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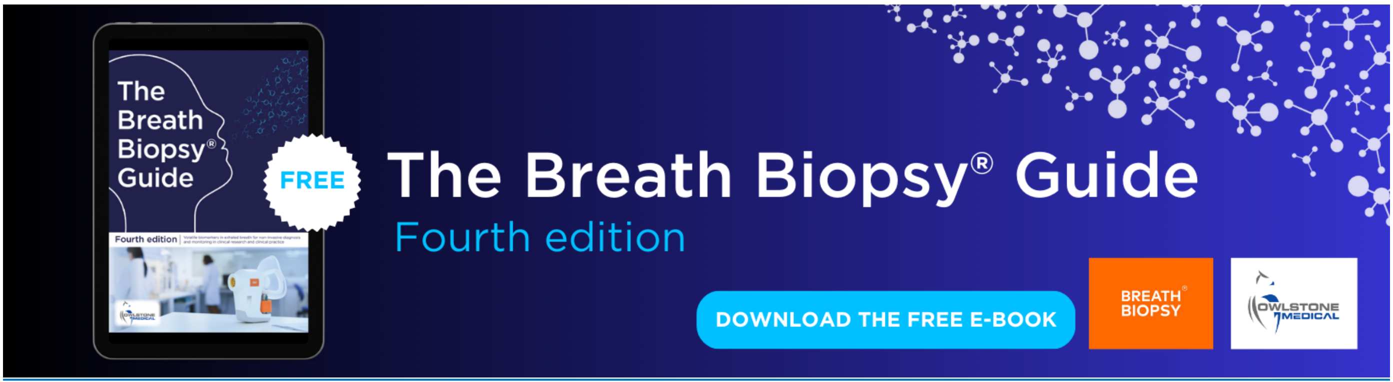

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TOPICAL REVIEW

Macro- and micro-plastics change soil physical properties: a systematic review

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Abstract

Plastic pollution in terrestrial environments is a global issue due to its adverse effects on soil health, with negative impacts on ecosystem services and food production. However, the enormous heterogeneity of both plastic and soil characteristics complicate the assessment of the impact and overall trends in plastic-induced changes in soil properties beyond experimental conditions. In this work, we have carried out a systematic and in-depth review of the existing literature on the impact of plastics on soil physical properties. To this end, we have quantified the effects of macro- (MaP, $>5000\ \mu$m) and micro-plastics (MiP, $<5000\ \mu$m) on soil bulk density, soil porosity, water-stable aggregates (WSAs), saturated hydraulic conductivity, and soil moisture at field capacity (FC), based on four characteristics of plastics: polymer types, shapes and sizes of plastic particles, and plastic concentrations in soil. Results showed that MaPs and MiPs significantly modified the values of the analyzed soil physical properties compared to the control without plastic in over 50% of the experimental dataset, albeit with a large variability, from a reduction to an increase in values, depending on the specific experimental conditions and the soil physical property. Depending on the plastic concentration, soil bulk density and porosity decreased moderately (4%–6%) with MiP and MaP. MiP reduced WSA by an average of 20%, ranging from a 40% decrease to a 20% increase depending on the shapes and concentration of MiP. Saturated hydraulic conductivity changed depending on the polymer types, shapes, and concentrations of MaP and MiP, varying from a 70% decrease to a 40% increase. Soil water content at FC varied depending on the soil texture, and concentration and sizes distribution of conventional MiP, decreasing from 10% to 65%. However, biodegradable plastic increased soil water content at FC. The few studies available provide evidence that not enough attention is being paid to soil physical properties influenced by plastic input. It is recommended to consider the wide range of characteristics of MaP and MiP and their effects on soil physical properties in future studies, for an advance understanding of the impact of MiP and MaP on soil health in the medium-long term under different environmental conditions.

1. Introduction

The March 2022 resolution of the United Nations Environment Assembly to develop a legally binding international instrument for plastic pollution highlights the magnitude of plastic pollution in the Anthropocene and the urgency of addressing it for a sustainable future. It is considered a top concern in the terrestrial system (CIEL 2019). Plastic pollution is approximately 4–23 times more abundant in soils than in oceans (Horton *et al* 2017). The heterogeneous sources of soil plastic pollution, such as those from agricultural and livestock inputs, soil amendments, irrigation and flooding, atmospheric pathways and others, as presented in table 1, illustrate the challenge and complexity of addressing plastic

Table 1. Anthropogenic sources of macroplastics and microplastics in soil.

Plastic sources		Common polymers	References
Agricultural practices	Plastic mulching, nets, twine (baler twine, string & rope), emitters and piping (irrigation & drainage), packaging (pesticides, fertilizers, seeds, …)	Low & high-density polyethylene, polypropylene, polystyrene, polyvinylchloride	(Kawecki and Nowack 2019, McKay *et al* 2022, Long *et al* 2023)
Soil amendments and fertilizers	Compost, sewage sludge, slow-release fertilizer, and polymer-covered seeds	Polyester, polyethylene, polypropylene	(Bläsing and Amelung 2018, Weithmann *et al* 2018, Accinelli *et al* 2019, Kawecki *et al* 2021)
Irrigation and flooding	Untreated wastewater (textile industry, laundry), treated wastewater, lake and river water	Polyester, polypropylene, polyethylene	(Faure *et al* 2015, Scheurer and Bigalke 2018, Cai *et al* 2021, Pérez-Reverón *et al* 2022)
Atmosphere	Atmospheric and wind deposition	Polyester, low-density polyethylene, polystyrene	(Allen *et al* 2019, Rezaei *et al* 2019)
Tire wear	Littering, agricultural machinery, and street runoff	Polystyrene, styrene, butadiene styrene, low-density polyethylene, ethylene vinyl acetate, polypropylene	(Järlskog *et al* 2022, Koutnik *et al* 2022)

pollution in a terrestrial environment. The variation in the abundance and morphological traits and chemical composition of microplastic (MiP, size <5000 μm) in soils increases the complexity of the problem (Yang *et al* 2021). Moreover, plastic consumption increased by 200% in livestock production systems and 475% in crop production systems from 2019 to 2021, greatly increasing the risk of plastic pollution, as MiP concentration in the soil is correlated with agricultural-livestock practices (UNEP 2021, Long *et al* 2023).

The application of treated sewage sludge to agricultural land is an important pathway through which MiP enters terrestrial ecosystems, up to 1353 plastic particles per gram of sludge dry weight (Sivarajah *et al* 2023). Compost fertilization is another pathway of entry of MiP and macroplastic (MaP, >5000 μm) into arable soil (Kawecki and Nowack 2019, Kawecki *et al* 2021). In arable areas of North Rhine-Westphalia (Germany), soils fertilized with compost showed 40 times more MaP particle contamination compared to soils without compost application (Stefano and Pleissner 2022). Agricultural and horticultural sites exposed to sewage sludge and mulching film application showed global MiP amounts of up to 13 000 items kg^{-1} and 4.5 mg kg^{-1} of dry soil, and these levels were more than 10 times higher in soils near municipal areas compared to rural sites (Büks and Kaupenjohann 2020). Industrial areas soils also contained an extremely high abundance of MiP, ranging from 0.03% to 6.7% w/w of soil (Fuller and Gautam 2016). Recently, Tunali *et al* (2023) using a probabilistic approach performed a potential risk assessment of MiP in soils by calculating the risk characterization ratio (RCR) (ECHA 2016) for different land uses and geographical regions, resulting that for soil ecosystems the proportion of RCRs above 1 (risk if RCR $\geqslant 1$) was 40 and 240 000 times higher than that predicted for freshwater and marine habitats, respectively, and that urban and industrial soils had the highest RCR, followed by agricultural and natural soils. Inconsistencies in reporting plastic pollution in terrestrial systems with unit variations could exacerbate the complexity of understanding its impact on soil health-related soil properties.

The abundance of MaP and MiP can change key soil properties, creating a potential risk for sustainable soil use (Gao *et al* 2019, Koelmans *et al* 2022, Khalid *et al* 2023). Soil physicochemical properties change due to the photo-oxidation of plastic particles, which release chemical compounds into the soil water. These compounds alter the cation exchange capacity and cations in the soil solution (Bandow *et al* 2017, Boots *et al* 2019), affecting soil pH, nutrient availability and soil urease activity, ultimately impacting soil biogeochemical cycles (e.g. nitrogen and phosphorus) (Qi *et al* 2020, Lozano *et al* 2021a, Ingraffia *et al* 2022b, Yin *et al* 2023). Biodegradable plastic can be considered environmentally friendly but can also cause various environmental issues (Serrano-Ruiz *et al* 2023). Thus, Qin *et al* (2021) reported that incomplete degradation of biodegradable plastic would increase the abundance of biodegradable MiP in soil. This, in turn, affects soil biological activities, as MaP and MiP induce new inhabitants and hotspots for microbiomes (Kublik *et al* 2022, McKay *et al* 2022) and ecotoxicity for micro- and mesofauna (Selonen *et al* 2023), which also influence the functional diversity of the soil microbial community. This alteration will ultimately change plant biomass above and below ground, causing organic matter decomposition and increasing soil respiration by excessive carbon input and emission of greenhouse gases (Boots *et al* 2019, Qin *et al* 2021, Wang *et al* 2022).

Change in soil physical properties is a process that usually takes longer to develop and presents variation compared to other soil properties. However, introducing foreign matter, such as MaP and MiP, would change soil physical properties instantaneously or modify the soil processes, depending on the plastic characteristics. For example, MiPs prolonged phase 1 of soil evaporation and water loss, reducing soil porosity (Jannesarahmadi *et al* 2023), while MaPs reduced cumulative evaporation (Wen *et al* 2022). Soil physical properties mainly depend on the soil structure, formed by the pore space and the aggregation of soil particles due to emerging and binding elementary soil particles following a bottom-up process (Yudina and Kuzyakov 2023). MaP and MiP are likely to disrupt the soil pore interface during aggregation, influencing soil structure (Wang *et al* 2020, Shafea *et al* 2023b). For instance, MiPs and their various shapes modulate soil aggregates formation and organic matter decomposition, specifically fiber-shaped ones (Lehmann *et al* 2021). This could increase soil erodibility and act as a pathway for MiP transport from arable lands to aquatic systems (Rehm *et al* 2021). Even MiP fibers at a certain level (3% w/w) can reduce soil stabilization from a geotechnical perspective (Jalal *et al* 2021). Meanwhile, residual MaP can affect the transport and distribution of water and nitrate in the soil due to its physical presence (Yuanqiao *et al* 2020). The demand for biodegradable plastic is increasing enormously and it behaves differently than conventional plastics in relation to the change in soil hydraulic properties. Incomplete degradation of biodegradable plastics leads to abundance of residual MiP in soil, which causes more negative effects than conventional MiP (Qin *et al* 2021). Biodegradable MiP can induce considerable variation in soil-saturated hydraulic conductivity (K_s, up to 480% at 2% w/w) compared to conventional MiP (Qi *et al* 2020). Shafea *et al* (2023a) reported that increasing conventional MiP concentration reduced K_s and soil water retention, regardless of MiP sizes and polymer types. However, Yu *et al* (2023) highlighted that MiP tended to increase the water contact angle and K_s while decreasing soil bulk density and water-holding capacity, depending on the shapes, polymer types, and MiP concentration. These results complicate the prediction of possible changes in soil physical properties induced by plastics of different shapes and sizes, polymer types, or abundance. For example, it could amplify uncertainty when estimating net primary productivity in water-limited ecosystems with low permeability soils, due to information gaps regarding the effect of plastics on soil structure formation process and hydraulic properties (Or *et al* 2021, Paschalis *et al* 2022).

The heterogeneity between the different experiments available in the literature regarding plastic characteristics (e.g. polymer types, sizes, shapes, degree of weathering, and additive composition), soil type, experimental setup, and experiment duration could explain the variability of the results found. Despite abundant research on plastic–soil interaction carried out in the last decade, considerable uncertainty remains regarding the quantitative impact of plastics on soil physical properties or other key soil functions. In this review, we present a systematic analysis of the impact of plastics on soil physical properties based on the results of existing experimental studies, with the following objectives: (i) to establish a clear picture of the effect of plastic pollution on soil physical properties, (ii) to provide information to extrapolate results under different environmental conditions, and (iii) to identify information gaps that require further investigation. In addition, two hypotheses were tested: first, that MaP and MiP have different impacts on soil physical properties, and second, that biodegradable and conventional plastic affect soil physical properties differently.

2. Methodology

2.1. Literature search and screening

A search was conducted in the Web of Science Core Collection using the keywords *plastic* and *soil* with truncation symbols (*) to find articles reporting on plastics and soil physical properties up to December 2022. To avoid articles related to water environments and materials science, the Boolean operator NOT was used with *marine* and *plasticity* to narrow the search. Initially, 8692 articles were found and screened based on the abstract. Articles were included in the review if they met the following predefined criteria: (i) published in English, (ii) peer-reviewed, (iii) full text available, (iv) contain information about plastics or MiPs, including at least the polymer type, particle size or concentration in the soil, (v) include soil information (at least soil type or textural class), (vi) present data on soil physical properties, in numerical or legible graphic format. After the screening, 16 articles, listed in table 2, which included 30 different experiments, met these criteria and were selected for this systematic review. These articles provided information on the effect of plastic pollution on some of these five soil physical properties: soil porosity, bulk density, water stable aggregates (WSAs), saturated hydraulic conductivity (K_s), and soil water content at field capacity (FC).

2.2. Data extraction and processing

When data were unavailable in numerical or table form, the PlotDigitizer v.3©PORBITAL app was used to digitize the data from graphs. To ensure the dataset quality, if the article reported on soil and plastic treatment (including the addition of litter, biota, compost

Table 2. Descriptive summary of literature review on the effect of plastics on soil physical properties, including bulk density (BD), saturated hydraulic conductivity (K_s), water stable aggregate (WSA), soil porosity (P), and water content at field capacity (FC), along with soil texture and plastic characteristics. Microplastics (MiP), macroplastics (MaP), biodegradable plastic (Bio: STP, PLA, PBAT, or blend of both), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene terephthalate (PET), polyacrylic (PC), polyacrylonitrile (PCN), polyamide (PA), polycarbonate (PCB), polyester (PES), polypropylene (PP), polystyrene (PS), and polyurethane (PU).

				Plastic characteristics							Soil physical property				
Article ID	Country	Reference	Soil texture	Polymer type	Plastic-type	Plastic size (μm)	Average plastic size (μm)	Concentration (%, w/w)	Shape	Lab/Field	P	BD	WSA	Ks	FC
1	UK	(Boots et al 2019)	Sandy clay loam	HDPE, Bio, PES#	MiP	102.6, 65.6	<2000–>7000+	0.001, 0.1	Fiber				✓		
2	China	(Chen et al 2022)	Loamy	LDPE, PET, PCN	MiP	200		0.5		Lab			✓		
3	Germany	(de Souza Machado et al 2018)	Loamy sand	PES, HDPE, PC, PA	MiP	5000		0.05, 0.1, 0.2,0.25, 0.4, 0.5, 1.0, 2.0	Fiber, Fragments #	Lab		✓	✓	✓	
4	Germany	(de Souza Machado et al 2019)	Loamy sand	HDPE, PA, PET, PS, PP, PES,	MiP	643**, 17.5**, 240**, 551**, 700**, 4999#	643, 15–20, 222–258, 547–555, 647–754 240, 64, 5000	0.2, 2.0	Fiber, Fragments, Fiber#	Lab		✓	✓		
5	Germany	(Ingraffia et al 2022a)	clay loam, loamy	PES	MiP	2870		0.5	Fiber	Lab		✓	✓		
6	China	(Guo et al 2022)	Loamy, clay, sandy	PP	MiP	20, 200, 500		0.5, 1, 2, 4, 6	Pellets	Lab				✓	✓
7	China	(Jiang et al 2017)		LDPE	MaP	5001		0.002† (0.3 kg ha^{-1})	Film	Field	✓				
8	China	(Koskei et al 2021)	Silt clay	LDPE, Bio	MaP	50 000		0.003, 0.006, 0.013† (75, 150, 300 kg ha^{-1})	Film	Field	✓	✓			
9	Germany	(Lehmann et al 2019)	Sandy silt	PES	MiP	5000		0.1	Fiber				✓		
10	Germany	(Lozano et al 2021b)	Loamy sand	PA, PES, PP, LDPE, PET, PS, PCB, PU	MiP	4000, 4999#		0.1, 0.2, 0.3, 0.4	Fiber, Fragments, Fibers, Foam	Lab			✓		

(Continued.)

Table 2. (Continued.)

				Plastic characteristics							Soil physical property				
Article ID	Country	Reference	Soil texture	Polymer type	Plastic-type	Plastic size (μm)	Average plastic size (μm)	Concentration (%, w/w)	Shape	Lab/Field	P	BD	WSA	Ks	FC
11	Germany	(Lozano *et al* 2021a)	Sandy loam	PES	MiP	1280		0.4	Fiber				✓		
12	Netherland	(Qi *et al* 2020)	Sandy	LDPE, Bio	MiP, MaP	366*	<50–1000	0.5, 1.0, 2.0	Film	Lab	✓	✓		✓	✓
13	China	(Xing *et al* 2021)	Silt loam	LDPE	MiP	180*	0–500	1, 4, 7	Film	Lab				✓	✓
14	Netherland	(Yu *et al* 2020)	Sandy	LDPE	MiP	575*	<150–1000	7	Film	Lab				✓	
15	China	(Wang *et al* 2020)	Sandy, sandy-loam, loam	LDPE	MaP	20 000		0.002, 0.003, 0.007, 0.013† (50, 100, 200 400 kg ha^{-1})	Film	Lab		✓			✓
16	US	(Reid *et al* 2022)	Clay loam, coarse silt	Bio	MaP	5001$^{\#}$		0.005, 0.049, 0.005, 0.031† (127, 1302, 132, 827 kg ha^{-1})	Film	Field			✓		

* Weighted average.

** Average of the most abundant or common size.

$^{+}$ Fiber length range.

† Estimated concentration of plastic input, from kg ha^{-1} or kg per plot size.

$^{\#}$ Assumed polymer type, size, or shape based on information mentioned in the text.

or organic matter), these data were excluded from the analysis and were considered irrelevant. If the article used the term 'residual plastic' without specifying the size, it was assumed that it was referring to MaP films. Some studies used various plastic sizes in their experiments, and, in such cases, the weighted average based on the weight of each size was taken as the particle size. To harmonize the results on soil physical properties with plastic concentrations, the inputs of MaP and MiP reported in kg ha^{-1} were converted into the plastic/soil mass ratio (w/w), marked (†) in table 2. When MaP or MiP weights were not reported, we used the reported soil bulk density and sampling depth to calculate the plastic/soil mass ratio (w/w). In a few experiments, the shape of the plastic particles was not mentioned. In these cases, the closest shapes were assumed based on polymer types and particle sizes, marked (#) in table 2. Soil water content at FC was the soil water content at −33 kPa soil matric potential. The relative changes in each soil physical property (in percentage) were calculated in relation to the absolute value of the control (without plastic). The supplementary material contains all extracted raw data and relative changes (table S1).

2.3. Statistical analyses and data visualization

STATA® 17.0 statistical package program (StataCorp, USA) was used for statistical analyses. The statistical significance of differences in soil physical properties changes was determined using a Kruskal–Wallis test at the $p < 0.05$ level. Principal component analysis (PCA) was performed individually for each soil physical property based on four plastic characteristics, formatted into categorical variables. These categories were: (1) polymer types: 12 classes, i.e. biodegradable (Bio), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene terephthalate (PET), polyacrylic, polyacrylonitrile, polyamide, polycarbonate, polyester, polypropylene, polystyrene, and polyurethane; (2) particle shapes: five shapes, i.e. fibers, films, foams, fragments, and pellets; (3) particle sizes: nine sizes, i.e. <50, 50–100, 100–250, 250–400, 400–650, 650–2000, 2000–4999, ⩾5000, and ⩾10 000 μm, and (4) plastic concentrations: four concentration ranges, i.e. ⩽0.1, 0.1 ⩽ 0.5, 0.5 ⩽ 2, and 2 ⩽ 7% w/w. STATA® was used to visualize figures 1 and 7, while Microsoft Excel 2019 ® was used to visualize figures 2–6.

3. Results and discussion

3.1. Effect of plastics on soil physical properties

An overview of the raw results in absolute values for porosity, soil bulk density, WSAs, saturated hydraulic conductivity, and water content at FC is shown in figure 1. The results are presented for each soil physical property separately based on plastic concentration in soil and differentiating by type of plastic (biodegradable vs. conventional) combined with MaP vs. MiP, identifying each value with the identification number (ID) of the source article, as in table 2. In approximately over 50% of the experimental data for all soil physical properties analyzed, statistically significant differences were detected with plastic input compared to the control treatment (filled symbols in figure 1). An overall appraisal of the trend of these changes for each soil physical property, in relative terms with respect to the control treatment, is shown in figures 2–6, analyzing the data separately according to plastic characteristics, i.e. polymer types, particle shapes, particle sizes, and input concentration of the plastic in the soil.

3.1.1. Porosity

LDPE film shape MaP tended to decrease soil porosity to a greater extends compared to biodegradable MaP (figure 2(A)). Since the results come from different studies, it is hard to state the effect of the different types of polymers because of the different experimental conditions. All the studies reporting porosity values for MaP and MiP used film shapes (figure 2(B)), reflecting that these studies were oriented toward plastic contamination in agricultural fields. Studies with MaP reported a moderate decrease in porosity (in the average range of 4%–5%), which were focused on particle sizes larger than 10 000 μm (figure 2(C)). The number of studies about soil porosity reporting MaP or MiP concentrations was minimal, with only a limited subset of studies reporting porosity results with MaP at concentrations smaller than 0.1% (figure 2(D)). Soil porosity was measured in a small number of experimental studies (table 2), so more experiments would be required to analyze the effect of plastics on this soil property. Changes in soil porosity due to MiP presence can have a large impact on water transport, which can affect soil hydraulic conductivity (Tsai and Jang 2014) and the transport of chemical compounds (e.g. oxytetracycline) (Li *et al* 2021). Pore size distribution is an important parameter to characterize soil hydraulic properties (Araya *et al* 2022, Talukder *et al* 2023), but it is also important for soil ecological functioning, as pores serve as a transit route and habitat for the soil's living phase and plant roots (Yudina and Kuzyakov 2023). However, average porosity does not provide pore size distribution information, which needs to be studied with the MaP and MiP inputs.

Pore space is a key soil characteristic based on which many decisions regarding soil management and sustainable agricultural practices are considered in arable land. Our analysis suggests that soils contaminated with MaP are prone to experience a moderate decrease in soil porosity, which could affect soil hydraulic properties. Likewise, to evaluate this trend with MiP, a greater number of studies would be necessary. Increasing the database of experimental studies measuring the effect of MaP and MiP on soil porosity is crucial under standardized conditions. Ideally,

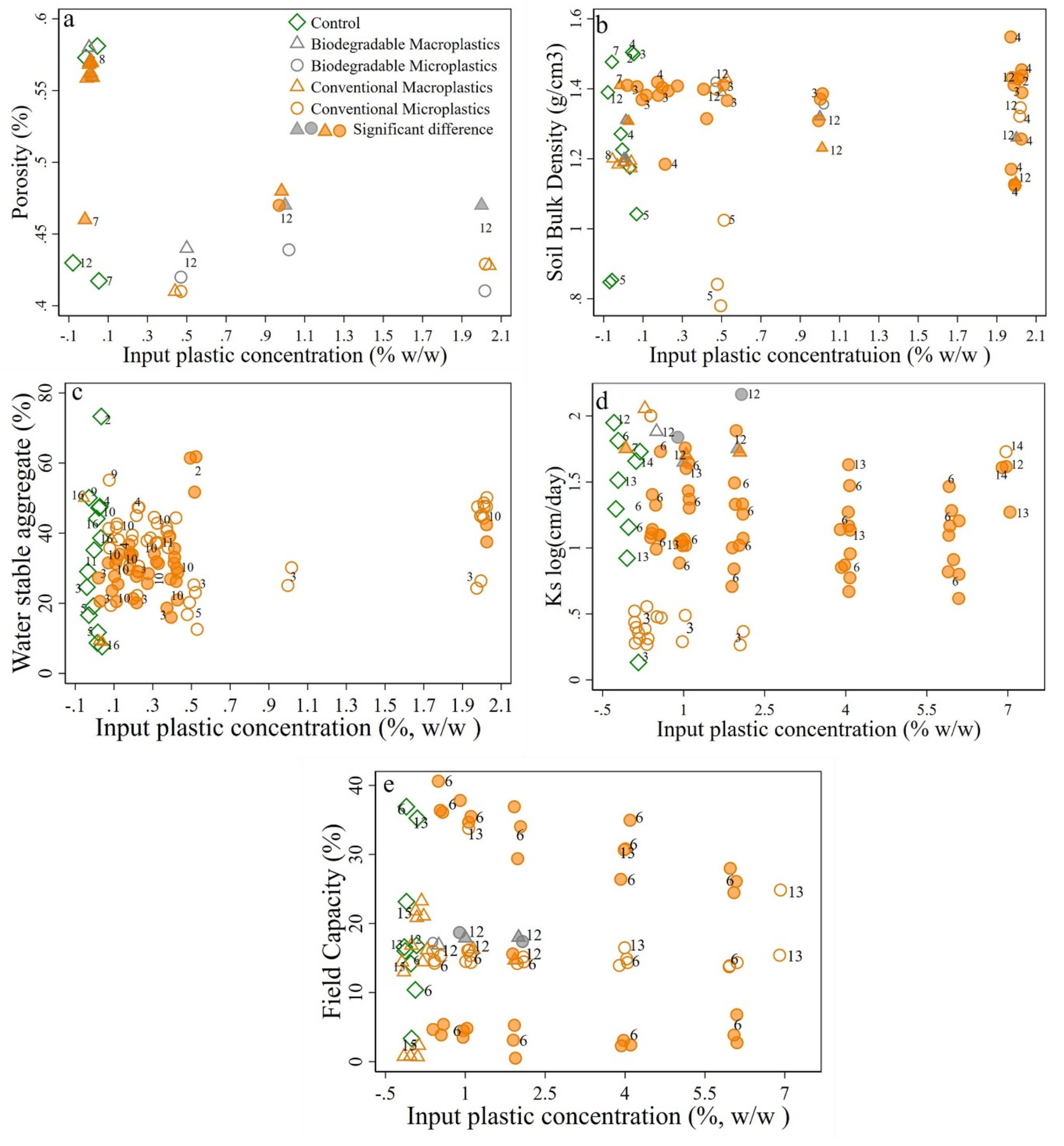

Figure 1. Values of soil physical properties by input plastic concentration (%, w/w), pointing out the significant differences with respect to the control (filled symbols). (A) soil porosity, (B) soil bulk density, (C) water-stable aggregates, (D) saturated hydraulic conductivity, and (E) water content at field capacity. The number in the proximity of each cluster indicates that the data belongs to the literature article (ID) referred to in table 2.

they should include an analysis of their impact on soil pore distribution, which would close some gaps in the current knowledge on the effect of MaP and MiP on soil physical properties. Physically based models (Peters *et al* 2021) can provide insights but require extensive experimental datasets that are not currently available. This would require careful experimentation at the laboratory scale. However, these data must be validated with field experiments, in which the implementation of different treatments, proper appraisal of the spatial variability of soil properties and careful handling of undisturbed samples will be critical issues (Gómez *et al* 2005, Deluz *et al* 2023). This information will be essential for understanding the effect of MaP and MiP contamination of agricultural soils and their removal and soil restoration.

3.1.2. Soil bulk density

A limited number of studies on MaP and MiP in soils were found reporting bulk density values, with only four for MiP and three for MaP (table 2). In general, MiP (>80% of data points) reported a decrease in bulk density (figure 3). MiP decreased bulk density by 5.7% on average, ranging from a 13% decrease to a 4% increase, while MaP decreased it on average by 2.3%, ranging from a 15% decrease to a 7% increase, based on the limited number of studies available (figure 3). Film shape MaP and MiP and fiber shape MiP are listed to increase bulk density (figure 3(B)). MaP with particle sizes smaller than 10 000 μm reduced soil bulk density compared to MaP with sizes larger than 10 000 μm, which increased it (figure 3(C)). A consistent decrease in soil

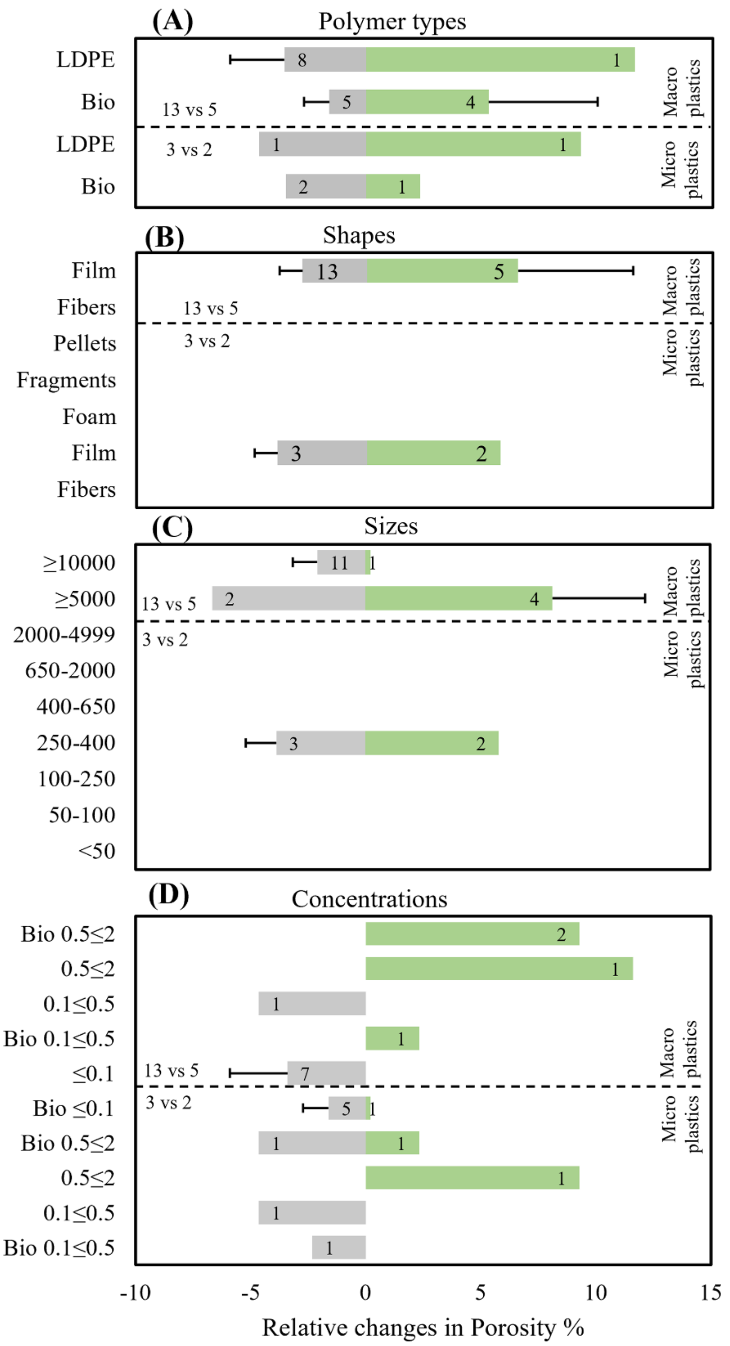

Figure 2. Relative changes in soil porosity (%) by plastics characteristics, according to (A) polymer types, (B) shapes, (C) sizes (μm), and (D) concentration (%, w/w) of plastics. Errors bars represent the standard deviation. A numerical number in each bar plot indicates data points. LDPE: low-density polyethylene, and Bio: biodegradable plastics.

bulk density with MaP was observed for the highest concentrations (0.5%–2% w/w), for both biodegradable and non-biodegradable plastic. Likewise, MiP studies showed a general trend of decreasing soil bulk density at all concentrations of plastics, biodegradable and non-biodegradable (figure 3(D)).

Overall analysis carried out indicated a moderate decrease in soil bulk density compared to the pristine soil (control), which can be expected when the soil contains MiP, depending on the concentration. Typically, plastic particles have a lower density than soil particles, which justifies the relationship between the increase in MiP concentration and the decrease in soil bulk density (Wang *et al* 2022). However, in a few cases, the addition of MiP increased bulk density. These results contradict the previously reported trend for soil porosity, as both properties are reciprocal, since a reduction in bulk density will increase soil porosity and vice versa (Robinson *et al* 2022). The lack of standardization in the experimental conditions and the different analytical methods used among experiments could partly explain these results. MiP-induced changes (6% reduction on average in this review) in soil bulk density, which in natural conditions might range from 1.2 to 1.5 g cm^{-3}, must be put in perspective (Makovníková

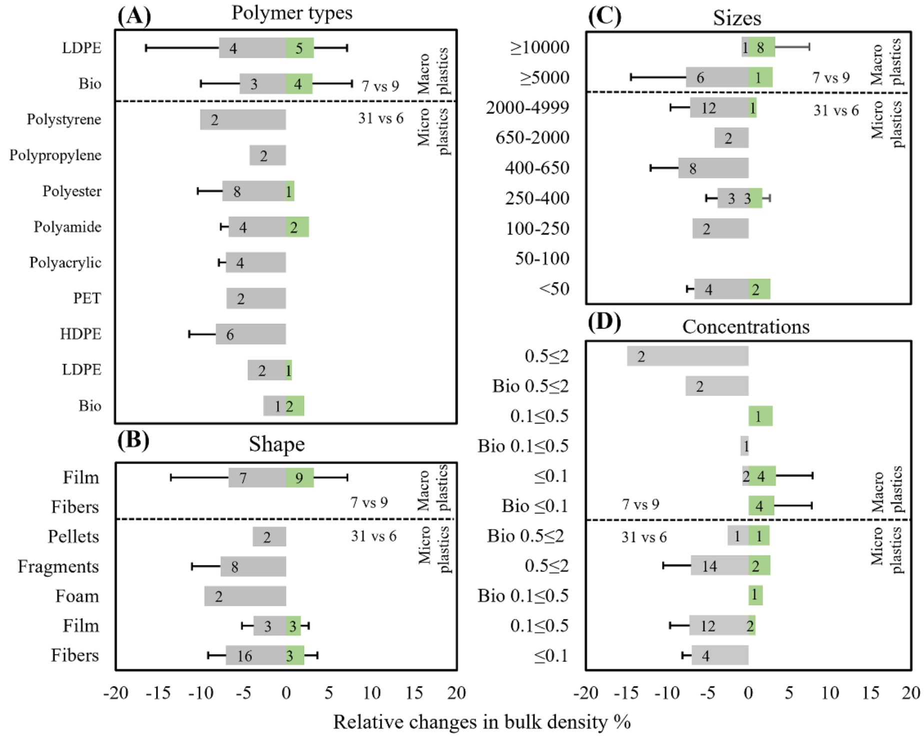

Figure 3. Relative changes in soil bulk density (%) by plastics characteristics, according to (A) polymer types, (B) shapes, (C) sizes (μm), and (D) concentration (%, w/w) of plastics. Errors bars represent the standard deviation. A numerical number in each bar plot indicates data points. LDPE: low-density polyethylene, high-density polyethylene (HDPE), polyethylene terephthalate (PET), and Bio: biodegradable plastics.

et al 2017). Decreasing bulk density of topsoil due to MiP with increasing subsoil stress due to modern farm machinery load will further accelerate ecological risk for subsoil compaction in arable land (Keller and Or 2022). The decrease in soil bulk density in response to MaP input seems slightly ambiguous. Although this could be biased by the small number of studies found for MaP, it appears that the presence of MaP of large sizes tends to increase the bulk density slightly. This raises the need to perform experimental studies with MiP and MaP to measure a broad range of soil physical properties simultaneously.

3.1.3. WSAs

Polyester MiP fibers and HDPE MiP fragments increased WSAs (figures 4(A) and 4)), unlike other polymer types, where WSA decreased apparently. Figure 1(C) shows a wide range of reported WSAs values, suggesting that available experiments cover diverse soil conditions. Partially, this variability can result from using slightly different protocols to measure WSA. MiP (>80% of data point) reported a decrease in WSA (figure 4(C)), suggesting this general trend. However, MaP showed a trend to increase WSA compared to MiP, although with only one study reported for sizes larger than 5000 μm (MaP) and eight studies for sizes smaller than 5000 μm (MiP) (table 2). Lower concentrations (<0.5%, w/w) of non-biodegradable MiP tended to decrease WSA (figure 4(D)). For higher MiP concentrations, mixed trends from reducing to increasing WSA were observed. Overall, MiP decreased WSA by an average of 20%, ranging from a 40% decrease to a 20% increase. MaP tended to increase the WSA moderately, unlike MiP, but this observation is based on a limited dataset.

Our analysis of available data indicates that soil contamination with MiP diminishes WSA, which appears to be an overall trend. WSA is a commonly used indicator of soil health because decreases in aggregate stability are related to increasing erodibility and reduced soil–water dynamics (Karlen *et al* 2021). Our results do not agree with the recent study of Lehmann *et al* (2021), who noted an increase in WSA in soils contaminated with MiP in different shapes but not when similar concentrations were added in fiber shape. This discrepancy might be due to the different incubation times used by Lehmann *et al* (2021) and the ones reported in our review, which tend to be, on average, much longer. This issue would be related to particle shape and particularly incubation time (since MiP incorporation) affects WSA, which requires further studies. Moreover, when designing the experiment, the size distribution range of MiP should also be considered, as it widely varies from <50 to >5000 μm in farmland (Chen *et al* 2020). The endorsement of proper standardized experimental conditions will expand an experimental database that could be analyzed in a meta-analysis. Considering a technique that could be broadly applied, Rieke *et al*

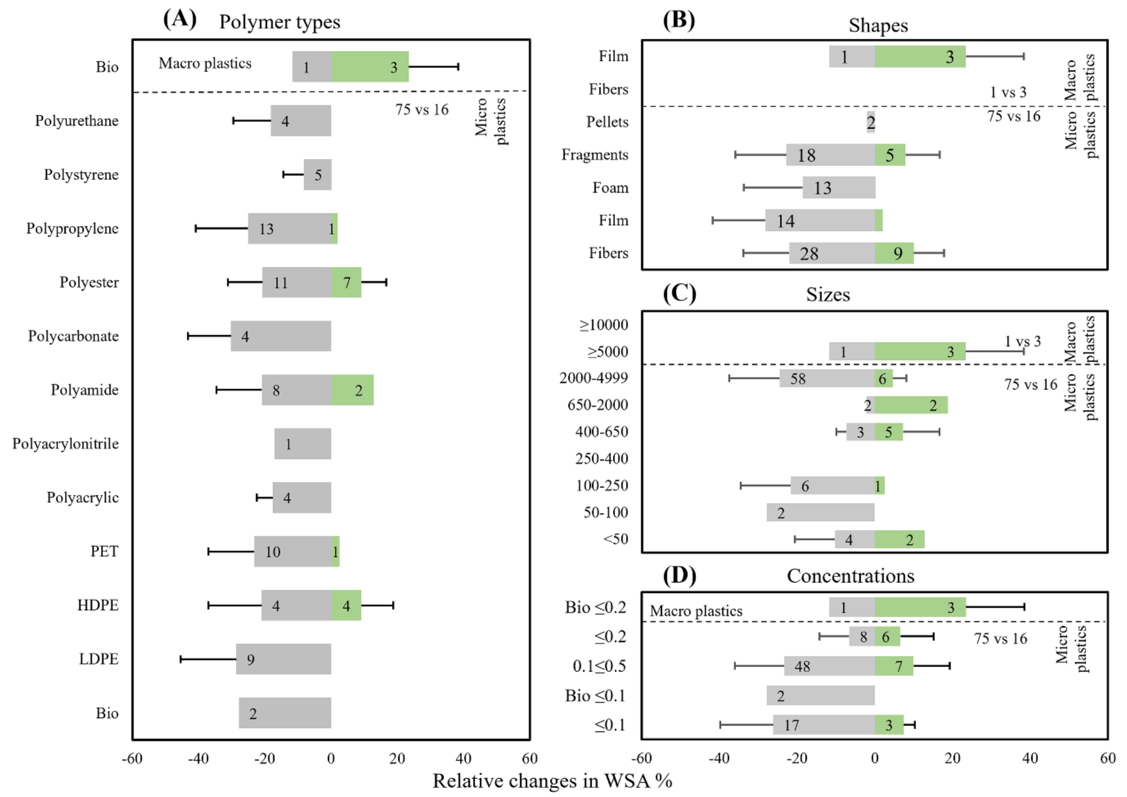

Figure 4. Relative changes in water stable aggregates (WSA) (%) by plastics characteristics, according to (A) polymer types, (B) shapes, (C) sizes (μm), and (D) concentration (%, w/w) of plastics. Errors bars represent the standard deviation. A numerical number in each bar plot indicates data points. LDPE: low-density polyethylene, high-density polyethylene (HDPE), polyethylene terephthalate (PET), and Bio: biodegradable plastics.

(2022) reported different WSA measurement methods that can orient the adoption of the standardized approach.

The possibility that MiP and MaP might have a different or opposite effect on WSA requires further comparative research, which is currently lacking (table 2). Only one study reported results of the impact of MaP on WSA under field conditions, which could differ at a laboratory scale. This highlights the demand for field studies as the prevalence of secondary MaP and MiP is directly associated with plastic mulch film residues in arable land (Koskei *et al* 2021, Khalid *et al* 2023, Long *et al* 2023). From 5%–15% variability of WSA exists in natural soil conditions (Ma *et al* 2022), which is cyclical due to temporal variability within the same soil (Dimoyiannis 2009). MaP- and MiP-induced variability in WSA beyond natural variability can increase soil erodibility and pathways of MiP from arable land to aquatic systems (Rehm *et al* 2021) and can accelerate sediment displacement in agricultural practices (van Oost *et al* 2009). Consequently, the modification of WSA could significantly affect the intra-aggregate pores and soil physical properties that disrupt the pore size distribution, impairing the structure and soil stable pedogenic feature (Yudina and Kuzyakov 2023).

3.1.4. Saturated hydraulic conductivity

Soil saturated hydraulic conductivity (K_s) modification by plastic ranged from a 70% decrease to a 40% increase, indicating a significant uncertainty in the prediction of K_s due to MaP and MiP. Polyester, polyamide, polyacrylic, HDPE and LDPE used in the experimental studies showed a trend to increase K_s. However, polypropylene was the most widely used MiP in these studies and showed a decrease in K_s. Figure 5(A) shows how the trend observed for the MiP polymer types is diverse, with approximately 60% of the studies reporting decreased K_s. This is likely to be the trend for MaP, although there is a very limited number of data for MaP, with only five experimental studies for MiP and one for MaP (table 2). On the contrary, the impact of MiP pellets and fibers was noted to increase K_s (figure 5(B)). Film MaP tends to decrease K_s, unlike film MiP, which increases K_s. Some substantial changes in K_s were noted, such as with biodegradable MiP (concentration of 2% w/w) which reported a 480% increase in K_s, illustrating that the plastic does not belong to the soil parent material. Higher concentrations of biodegradable and conventional MiP and MaP (0.5%–7% w/w) tended to decrease K_s compared to lower concentrations (<0.5% w/w) that increased K_s (figure 5(D)).

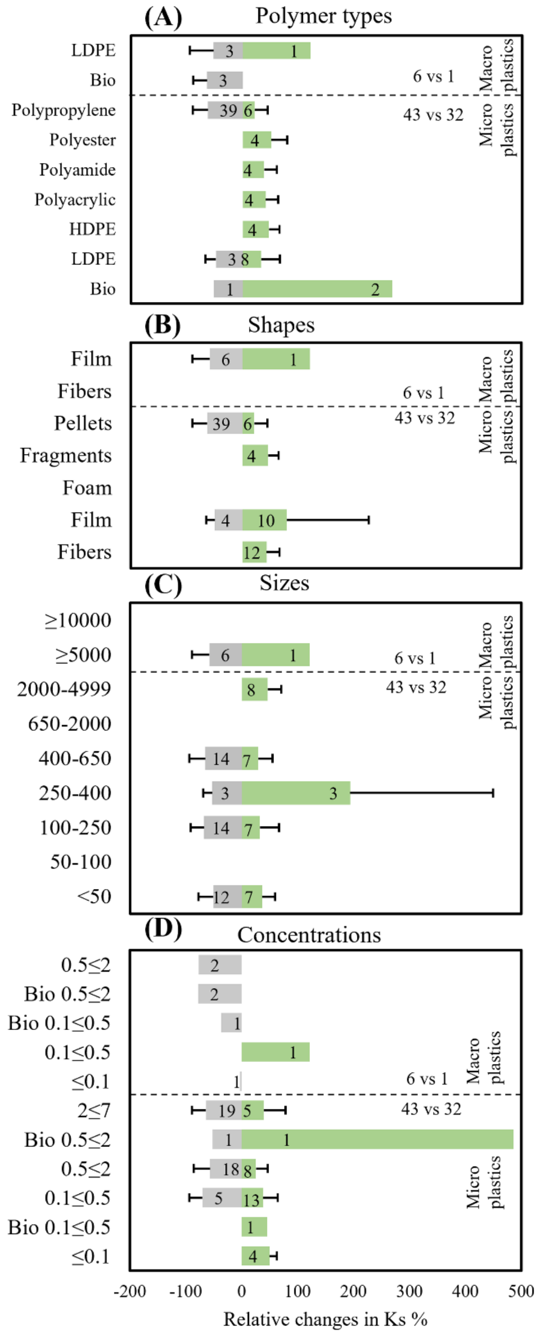

Figure 5. Relative changes in saturated hydraulic conductivity (%) by plastics characteristics, according to (A) polymer types, (B) shapes, (C) sizes (μm), and (D) concentration (%, w/w) of plastics. Errors bars represent the standard deviation. A numerical number in each bar plot indicates data points. LDPE: low-density polyethylene, high-density polyethylene (HDPE), and Bio: biodegradable plastics.

Generally, K_s is sensitive to soil bulk density (Araya and Ghezzehei 2019), suggesting that slight changes in it would greatly influence K_s. With MaP and MiP, changes in K_s were primarily driven by soil texture-associated structure and secondarily by plastic size distribution-associated water repellency (Wang *et al* 2020, Guo *et al* 2022). Soil water repellency is influenced primarily by soil physicochemical properties associated with organic matter content (Zema *et al* 2021). MaP and MiP could also play an impactful role (Qi *et al* 2020). MiP induced hydrophobicity in soil without organic matter (Cramer *et al* 2022), while the presence of organic matter can reduce surface hydrophobicity and enhances the mobility of MiP in saturated media (Ivanic *et al* 2023). This suggests that the modification in K_s can also be influenced by the organic matter content with MaP and MiP. In the future, studying soil physical properties in conjunction with chemical properties would provide a more comprehensive understanding of the effects of MaP and MiP on K_s under different environmental conditions.

Higher concentrations of MaP in this review tended to reduce K_s, as reported previously by de Souza Machado *et al* (2018) and Guo *et al* (2022). Additionally, MaP reduced the soil infiltration rate and wetting front (Wen *et al* 2022). Increasing MiP concentrations also decreased K_s and increased soil water repellency (Shafea *et al* 2023a). Relating K_s modification by MiP to other soil physical properties is complicated as most studies only measured a few soils physical properties. Nevertheless, the decrease in K_s by MaP is aligned with the trend toward an overall reduction in soil porosity and WSA. The apparent increase in K_s reported in several MiP studies points to different processes regulating the modification related to water transport in soils with MiP size, which requires further studies. The range of variation of K_s values found (40%) is not significantly large in comparison to its coefficient of variation (75%) under natural environmental conditions (Usowicz and Lipiec 2021). Many studies in our review detected statistically significant differences in K_s under laboratory conditions (potentially reducing variability between replications) by plastic amendment. These moderate changes in K_s upon plastic input, with the expected spatial variability under field conditions, are a caveat for careful planning of field experiments for further studies of plastic pollution in agricultural soils.

3.1.5. Soil water content at FC

The results reported on soil water content at FC were different for biodegradable and non-biodegradable plastic. Biodegradable plastic always reported slightly increased (10%) soil water content at FC. Unlike LDPE and polypropylene, which consistently caused a decrease in water content at FC (figure 6(A)). Pellet-shaped MiP, followed by film-shape MiP and MaP, showed a reduction in water content at FC (figure 6(B)). Mainly MiP reported a decreased water content at FC for all particle sizes (figure 6(C)), although for MiP and MaP sizes only three and two studies reported water content at FC, respectively. As the concentration of conventional MiP in the soil increases, the soil water content at FC is likely to be reduced (figure 6(D)). MaP reported a trend toward

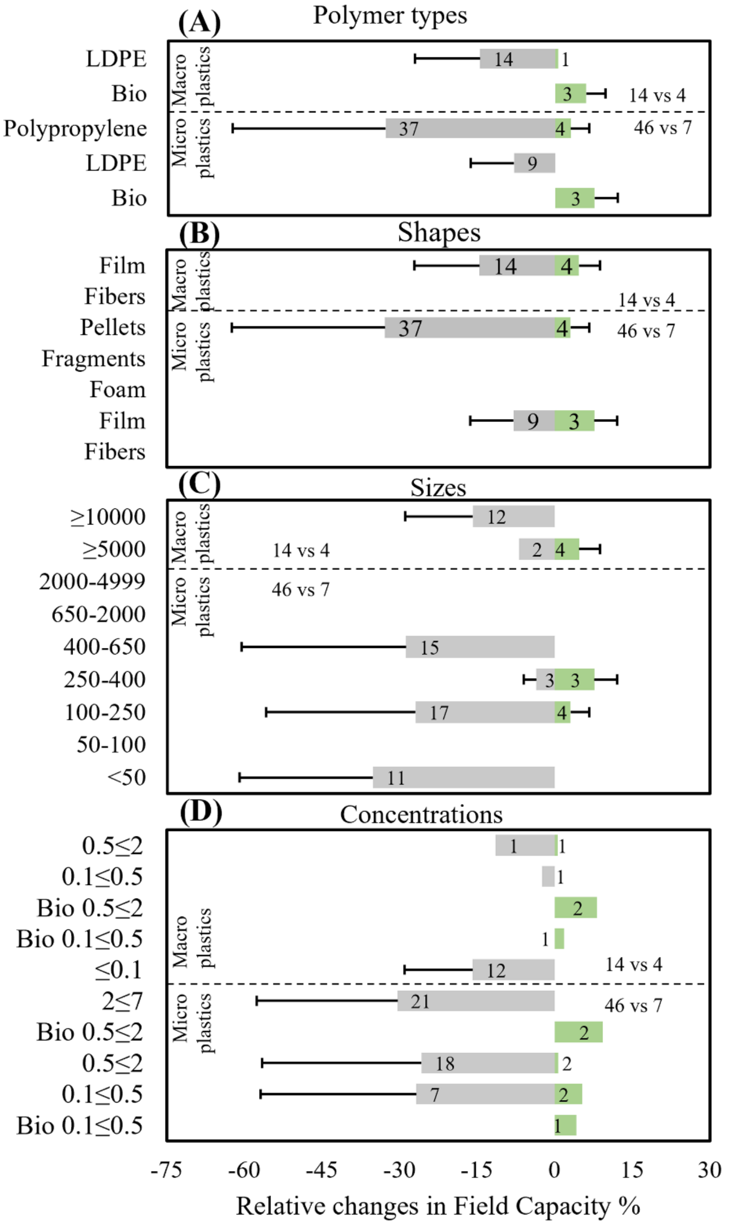

Figure 6. Relative changes in soil field capacity (%) by plastics characteristics, according to (A) polymer types, (B) shapes, (C) sizes (μm), and (D) concentration (%, w/w) of plastics. Errors bars represent the standard deviation. A numerical number in each bar plot indicates data points. LDPE: low-density polyethylene, and Bio: biodegradable plastics.

decreasing soil water content at FC. The average relative decrease in water content at FC was approximately 25%, ranging from a 30% decrease to a 10% increase. The water content at FC was decreased by 65% for sandy soil, 10% in loamy soil, 30% in clay soil, and 20% in silt loam soil, depending on the input concentration and size of MiP.

Generally, soil texture and structure are the primary key factors controlling the soil water content at FC (Fayos 1997). Guo *et al* (2022) reported that soil texture was also the main influencing factor in assessing the effect of plastic on soil hydraulic properties. Overall analysis in this review indicated that conventional plastic decreased soil water content at FC, while biodegradable plastic increased it. Studies that have used biodegradable plastics to report water content at FC (–33 kPa soil matric potential) using either a sandbox suction table or pressure plates. These methods usually take 6–12 weeks to reach the suction potential associated with FC. Assuming that biodegradable plastic has not degraded in the soil during this short period, the related increase in water content at FC can be attributed to natural variations, which may not be a valid explanation. The mechanism by which biodegradable plastic gradually degrades to a certain extent, ranging from 10%–24% during a short period of 6–12 weeks, is due to the hydrolytic breakdown of non-mineralized bio-based carbon (^{13}C) that remains in the soil, as reported by Nelson *et al* (2022). Due to the polar nature of water molecules, the ^{13}C surface potentially surrounds and stabilizes the anion and cation charges at the soil–water interphase (Duckworth *et al* 2014). This could create a solvation sphere around ^{13}C, leading to an increase (up to 10%) in soil water content at FC by biodegradable plastics. However, this phenomenon does not exist for conventional plastic. It might cause a reduction in water content at FC due to the modification in pore size, pore distribution, and induced water repellency in soil (Wang *et al* 2020, Cramer *et al* 2022, Shafea *et al* 2023a). These point-scale changes in agrosystems, where the most abundant residual plastics were reported, could be reflected during the regional drying trend of soil moisture on soil surface and in the root zone (Liu *et al* 2023).

3.2. Exploratory analysis of the effect of plastic characteristics on soil physical properties

To test our hypothesis, PCA was conducted to determine the association between plastic characteristics and each of the soil physical properties. As shown in table S1, the first two principal components (PC) have eigenvalues greater than or approximately equal to 1. The first two PCs explained 78.9%, 79.5%, 76.1%, 69.9%, 67.4%, and 55.8% of the variation in the data for plastic characteristics, water content at FC, porosity, saturated hydraulic conductivity, bulk density, and WSAs, respectively.

For plastic characteristics, PC1 was positively associated with the eigenvectors of polymer types and particle shapes, as these are primary factors for the assessment of the impact on soil physical properties. PC2 for plastic characteristics had a significant negative association with plastic concentrations. Polymer types, shapes, and concentration of plastics significantly influenced the negative changes in bulk density, K_s, and soil water content at FC, as PC1 had positive associations with them (table S2). These plastic characteristics primarily influence soil hydraulic properties. Plastic shapes and concentrations significantly affected soil structure due to the positive association of PC1 with WSA. Plastic shapes are an important factor in responses to soil aggregation (Lehmann *et al* 2021). Plastic concentration significantly influenced changes in porosity because a greater number of plastic particles can change the soil pore size distribution.

The first two PCs were plotted to find potential clusters against plastic types (between MiP and MaP) and plastic nature (between biodegradable and conventional plastics) to understand their interaction with soil physical properties, as shown in figure 7. The variation was enormously different across biodegradable and conventional plastics because of the discrete clustering of groups (figures 7(A), 7), 7) and 7)). It indicates that biodegradable plastics had a prominent effect on soil bulk density, WSA, and FC compared to other polymer types. In contrast, biodegradable and conventional plastic similarly affected soil porosity and saturated hydraulic conductivity (figures 7(B) and 7)). MaP had a differential effect on soil porosity, bulk density, and water content at FC compared to MiP (figures 7(B), 7), and 7)).

3.3. Research gap and perspectives

Our analysis indicates that, despite numerous valuable experimental studies on the impact of macro- and micro-plastic on soil physical properties, these studies represent only a small fraction of the total number on soils and plastics studies available in the Web of Science database. The heterogeneity and ambiguity between experimental conditions prevent us from quantitatively predicting the impact of plastics outside the experimental conditions for current studies. Research on the implications of plastic pollution in soil has grown tremendously in the last 5 years. The focus should be on soil health parameters like soil bulk density, soil aggregation, and water flow, all of which are physical properties. However, fewer reported studies provide evidence that sufficient attention has not been paid to soil physical parameters. Significant contributions are required in this domain from future studies. Likewise, reporting changes in soil physical properties due to plastics must also consider variations in natural environmental conditions and high variability in soil properties.

Underneath this significant research gap, there are several more specific issues as follows:

From a plastic point of view:

- To provide more information in future studies regarding plastic characteristics on soil physical properties considering polymer types, shapes, sizes, and concentrations. This will facilitate data harmonization and predict the effect of experimental conditions on natural environmental conditions. Moreover, the availability of molecular weight of the polymer type used in plastic studies could assist in understanding the impact of polymer chains on soil physical properties for long-term implications during degradation and fragmentation. It is also relevant for multidimensional studies regarding microbial community impact on soil structure and how chemical release from plastic might influence it.
- The lack of comparative studies of pristine vs. aged or degraded plastic has limited the probability of observing different impacts on soil physical properties. Currently, most studies use pristine plastic to assess the effect on soil's physical properties.
- The range of environmental size distribution of MaP (>5000 μm) and MiP (<50–5000 μm) should be considered to simulate natural ecological conditions in future studies. Currently, most studies use only certain sizes of plastic to investigate the impact on soil physical properties.

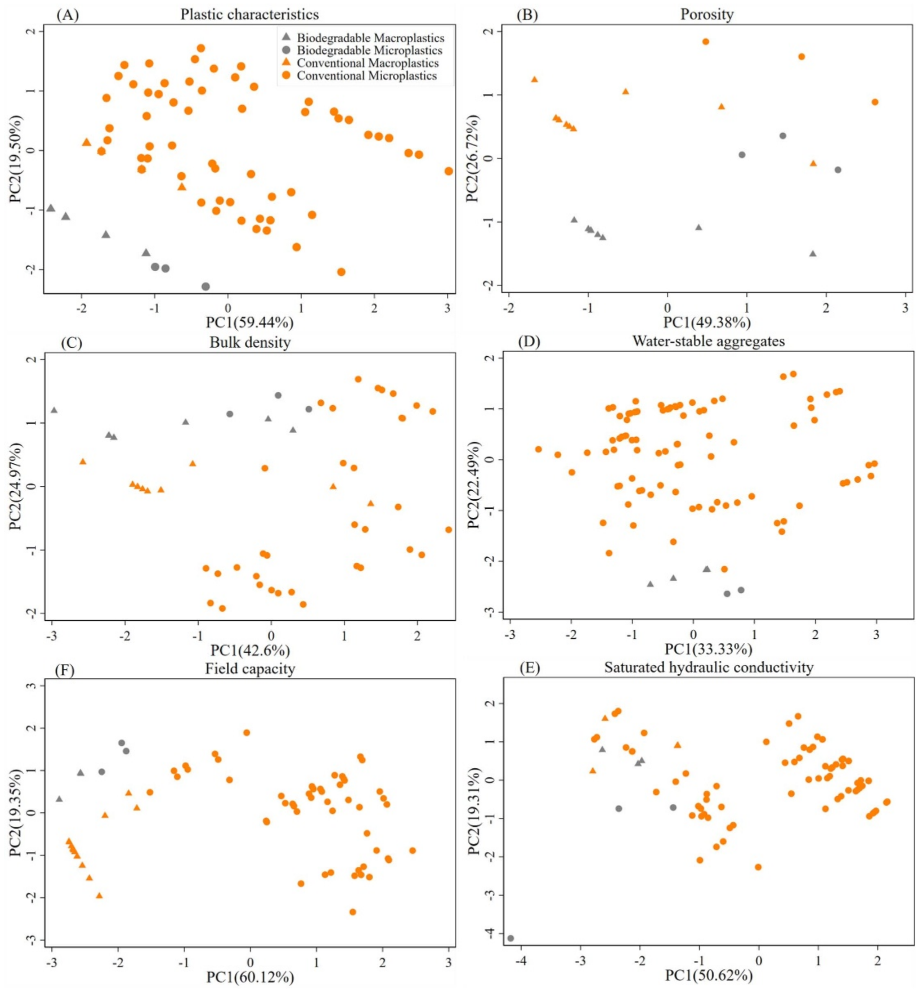

Figure 7. Principal component analysis (PCA) of (A) plastic characteristics, which are polymer types, particle shapes, particle sizes, and plastic concentrations, and relative changes of (B) porosity (C) soil bulk density, (D) water-stable aggregates, (E) saturated hydraulic conductivity and (F) soil water content at field capacity with plastic characteristics.

- To regularize sustainable agricultural plastic use, a specific threshold should be determined in arable soil with a high abundance of microplastics.

From a soil point of view:

- Most studies provide information on selective soil physical properties, which precludes a comprehensive understanding of the influence of plastic contamination on soil physical properties, which are always interrelated. Ideally, multiple soil physical properties must be investigated simultaneously in future experiments, especially reciprocal ones. This will provide a robust base to understand how plastic influences crops, including changes in organic matter content, climate and soil texture, tillage, and cropping system under cover crops that are yet to be explored. It is also relevant to understand the impact of microbial community activity on soil structure and physicochemical properties.
- Soil hydraulic properties, including soil water repellency, unsaturated hydraulic conductivity, and plant available water content, need to be studied for full moisture range from saturated to dry conditions. Currently, most studies only provide an impact of MiP on soil-saturated hydraulic conductivity. However, it is important to study how unsaturated hydraulic conductivity changes to understand soil moisture changes in the vadose zone with MaP and MiP in topsoil. Likewise, currently, most studies provide information on changes in water content availability at FC. However, it is crucial to study the water retention at least until the wilting point of soil to quantify water changes available to the plants with MaP and MiP. Changes from saturated to dry range with MaP and MiP are also critical to understanding the soil pore size distribution to estimate soil water storage and fluxes. All this information might be highly relevant to improving agronomical practices in plastic-contaminated soils during restoration.
- Soil thermal properties, including thermal conductivity, volumetric heat capacity, and thermal diffusivity, need to be studied with plastic and are often overlooked when characterizing soil physical

properties. For instance, the temperature and soil thermal properties could vary with plastic, influencing topsoil water storage, seed germination, root growth, nutrient supply, biological activity, and other soil functioning processes, reflecting changes in the energy balance for land surface and atmospheric modeling.

- Only a limited number of studies have examined the impact of plastic on soil physical properties (table 2), indicating that more field studies are required. It implies that plastic remediation in soils should be a priority, with considerations extending beyond its impact solely on soil physical properties during the removal or degradation of plastic in agricultural soils. The overall health of the soil ecosystem should also be considered.

Utilizing biodegradable plastic films could be an alternative solution for sustainable food production in agrosystems. However, it may not be a sustainable approach in the long-term (Steinmetz *et al* 2016, Serrano-Ruiz *et al* 2023). As biodegradable plastic has different effects compared to conventional plastic, it is essential to study the residual biodegradable MaP mulch film in the field. Due to its increasing use in agrosystems, secondary MiP produced from MaP is not under microplastic regulation to control contamination (Mitrano and Wohlleben 2020). In some cases, residual biodegradable MaP film has shown either limited or improved impact on soil's physical properties (Sintim *et al* 2021, Reid *et al* 2022). Therefore, the long-term effect of residual biodegradable MaP film on soil's physical properties needs to be considered on a priority basis. For instance, how much soil can degrade over the years if residual plastic mulch continually accumulates in the soil? How will this accumulation influence water transport in the soil and rhizosphere? What happens if soil reflects resilience to the degradation of biodegradable plastic at a certain period? How will this impact soil tillage processes and soil organic carbon content? This series of questions should be addressed in future studies.

4. Conclusions

This review attempted to harmonize the results on soil physical properties and overcome the complexity of plastics, considering polymer types, shapes, sizes, and concentrations. Biodegradable plastics have a distinguished effect on soil bulk density, WSAs, and FC compared to conventional plastics. Specifically, MaP has a distinct impact on soil bulk density, porosity, and FC compared to MiP. MaP shows a moderate decrease in porosity (approximately 4%–5%) depending on concentration. However, further research is needed to quantify the effects of MaP and MiP on soil porosity and pore size distribution. Soil bulk density decreased moderately (approximately 6%) with plastic, depending on concentration. MiP reduces by 20% WSA, ranging from a 40% decrease to a 20% increase depending upon shape and concentration. Saturated hydraulic conductivity changes with MaP and MiP approximately from a 70% decrease to a 40% increase, depending on polymer types, shapes, and concentrations. Water content at FC is influenced by soil texture, input concentration, and size distribution of conventional MiP that decreased by 65% for sandy soil, 10% for loamy soil, 30% for clay soil, and 20% for silt loam. In addition, this review contributed that biodegradable plastic tends to increase the soil water content at FC due to plastic degradation. Generally, MiP reduces soil physical properties, but the outcome varies depending on specific experimental conditions. The effect of MaP on soil physical properties does not seem to differ from MiP, but a more comprehensive investigation is still needed. Research on the implications of plastic pollution for soil has grown substantially in recent years. However, a noticeable gap in studies focusing on soil physical parameters requires more datasets. From a plastic point of view, acquiring complete information about different plastic characteristics would enable us to harmonize and predict their impact on soil physical properties. Comparative studies of pristine vs. aged plastic are essential to enhance understanding of the impact of soil physical properties alongside physicochemical properties. From a soil point of view, it is crucial to investigate soil hydraulic properties across the entire moisture range, from saturated to dry point, to understand the impact of MaP and MiP. It is recommended to consider the wide range of MaP and MiP size distribution and multiple soil physical properties, especially reciprocal ones, as a holistic approach in future studies that would be more realistic to environmental conditions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The author(s) declares no conflicts of interest.

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