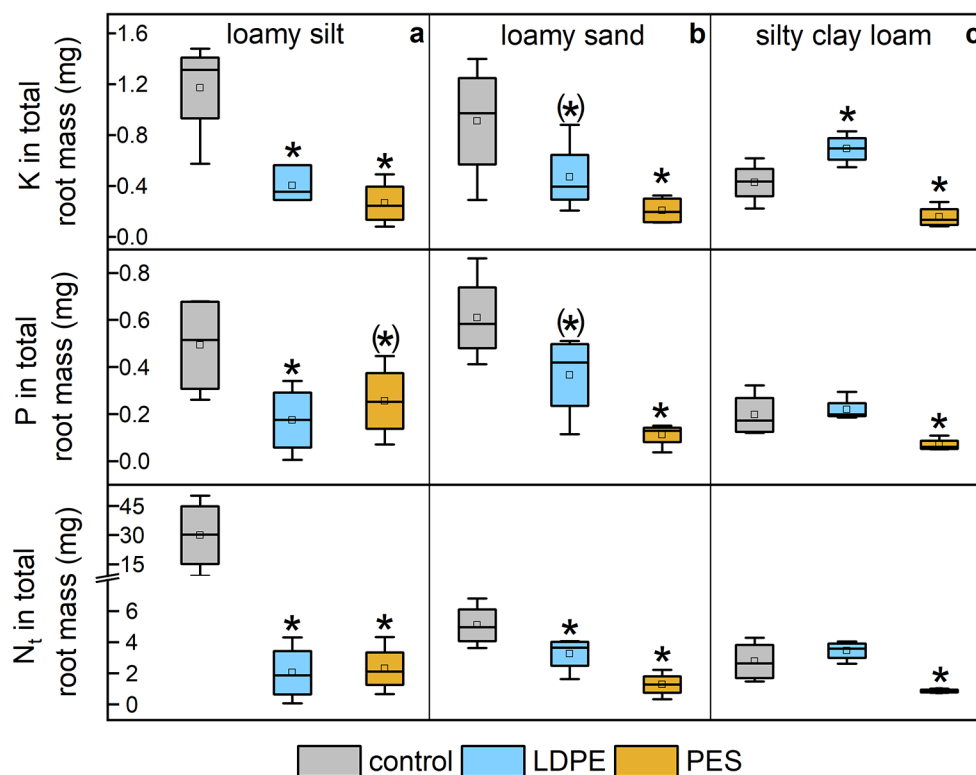
3.2 Soil analysis

3.2.1 Nutrient content in soil

In general, the analysis showed that after the 42-day growth period of winter wheat plants, all soil types exhibited decreased nitrogen levels compared to the initial concentrations before planting (Fig. 3). The most significant reduction after the growth period was found for the nitrate (NO_3^-) content in LU (Fig. 3a), with a decrease of approx. 97%, possibly due to heavy rainfall and leaching events. However, the P_{av} content increased during the growth period, particularly in the loamy silt LU ($+49\% \pm 20\%$, $p=0.02$) and the loamy sand AL ($+42\% \pm 27\%$, $p=0.02$). Conversely, there was no increase in P_{av} content in the silty clay loam CH after the growth period.

While in the LU and CH the contents of most of the N_{min} compounds (NO_3^- , NO_2^- and NH_4^+) and P_{av} and K_{av} remained stable despite the addition of MP, in the sandy AL, nitrite (NO_2^-) and P_{av} content was increased in the presence

Fig. 2 Nutrient content including potassium (K), phosphate (P) and total nitrogen (N_t), in dry pulverized roots of winter wheat grown in (a) the loamy silty Luvisol, (b) the loamy sandy Albic Luvisol, and (c) the silty clayey loamy Chernozem soil for 42 days. Plants were grown with the additions of the microplastic types low-density polyethylene (LDPE) particles and polyester fibers (PES) at 0.4%-w in dry soil. Control is the respective soil type without MP addition. Boxes are the interquartile range (IQR) from the 25th to 75th percentile, lines inside boxes indicate the median, white squares indicate the mean values, upper and lower whiskers are 1.5 times the IQR, and markers are individual data points. Asterisks show significant difference to the control ($p \leq 0.05$), while asterisks in parentheses show weak significance to the control ($p \leq 0.1$), tested via heteroscedastic, paired t-test



of PES fibers compared to the control. Specifically, in the bulk soil of PES-treated AL, P_{av} levels were significantly more increased by $29\% \pm 16\%$ ($p=0.04$) than in the corresponding rhizo soil, which was increased by $20\% \pm 17\%$ ($p=0.09$). LDPE particles in the loamy silt LU led to a slight increase in NO_2^- levels by $30\% \pm 22\%$ ($p=0.07$). Conversely, NO_3^- concentrations decreased by approx. 70% ($p=0.06$) compared to the control in both rhizo and bulk soil of CH.

3.2.2 pH and water content in soil

The pH values were lowest for the loamy sand AL (5.53 ± 0.15) (Fig. 4b), slightly higher for the loamy silt LU (6.58 ± 0.16) (Fig. 4a) and the highest for the silty clay loam CH (7.41 ± 0.04) (Fig. 4c). In the LU, no significant differences in pH were found between bulk and rhizo soil, nor between the MP-treated and control soils. However, pH values were significantly enhanced in the PES-amended AL, where the pH in the rhizo AL was elevated by 0.41 ± 0.23 units ($p=0.02$) and in the bulk AL by 0.32 ± 0.14 units ($p=0.02$). In addition, the pH of the LDPE-treated AL bulk soil was higher than that of the rhizo soil ($+0.13 \pm 0.04$ pH units, $p=0.06$) and also slightly higher than the pH of the control soil. The pH of the PES-treated CH soil was significantly lower than that of the control (-0.08 ± 0.04 pH units, $p=0.03$), and slightly lower in the rhizo soil compared to the respective bulk soil (-0.04 ± 0.04 pH units, $p=0.08$).

In general, the silty clay loam CH had the highest water content, with average gravimetric water content in the CH control of $31\% \pm 1\%$ in rhizo and $26\% \pm 4\%$ in bulk soil (Fig. 5c). Conversely, the silty loam LU contained less water, with average values of $26\% \pm 2\%$ in rhizo and $24\% \pm 3\%$ in bulk soil (Fig. 5a), while the loamy sand AL had the lowest gravimetric water content, averaging at $10\% \pm 2\%$ in both rhizo and bulk soil (Fig. 5b). Notably, PES fibers within the rhizo soil of the finer-textured soil types LU and CH were associated with a considerable variability of soil water content, tending towards lower values compared to their respective controls. However, this trend was not observed in the PES bulk soil. Interestingly, in sandy AL rhizo soil, PES fibers increased water content by $25\% \pm 16\%$, albeit only with marginal significance at $p=0.09$.

3.3 Leaf analysis

3.3.1 Chlorophyll and carotenoid content in leaves

The presence of LDPE in AL consistently resulted in weakly significant reductions in leaf chl_a , chl_b , and car levels, with reductions of $37\% \pm 28\%$ ($p=0.09$), $36\% \pm 29\%$ ($p=0.09$), and $44\% \pm 25\%$ ($p=0.09$), respectively (Fig. 6b). Conversely, LDPE in CH was associated with significant increases in chl_a , chl_b and car leaf contents by 43–47% $\pm 25\%$ ($p=0.05$) compared to the control (Fig. 6c). In contrast to AL and CH, plants grown in MP-amended LU showed no

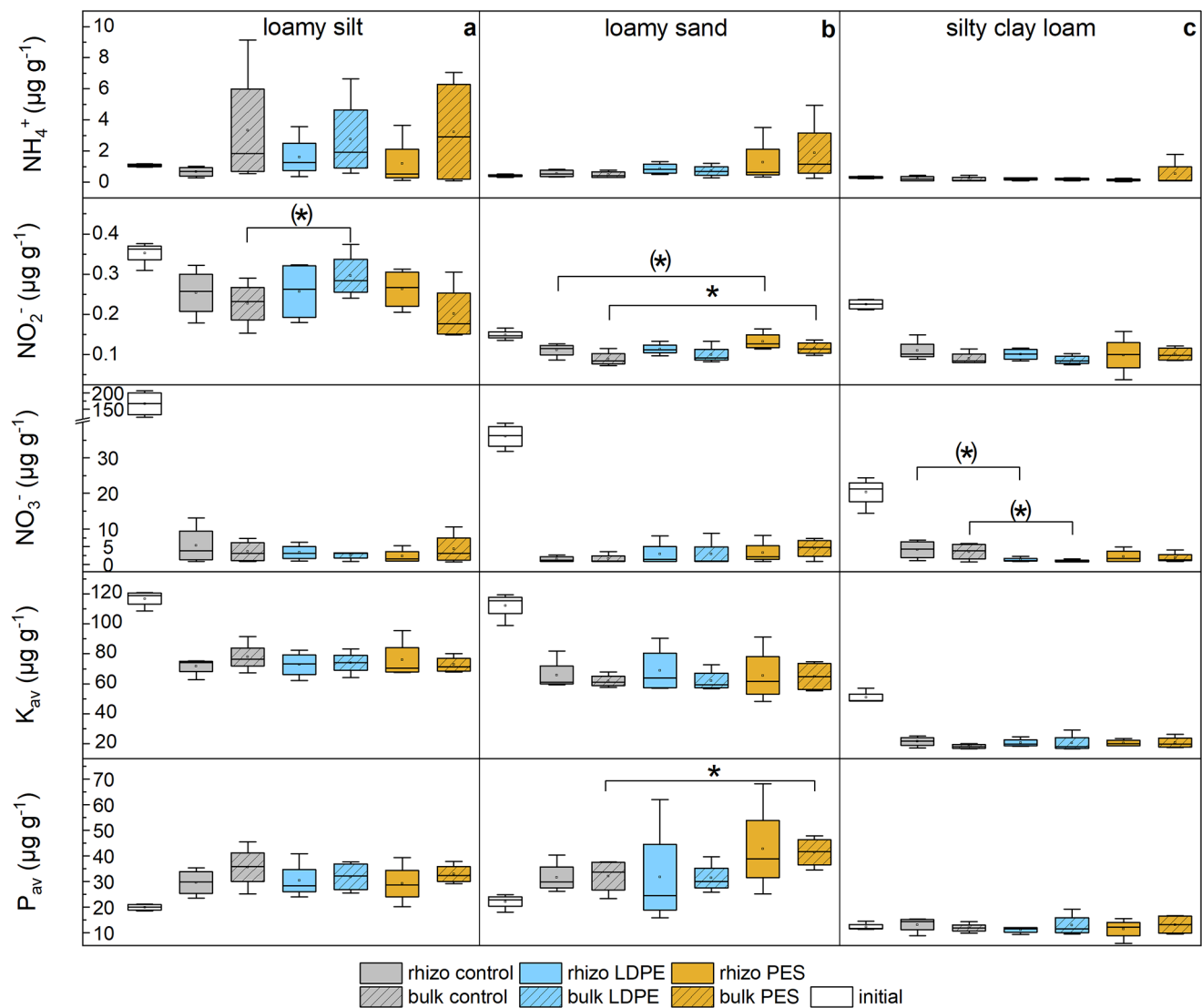


Fig. 3 Soil nutrients including plant-available nitrogen compounds (NH_4^+ = ammonia, NO_2^- = nitrite, NO_3^- = nitrate) and plant-available potassium (K_{av}) and phosphate (P_{av}) content in (a) the loamy silt Luvisol, (b) the loamy sand Albic Luvisol and (c) a silty clay loam Chernozem after the winter wheat growth period of 42 days. Initial refers to the respective nutrient concentration before plants were seeded. Microplastic (MP) types mixed at 0.4%-w in soil were low-density polyethylene (LDPE) and polyester fibers (PES). Control is the respective oil type without MP addition. It was differentiated between

rhizosphere soil (rhizo), which was shaken off the roots, and bulk soil not attached to the roots. Boxes are the interquartile range (IQR) from the 25th to 75th percentile, lines inside boxes indicate the median, white squares indicate the mean values, upper and lower whiskers are 1.5 times the IQR, and markers are individual data points. Asterisks show significant differences to the control ($p \leq 0.05$), while asterisks in parentheses show weak significance ($p \leq 0.1$), tested with heteroscedastic, paired t-test

statistical differences in their *chl* and *car* contents compared to the control (Fig. 6a).

3.3.2 Nutrient content in leaves

The analysis of K, P and N_t content in leaves revealed different patterns among different soil types (Fig. 7). Overall, leaves from plants grown in the loamy silt LU had the highest nutrient contents (Fig. 7a), albeit with the highest variability between replicates. Conversely, leaves of plants

grown in the loamy sand AL (Fig. 7b) showed slight reductions with less variability between replicates, while those of plants grown in the silty clay loam CH (Fig. 7c) had the lowest values of all nutrients tested. Leaves of plants grown in LDPE-treated AL exhibited lower nutrient contents compared to the MP-free control, with a $51\% \pm 10\%$ reduction in K ($p=0.06$), $46\% \pm 6\%$ reduction in P ($p=0.06$), and $45\% \pm 8\%$ reduction in N_t contents ($p=0.03$). The presence of PES in AL led to a slightly significant reduction in P content ($p=0.08$) and a significant reduction in N_t content ($p=0.04$),

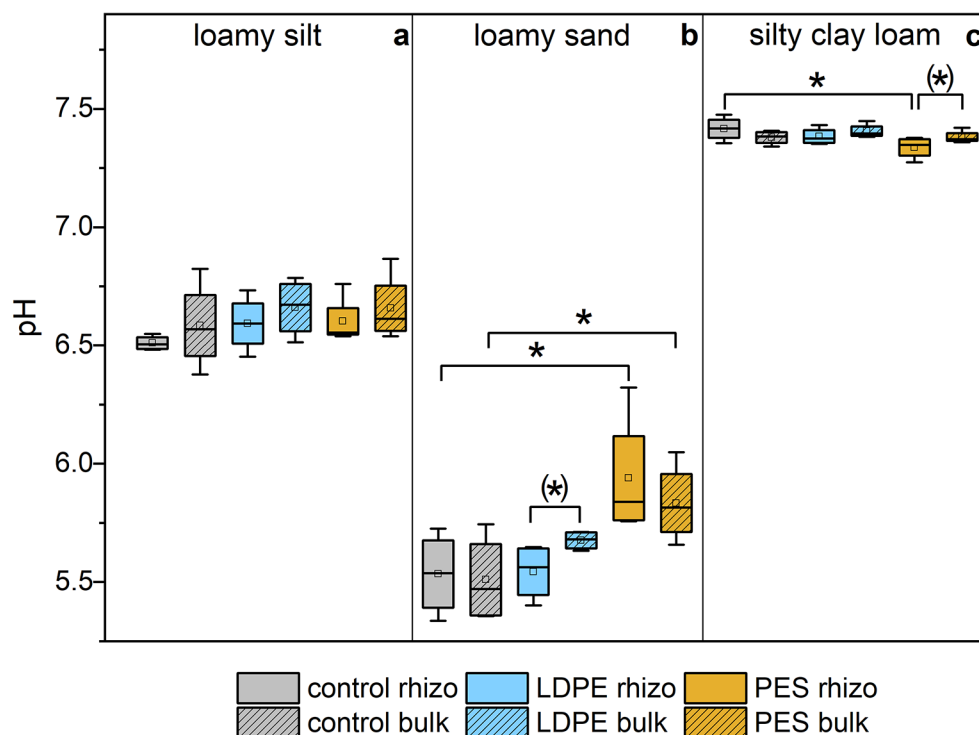


Fig. 4 Soil pH measured in calciumchloride extractions of (a) the loamy silt Luvisol, (b) the loamy sand Albic Luvisol, and (c) the silty clayey loam Chernozem soil measured after the winter wheat growth period of 42 days. Plants were grown with the addition of the microplastic types low-density polyethylene (LDPE) particles and polyester (PES) fibers at 0.4%-w in dry soil. Control is soil type without MP addition. It was differentiated between rhizosphere soil (rhizo), which

was shaken off the roots, and bulk soil not attached to the roots. Boxes are the interquartile range (IQR) from the 25th to 75th percentile, lines inside boxes indicate the median, white squares indicate the mean values, upper and lower whiskers are 1.5 times the IQR, and markers are individual data points. Asterisks show significant difference to the control ($p \leq 0.05$), while asterisks in parentheses show weak significance ($p \leq 0.1$), tested with a heteroscedastic, paired t-test

both decreased by $41\% \pm 9\%$ compared to the control. In LU, only LDPE particles caused a slight reduction in P contents in leaves ($-44\% \pm 22\%$, $p=0.08$). In contrast, plants grown in CH soil did not exhibit significant changes in their leaf nutrient contents in response to the addition of the two MP types.

3.4 Plant biomass and root-to-shoot ratio

In the loamy silt LU, the LDPE treatment significantly decreased root biomass ($p=0.03$), although this did not translate into changes in shoot biomass or the root-to-shoot ratio (Table 2). Plants in the PES fiber-amended LU exhibited slightly reduced root biomass ($p=0.07$) and a corresponding slight decrease in the root-to-shoot ratio ($p=0.1$). In loamy sand AL, plants grown in both the LDPE and PES treatments showed significantly decreased root biomass ($p_{LDPE} = 0.03$, $p_{PES} = 0.009$) and slightly reduced shoot biomass ($p_{LDPE} = 0.05$, $p_{PES} = 0.1$). Among these, only plants grown in the PES-amended sandy AL soil showed a significant reduction in their root-to-shoot ratio ($p=0.03$). Plants grown in the LDPE-amended AL did not differ statistically

from the control, as both root and shoot biomass were equally reduced, leaving the ratio unaffected.

As expected from the root length data, in the silty clay loam CH, the LDPE amendment led to slight increases in root biomass by $52\% \pm 23\%$ ($p=0.07$) and significantly increased shoot biomass ($+65\% \pm 16\%$, $p=0.003$). However, the PES amendments only led to significantly increased shoot biomass ($+43\% \pm 14\%$, $p=0.02$), while root biomass remained unaffected. Nevertheless, the root-to-shoot ratio remained the same, supposedly due to the high variability of the control replicates.

4 Discussion

The effect of LDPE MP particles and PES fibers in soil on winter wheat growth and performance was investigated in three different soil types with distinct textures: loamy silt Luvisol, loamy sand Albic Luvisol and silty clay loam Chernozem. After a growth period of 42 days, soil N, P and K content, pH and water content, root length and nutrient content, and leaf chlorophyll, carotenoid and nutrient contents were analyzed. The results clearly show that LDPE

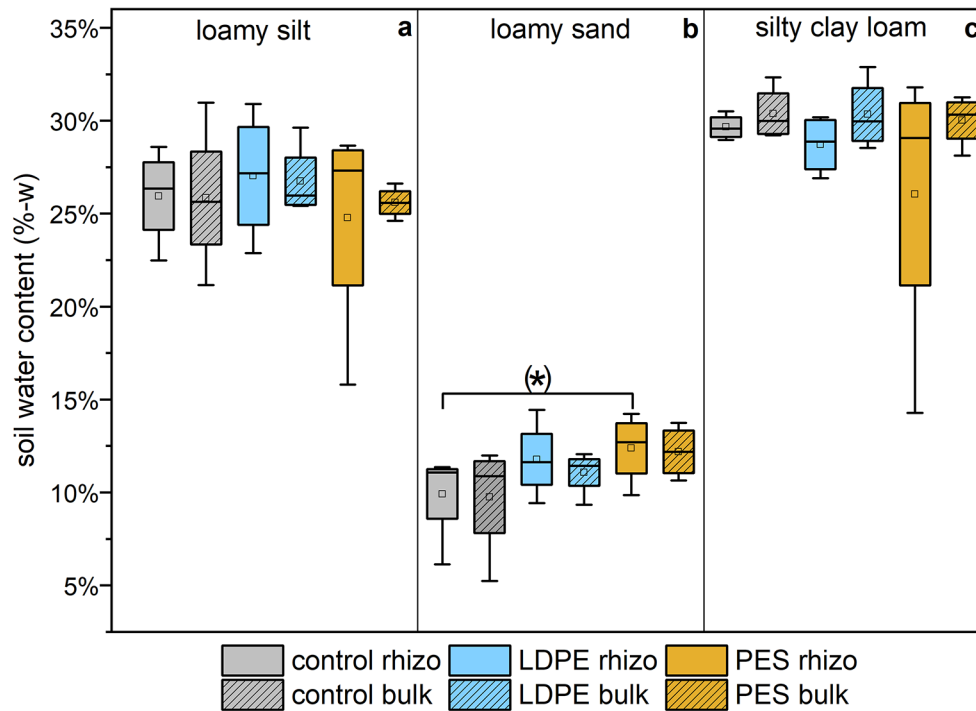


Fig. 5 Soil water content measured gravimetrically in (a) the loamy silt Luvisol, (b) the loamy sand Albic Luvisol, and (c) the silty clayey loam Chernozem soil measured after the winter wheat growth period of 42 days. Plants were grown with the additions of the microplastic types low-density polyethylene (LDPE) particles and polyester fibers (PES) at 0.4%-w in dry soil. Control is the respective soil type without MP addition. It was differentiated between rhizosphere soil (rhizo),

which was shaken off the roots, and bulk soil not attached to the roots. Boxes are the interquartile range (IQR) from the 25th to 75th percentile, lines inside boxes indicate the median, white squares indicate the mean values, upper and lower whiskers are 1.5 times the IQR, and markers are individual data points. Asterisks show significant difference to the control ($p \leq 0.05$), while asterisks in parentheses show weak significance ($p \leq 0.1$), tested with a heteroscedastic, paired t-test

Fig. 6 Chlorophyll content, including chlorophyll-a (chl_a) and chlorophyll-b (chl_b), and carotenoid (car) content in total leaf dry mass of winter wheat, grown for 42 days in (a) the loamy silt Luvisol, (b) the loamy sand Albic Luvisol, and (c) the silty clay loam Chernozem, respectively. LDPE refers to plants grown in 0.4%-w low-density polyethylene particles and PES refers to plants grown in 0.4%-w polyester fibers. Control is the respective soil type without MP addition. Boxes are the interquartile range (IQR) from the 25th to 75th percentile, lines inside boxes indicate the median, white squares indicate the mean values, upper and lower whiskers are 1.5 times the IQR, and markers are individual data points. Asterisks show significant difference to the control ($p \leq 0.05$), while asterisks in parentheses show weak significance ($p \leq 0.1$), tested with a heteroscedastic, paired t-test

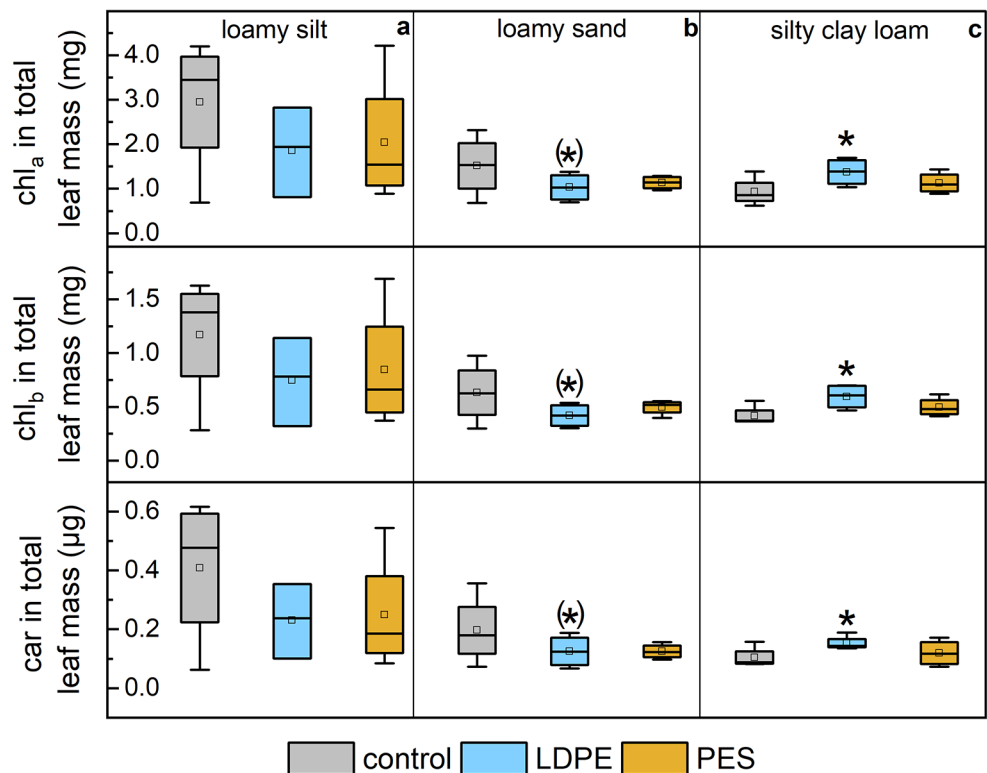


Fig. 7 Nutrient content in total leaf dry mass of winter wheat harvested after 42 days and grown in (a) the loamy silty Luvisol, (b) the loamy sandy Albic Luvisol, and (c) the silty clayey loamy Chernozem, respectively. LDPE refers to plants grown in 0.4%-w low-density polyethylene particles and PES refers to plants grown in 0.4%-w polyester fibers. Control is the respective soil type without MP addition. Boxes are the interquartile range (IQR) from the 25th to 75th percentile, lines inside boxes indicate the median, white squares indicate the mean values, upper and lower whiskers are 1.5 times the IQR, and markers are individual data points. Asterisks show significant differences to the control ($p \leq 0.05$), while asterisks in parentheses show weak significance to the control ($p \leq 0.1$), tested with a heteroscedastic, paired t-test

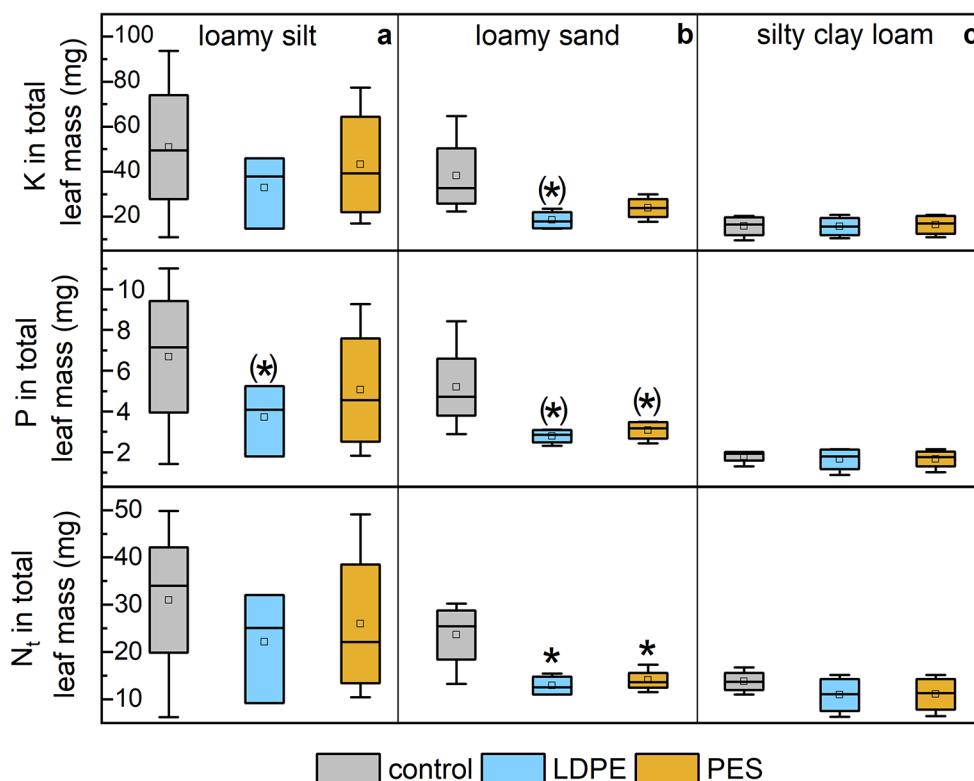


Table 2 Root and shoot biomass (in mg) and root-to-shoot ratio of winter wheat plants grown for 42 days in loamy silt luvisol, loamy sand albic luvisol and silty clay loam Chernozem, in the absence of microplastics (control), and with amendment of either low-density polyethylene (LDPE) particles or polyester (PES) fibers

	Root biomass (mg)			Shoot biomass (mg)			Root-to-shoot ratio (-)		
	control	LDPE	PES	control	LDPE	PES	control	LDPE	PES
Loamy silt	512±157	213±147 ^a	299±147 ^b	1157±665	633±475	1109±606	0.617±0.351	0.717±0.617	0.281±0.057 ^b
Loamy sand	604±154	322±130 ^a	213±43 ^a	875±359	406±78 ^b	528±95 ^b	0.746±0.198	0.844±0.425	0.415±0.107 ^a
Silty clay loam	270±122	411±62 ^b	184±44	400±86	662±58 ^a	572±56 ^a	0.765±0.516	0.626±0.115	0.324±0.076

^asignificant difference to the control ($p \leq 0.05$), ^bweak significant difference to the control ($p \leq 0.1$)

particles and PES fibers at a mass concentration of 0.4%-w influenced the growth and nutrient uptake of winter wheat. However, the observed effects varied depending on the MP type and, more importantly, on the soil type and texture.

4.1 MP effects in loamy silt (Luvisol)

4.1.1 Soil analysis reveals no significant change

At the end of the experiment, a decrease in NO_3^- in the LU was observed, which could be linked to either increased nitrogen uptake or turnover processes, as well as to increased leaching possibly due to heavy rainfall (Fig. S4). However, the presence of both MP types did not significantly affect soil NO_3^- content in our study. Moreover, the soil analysis in general did not reveal any significant statistical differences in nutrient content, pH or water content in the presence or absence of MP in the loamy silt LU. Only a slight

increase in NO_2^- levels in LDPE-treated bulk LU soil was detectable (Fig. 3a).

4.1.2 LDPE effects on root growth, soil structure and water availability

In addition, LDPE in LU significantly reduced wheat root length (Fig. 1a) and biomass (Table 2). Previous research has demonstrated that LDPE particles and fragments present in soil can impact soil structure, potentially reducing the stability of aggregates and fostering the formation of larger soil pores, known as macropores (Krehl et al. 2022). This alteration can accelerate drainage through macropores, as capillary forces are reduced, potentially leading to increased water loss. However, the extent of this effect varies depending on the concentration of LDPE particles and soil texture. For instance, it has been reported that LDPE fragments are capable of disturbing and expanding the soil structure in clay-rich soils with fine texture but not in sandy soils with

coarse texture (Krehl et al. 2022). In our study, the loamy silt texture of the LU was at the finer end of the soil texture spectrum. This suggests that LDPE particles at a concentration of 0.4%-w likely widened the soil texture, creating additional macropores and potentially reduced water availability to roots. As proposed by Daneshian et al. (2021), water flow in soil depends on the structure and connectivity of the pore space within the soil matrix. With additional macropores and less connected pore space, LDPE particles may have disrupted the continuous water phase within soil pores, which is essential for efficient water flow through the pore matrix. Roots growing in this altered loamy silt texture, characterized by increased macropores, may have more space for expansion but could have also faced reduced water and nutrient access compared to roots in the original texture, leading to impaired root development as observed in our results.

4.1.3 Nutrient reductions in LDPE-treated roots

Furthermore, the P, K and N_t content of the roots grown in LDPE-amended LU were significantly reduced (Fig. 2a). The significant reduction in P content of the roots was mirrored in slightly reduced P contents of the leaves (Fig. 7a). This is plausible as there is a strong relationship between root and shoot P levels in winter wheat. The regulation of phosphate influx involves complex root-shoot interactions, suggesting that P levels in roots directly influence those in leaves (AdAlsteinsson et al. 1994). In contrast, there was no significant difference in the root-to-shoot ratio of the LDPE treatment compared to the control. Literature indicates that while many MP types negatively impact root biomass, shoot biomass may either increase or remain unchanged, depending on soil type and MP concentration (Chen et al. 2025). Consequently, the root-to-shoot ratio is rarely significantly affected, as observed in our study. The fact that roots also showed reduced N_t contents at early growth stages of the plants suggests a reduced nitrogen availability, as also indicated by Farow et al. (2024).

4.1.4 Textural changes by PES fiber addition and effects on root growth

In the presence of PES fibers in loamy silt soil, almost the same results for root development and plant performance were obtained as in the presence of LDPE particles. This was reflected in reduced root elongation (Fig. 1a) and a slight reduction in root biomass (Table 2) as well as significantly reduced root nutrient contents (Fig. 2a), but without significant effects on leaf biomass or nutrient content (Table 2; Fig. 7a). Other studies also indicated a strong dependency of the MP effects, e.g., for PES fibers, on soil

physico-chemical properties, such as texture, clay mineralogy, organic matter content, as well as aggregation (Ingraffia et al. 2021). For example, while in a clay-rich Vertisol PES fibers increased macroporosity, no changes in the capacitive indicators of soil physical quality (including macroporosity) were observed in a loamy Entisol after the addition of PES fibers (Ingraffia et al. 2021).

However, our results indicate that the presence of PES fibers in the loamy silt LU led to changes in texture, potentially by restructuring the soil, enhancing the porosity and leading to accelerated water loss, through which the roots may have faced significantly lower water and nutrient availability. The reduction of soil aggregates, particularly in fiber-amended soil, has already been demonstrated due to the fibers' linear shape, hydrophobic nature and flexibility, which impedes macroaggregate formation from microaggregates (Lozano et al. 2021b). This rearrangement of soil pores influences soil-water characteristics, as larger pores facilitate soil drainage.

4.2 MP effects in loamy sand (Albic Luvisol)

4.2.1 Changes in soil nutrient content in PES fiber-treated loamy sand

After adding PES fibers, the loamy sand AL showed reduced NO_2^- and P_{av} levels (Fig. 3b). Moreover, plants grown in the loamy sand mixed with PES fibers also had reduced N_t and P contents in their root biomass (Fig. 2b). The enhanced NO_2^- level in soil could be linked to an imbalanced nitrification process in soil, potentially reducing nitrogen availability for plants. NO_2^- is an intermediate product of the nitrification process, which produces NO_3^- as end product, the main form of nitrogen used by modern cereal cultivars (Lyu et al. 2022). Enhanced levels of this intermediate product could be linked to different causes, such as incomplete nitrification (i.e., inhibition of nitrite oxidizers), anaerobic ammonium oxidation to NO_2^- or increased denitrification rates, reducing NO_3^- to NO_2^- (Giles et al. 2012).

4.2.2 Impact of PES fibers on oxygen availability for soil microorganisms and roots

Interestingly, soil water content and soil pH of the PES fiber-treated AL were significantly increased compared to the control, indicating on the one hand less aeration due to more water-filled soil pores, and on the other hand changed environmental conditions for microorganisms. Sandy soils typically show good water drainage associated with comparably low water-holding capacity due to the texture-related macroporosity. Recent studies have shown that the addition of fibers tends to increase water-holding capacity and water

retention in sandy soils (de Souza Machado et al. 2018b; Souza Machado et al. 2019; Lozano and Rillig 2020). As a result, air-filled pores are reduced, potentially limiting the oxygen availability for aerobic microbial processes and potentially promoting anaerobic microbial processes.

Considering that NO_2^- levels were significantly elevated in this sandy soil, it is likely that nitrite-oxidizing bacteria (NOB), which require oxygen as a terminal electron acceptor to oxidize NO_2^- to NO_3^- , were limited in their NO_2^- oxidation rates due to limited oxygen availability (Beman et al. 2021; Daims et al. 2016). These NOB prefer a neutral to alkaline pH between 7.0 and 7.8 (Daebeler et al. 2020). In our study, the pH of the PES fiber-amended AL ranged between 5.7 and 6.0, i.e., far from the preferred pH range of NOB, but still significantly less acidic than the control soil, which had a mean pH of 5.5 (Fig. 4b). As a result, the significantly reduced N content of roots grown in AL with PES fibers could be linked to a decreased nitrification rate due to a decreased NOB activity, providing less NO_3^- for the plant.

However, the reduced root growth (Fig. 1b) in the PES-amended AL can hardly be assigned to the factor of a decreased NOB activity alone. As the relationship between nitrogen content and root length in winter wheat is complex and depends on various factors (i.e., pH, interaction with other nutrients, feedback mechanisms; Shi et al. 2023), it can be assumed that also root gas exchange might have been impaired due to the reduced air-filled pores in the fiber-amended AL, leading to adverse conditions for roots. Overall, the changed environmental conditions as stated above could have been the driving factors for this strong reduction in root growth by 85%.

4.2.3 Reduced phosphate and potassium contents in PES-treated plants

The notable increase in soil P_{av} content found in PES fiber-treated AL might be attributed to a reduced P_{av} uptake efficiency by the roots, possibly due to the above-mentioned alteration of the soil water status. This assumption is further supported by the significant decrease (-64%) in root P content (Fig. 2b) and the marginal decline in leaf P content (Fig. 7b). However, the reduction in root K content did not correspond to a similar decrease in leaf K content. While speculative, it can be assumed that due to limited root uptake, plants may reallocate K from roots to younger, actively growing tissues like leaves to maintain adequate K levels and therefore crucial metabolic processes, such as photosynthesis (Sustr et al. 2019). This reallocation may have been the reason for reduced root development and K content, prioritizing leaf growth instead.

4.2.4 Reduced root-to-shoot ratio in PES fiber-treated plants

The root-to-shoot ratio of plants provides insight into the plant's resource allocation and growth dynamics. The root-to-shoot ratio of winter wheat grown in AL mixed with PES fibers was reduced by on average almost half (Table 2). That was due to the strong reduction in root biomass, but only low reduction in shoot biomass. In our study, all mean root-to-shoot ratios of winter wheat plants were below one. This trend towards lower root-to-shoot ratios in modern wheat cultivars likely reflects adaptation and selection under favorable conditions during breeding with sufficient water and nutrient supply (Zhu et al. 2019). Nonetheless, we could show that plants grown in PES fiber-amended sandy soil had an even lower root-to-shoot ratio, which indicates that plants invested even less in root growth than in shoot growth, although shoot growth was reduced compared to the control.

4.2.5 Reduced leaf nitrogen content in PES fiber-treated plants

The roots in PES fiber-treated AL may have experienced a reduced oxygen availability due to the increasing effect of the PES fibers on soil water retention, which can affect root nutrient uptake (Pais et al. 2023). The significantly reduced leaf nitrogen content (Fig. 7b) supports this assumption, although the leaf chlorophyll and carotenoid contents were not significantly affected (Fig. 6b), indicating that photosynthetic performance was most probably not affected despite the reduced nitrogen content.

4.2.6 LDPE effects on root growth and water availability

LDPE particles in loamy sand AL also reduced root length (Fig. 1b) and biomass (Table 2) by on average almost half. Moreover, roots showed slightly reduced P and K contents and were significantly reduced in their nitrogen content. A reason for the reduced root growth and impaired nutrient acquisition might be the direct interaction of LDPE particles with the sandy soil texture, thereby indirectly affecting water and root conditions in the soil. As already demonstrated previously, increasing concentrations of LDPE film fragments in sandy soils created larger pores between soil particles, thereby accelerating water loss (Krehl et al. 2022).

As this effect may be strongly correlated with the amount and material properties of the LDPE (film vs. particle), it could not be unambiguously revealed whether the LDPE particles used in our study led to comparable effects. Nevertheless, it is likely that LDPE particles interact directly with the soil matrix, blocking water pathways through the

soil pore space and limiting nutrient diffusion within the water phase, resulting in a negative impact on root growth. This has already been demonstrated by Tötzke et al. (2024), where plastic film fragments in soil impeded effective water pathways and significantly affected water flow in the soil, confirmed by X-ray tomography and neutron imaging.

4.2.7 Implications of LDPE effects on plant nutrient uptake and biomass

As a result, shorter roots take up less nutrients and provide less nitrogen for chlorophyll synthesis than longer roots (Fig. 6b), which could impair photosynthesis. Impaired photosynthesis leads to reduced supply of photosynthates, reflected in reduced biomass of both roots and shoots (Table 2), as it was observed for plants grown in the LDPE-amended sandy soil.

4.3 MP effects in silty clay loam (Chernozem)

4.3.1 Increased root length in LDPE-treated silty clay loam

In the silty clay loam CH soil, it was particularly striking that the LDPE treatment resulted in greater root length compared to the control. In addition, due to significantly higher root K levels and increased *chl/car* content in the leaves, plants grown in the LDPE-amended CH soil grew better than those in the control. We assume that the high water content of the silty clay loam CH generally led to more anoxic or microoxic conditions for the roots compared to the other two soils, as reflected in the reduced root length of the control. Furthermore, it can be concluded that LDPE particles provided better aeration of the root zone compared to the control without LDPE by creating macropores. This would explain why significantly higher root growth was observed in LDPE-treated CH (Fig. 1c), but only marginal increases in root biomass (Table 2) and slightly reduced NO_3^- content of the soil. The reduced NO_3^- content of the soil could be linked to increased NO_3^- absorption due to the greater root length in this treatment compared to the control (Fig. 1c).

4.3.2 LDPE-induced reduction of waterlogging and positive effects for root growth

Previous studies have shown that LDPE particles in soil can decrease soil bulk density and reduce the stability of soil aggregates, particularly when concentrations exceed 0.2%-w and when MP particles are larger than the soil particles, thereby disturbing aggregate formation (Joos and De Tender 2022; Krehl et al. 2022). Notably, our LDPE particles, ranging from 300 to 600 μm , exceeded the size of soil particles found in the clay and silt fraction of the

CH, which typically range from 2 to 50 μm for silt and <2 μm for clay. Consequently, soil water could be transported along the plastic surfaces at a significantly faster rate than between soil pores. Thus, the presence of LDPE particles could have created pathways and channels in the soil, enhancing hydraulic conductivity (Wan et al. 2019) and consequently reducing the negative effects of waterlogging, such as anoxic conditions for the roots. Guo et al. (2022) and Shafea et al. (2023) both reported an increase in macropores and therefore a reduction in water retention due to PS (Shafea et al. 2023) and PP (Guo et al. 2022) addition to soil. Moreover, the impact of macropore addition on water retention would be more pronounced in clay-rich soils with higher carbon content, such as our silty clay loam CH, compared to sandy or loamy soils (Guo et al. 2022). The potential creation of additional pathways could have stimulated roots to grow deeper into the soil compared to the control, as they might have faced better root conditions, such as better aeration of the subsoil. The alteration of the pore space both between and within aggregates, influencing water and air movement as well as root development, could explain the observed greater root length in the silty clay loam CH containing LDPE particles.

4.3.3 Increased potassium absorption due to enhanced root system in LDPE-treated silty clay loam

The root K content was significantly higher in the LDPE treatment, potentially due to the larger root system, providing more surface area with more absorption sites for K^+ ions (Bell et al. 2021). Also, a higher number of root hairs and finer branching increase the effective surface area for nutrient absorption (Bell et al. 2021), which was only seen for K absorption in our study. Moreover, an extended root system could have released more exudates like organic acids, helping to solubilize K from mineral sources in the soil, thereby increasing the availability for absorption (Xu et al. 2021). Consequently, the presence of LDPE particles likely mitigated the impairment of root absorption and the release of exudates near the root zone, compared to the control.

4.3.4 Resource allocation and plant growth in LDPE-treated silty clay loam

Although there was no indication of increased nitrogen uptake from the silty clay loam soil containing LDPE particles (Fig. 3c), nor of elevated leaf nitrogen content (Fig. 7c), the chlorophyll and carotenoid contents were increased (Fig. 6c). The increase in leaf biomass and a root-to-shoot ratio of 0.6 (Table 2) suggest that the plants primarily allocated their resources to aboveground tissue, indicating that

they were adequately supplied with the required nutrients by the extended root system.

4.3.5 PES fiber effects on soil structural changes in silty clay loam

For the PES treatment, alterations of the root systems were only minor, although a widening of the fine pore structure of the clay-rich soil by the PES fibers can be assumed, thereby decreasing soil bulk density and increasing macroporosity, as it was already shown for a clay-rich Vertisol (Ingraffia et al. 2021). Roots grown in PES fiber-treated silty clay loam CH were slightly longer than in the control (Fig. 1c), but with no significant difference in root biomass (Table 2) compared to the control. Interestingly, roots in the PES treatment showed significantly reduced K, P and N contents (Fig. 2c), completely opposite to the LDPE treatment. The increased macroporosity in the presence of PES fibers could have resulted in a disruption of water phase continuity along the soil pore space, thereby reducing diffusion and nutrient exchange between roots and soil water. Although increased macroporosity and reduced bulk density have a positive effect on microbial communities, as they have been shown to lead to more diverse microhabitats and greater bacterial diversity (Carson et al. 2010; Li et al. 2002), the disruption of the continuous water phase by MP fibers is likely to have a greater negative impact on microbial diversity in the future. A discontinuous water phase could result in restricted nutrient and oxygen diffusion or a disruption in the exchange of genetic material within the microbial community.

4.3.6 PES fibers and soil pH reduction

Finally, the soil pH was significantly lower after PES fiber addition (Fig. 4c). Since this phenomenon is not reported in the literature, it can only be assumed that the pH changes are a secondary effect of the altered soil structure. This alteration potentially influences water retention, oxygen availability and nutrient cycling, leading to different pH conditions over time. Changes in soil pH caused by MP contamination have been shown to significantly affect key enzymes involved in nutrient cycling, reducing their activity. In particular, β -D-glucosidase, cellobiosidase, and N-acetyl- β -glucosaminidase activity were decreased in the presence of MP fibers, foams and films (Zhao et al. 2021), which was shown to negatively affect microbial-mediated nutrient cycling (Guo et al. 2024). In addition, it was also stated that biodegradable MP would impact microbial metabolic pathways more drastically than conventional MP (Guo et al. 2024).

5 Conclusion

While soil texture has a direct effect on plant growth because it determines water retention and soil pore size, and thus water and oxygen availability and space for roots, we were able to show that the addition of MP alters the effect of soil texture on plant growth. This is novel, since previous studies of the effects of MP on plant growth have often not included different soil textures but have transferred observed effects to any soil type. We propose that the soil type is critical in determining the effect of MPs on soil macroporosity, water and oxygen availability and plant growth. However, because the results in the literature vary depending on whether fine-textured soils with high clay content or coarse-textured soils with high sand content were studied (e.g., Guo et al. 2022; Ingraffia et al. 2021; Krehl et al. 2022), a general assessment of MP effects and development of generic mitigation options for the wide range of agricultural soils is premature. Further research with soils of defined textures is needed to fully understand MP-soil interactions and their implications for plant health and ecosystem dynamics.

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Data availability The datasets are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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