Heliyon 9 (2023) e16587

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Impact of plastic film mulching on microplastic in farmland soils in Guangdong province, China

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ARTICLE INFO

Keywords:
Microplastics
Macroplastic residues
Plastic film mulching
Farmland soils
Pollution load index model
Polymer hazard index model
Laser direct infrared chemical imaging system

ABSTRACT

Plastic mulch film is often believed to be a significant contributor to microplastic pollution in farmland soil, however, its direct impact in areas with high human activities remains unclear due to the presence of multiple pollution sources. This study aims to address this knowledge gap by investigating the impact of plastic film mulching on microplastic pollution in farmland soils in Guangdong province, China's largest economic province. The macroplastic residues in soils were investigated in 64 agricultural sites, and the microplastics were analyzed in typical plastic film mulched and nearby non-mulched farmland soils. The average concentration of macroplastic residues was 35.7 kg/ha and displayed a positive correlation with mulch film usage intensity. Contrarily, no significant correlation was found between macroplastic residues and microplastics, which exhibited an average abundance of 22,675 particles/kg soil. The pollution load index (PLI) model indicated that the microplastic pollution level was category I and comparatively higher in mulched farmland soils. Interestingly, polyethylene accounted for only 2.7% of the microplastics, while polyurethane was found to be the most abundant microplastic. According to the polymer hazard index (PHI) model, polyethylene posed a lower environmental risk than polyurethane in both mulched and non-mulched soils. These findings suggest that multiple sources other than plastic film mulching primarily contribute to microplastic pollution in farmland soils. This study enhances our understanding of microplastic sources and accumulation in farmland soils, offering crucial information on potential risks to the agroecosystem.

1. Introduction

Plastic pollution is a considerable environmental problem as plastics are widely used and improperly disposed [1]. The plastic waste is estimated to be approximately 6.3 billion tons, with 9% recycled, 12% incinerated, and 79% buried or left in the environment [2]. As the trend in waste generation and management continues, 12.0 billion tons of plastic waste will be landfilled by 2050. In the context of agriculture, plastic waste includes various types, such as mulch films, greenhouse covers, and packaging materials. Among these, plastic mulch films have drawn significant attention due to their extensive use and improper disposal. Large plastics can break down into smaller ones due to UV radiation, industrial production, and other factors [3]. The formed small plastics with a size of less

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Abbreviations: Pollution load index, PLI; Polymer hazard index, PHI.

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https://doi.org/10.1016/j.heliyon.2023.e16587
Received 22 March 2023; Received in revised form 20 May 2023; Accepted 22 May 2023

than 5 mm are called microplastics [4], which have attracted extensive attention as they are widespread in the ecosystem [5]. Most studies have focused on microplastics in the marine ecosystem, while relatively fewer have studied microplastics in the terrestrial ecosystem. However, microplastics in the terrestrial ecosystem are much more than that in the ocean and are primary sources of marine microplastics [6]. Hence, more attention should be paid to microplastics in the terrestrial ecosystem.

Microplastics can act as carriers for pollutants and microorganisms and affect the soil ecosystem in many ways [7]. Previous studies have shown that microplastics could cause changes in the physical structures of the soil [8], such as changing soil bulk density, porosity, and the contents of water stable large macroaggregates, thus affecting water evaporation, water availability, and water-holding capacity. In addition, microplastics could also affect the chemical properties of the soil [9], such as the pH and organic matter. Moreover, microplastics could affect the structure and function of the microbial community [10], causing changes in the decomposition of organic materials, nutrient metabolism, soil respiration, and greenhouse gas emission. The impacts of microplastics on the soil ecosystem primarily depend on factors such as concentration, polymer composition, size, and shape [11], making it crucial to comprehend the characteristics of microplastics in order to assess their impacts.

Microplastics can be introduced into farmland soil in many ways. The solid wastes used for composting often contain plastic wastes, which will form microplastics through processes such as crushing, screening, and stacking. As the application of organic fertilizer increases because of its advantages of being green and economical, it has become one of the primary sources of soil microplastics [12]. The application of sludge also introduces microplastics into the farmland soil, as 90% of microplastics in sewage will be enriched in the sludge [13]. It is estimated that the amount of microplastics entering the environment through sludge is up to 1.56×10^{14} particles in China every year [14]. According to the application and load of microplastics in sludge, it is estimated that 6.3×10^4–4.3×10^5, 4.4×10^4–3×10^5, and 2.8×10^3–1.9×10^4 tons microplastics will be introduced into the farmland soils in Europe, North America, and Australia [15], respectively. Previous studies have preliminarily revealed that farmland soil is becoming a significant environmental reservoir of microplastics, but more information on source analysis is needed.

The use of plastic mulch film in agriculture has raised concerns about its potential contribution to microplastic pollution in farmland soil. However, the direct effect of plastic film mulching on microplastics is suspected to be limited in areas with high human activities, as microplastics can enter the agroecosystem through various pathways. Therefore, this study aims to investigate the impact of plastic film mulching on microplastic pollution in farmland soils in Guangdong province, China's largest economic province. The macroplastic residues in soils were investigated in 64 agricultural sites, and the microplastics were analyzed in typical plastic film mulched and nearby non-mulched farmland soils, mainly using a laser direct infrared (LDIR) chemical imaging system, pollution load index (PLI) model, and polymer hazard index (PHI) model. The findings highlight the importance of considering multiple sources of microplastic pollution in farmland soils and provides crucial information for evaluating potential risks to the agroecosystem.

2. Materials and methods

2.1. Study area

Guangdong province is the largest economic province in China, with a GDP of $1.9 trillion and a population of 126.8 million in 2022. It can be divided into four regions: the Pearl River Delta (PRD), East Guangdong (EG), West Guangdong (WG), and North Guangdong (NG). The PRD is one of the most economically developed regions in China. The main crops in the PRD mulched with the plastic film are potatoes, sug-arcane, etc. It is cold in winter in the EG and NG, and the main crops, including pea-nuts and sweet potatoes, require plastic mulch film for heat preservation. Some farm-lands in the WG are dry, and plastic mulch film is needed to retain water for cultivat-ing crops such as pineapple and sugarcane. In total, an estimated 1.32×10^5 ha of farmland in Guangdong province are covered with plastic mulch film annually according to the China Rural Statistical Yearbook.

2.2. Macroplastic residue sampling and weighing

Macroplastic residue was collected and analyzed using the method based on the "National Farmland Mulch Residue Monitoring Program" issued by the Ecological Environment General Station of China's Ministry of Agriculture and Rural Affairs. According to the principle of representativeness, a total of 64 sampling sites were designated to investigate the abundance of macroplastic residues in the farmland soils in the study area. 17 sampling sites in the PRD, 12 sampling sites in the EG, 19 sampling sites in the WG, and 16 sampling sites in the NG. At each sampling site, the usage intensity of mulching film was investigated, and 5 sampling plots were established randomly. A total of 320 macroplastic residue samples were collected using the method that had been applied in the previous study [16]. When collecting the macroplastic residue sample, a GPS locator was used to record the longitude and latitude of the sampling point. The macroplastic residues were collected from 0 to 30 cm soil layers of 1 m × 1 m squares after passing a 5 mm stainless steel sieve. The collected macroplastic residues were then stored in transparent PE self-sealing bags, with paper sample labels placed outside the bags, and further treated in the laboratory. After removing the attached soil, the macroplastic residues were soaked in water, washed to remove the impurities on the films, and washed with a microwave cleaner. After washing, the macroplastic residues were dried in a cool and dry room and weighed at intervals until they were constant using a weighing scale (Secura324-1CN, Sartorius, Germany).

2.3. Analysis of microplastic in the farmland soils

Soil samples were collected from typical plastic film mulched farmlands and nearby non-mulched farmlands to analyze the accumulation and characteristics of microplastics. The non-mulched farmlands were either under cultivation without the use of plastic mulch or deserted farmlands covered with weeds, which were less disturbed by human activities. The inclusion of deserted farmlands provides additional insight into the presence of microplastics in farmland areas less affected by plastic mulch usage. After macroplastic residue sampling, and before refilling the soil, the soil from the five sampling squares that had passed through the stainless steel sieve and been picked up was mixed using a stainless steel shovel. Following the quartering method, 2 kg of mixed soil samples were collected and placed into amber glass bottles, with sample labels placed outside the bottles. The soil samples were then pretreated in the laboratory. The mixed soil samples were dried to a constant weight at 40 °C. Then 15 g of dried soil was added into 60 ml saturated zinc chloride solution with a density of 1.8 g/ml, stirred, and ultrasonic treatment was performed to make the microplastics in the soil release into the saturated salt solution. The suspension containing microplastics was separated from the soil by standing and digested with H_2O_2 to remove organic matter. The digested samples were then filtered to obtain filter membranes containing microplastics.

The obtained microplastics were identified and analyzed for their abundance, polymers, size, and shape using a stereo microscope (SMZ-171, EOC, China) and laser direct infrared chemical imaging system (8700 LDIR, Agilent Technologies Inc., USA) according to a previous study [17]. The minimum detection limit of 8700 LDIR for identifying microplastic was 10 μm. The spectrum of each microplastic was obtained in the wavenumber range of 975–1800 cm^{-1}, and only the spectrum with a matching degree of more than 65% with Agilent 8700 LDIR database were selected for analysis [18]. To ensure the accuracy and quality control of the microplastics' analyses, a rigorous Quality Assurance and Quality Control (QA/QC) procedure was implemented. All reagents were filtered through a 0.22 μm membrane before use, and 100 ml of the concentrated solution was tested using LDIR to ensure the number of microplastic particles was less than or equal to 1. All glassware used in the experiments was rinsed three times with ethanol solvent. Quality control was performed using self-produced PS microplastics and mixed microplastics containing polyethylene (PE), polypropylene (PP), polycarbonate (PC), Polyamide (PA), polymethyl methacrylate (PMMA), polyethylene terephthalate (PET), polyurethane (PU), polyvinylchloride (PVC), polystyrene (PS), and silicone (SR) to ensure that each microplastic particle could be identified with a match rate greater than 65%. Additionally, the recovery rate of microplastics in soil samples was evaluated, and the calculated recovery rates for various types of microplastics were found to be within an acceptable range: over 95% for PP, PE, and PS, 87% for PVC, 91% for PET, 112% for PU, 93% for SR, and 86% for PA. 25 polymers were identified in the farmland soils, and this study focuses on the top 6 significant polymers with the highest abundance, while the rest are collectively referred to as "others." The shape characteristics of the microplastics determined in this study mainly include circularity and solidity. The circularity represents the similarity between the microplastic particle and the circle, and the solidity represents the ratio of the area of the microplastic particle to its boundary. According to the properties of circularity and solidity, the shape of microplastics can be further divided into microsphere (circularity >0.8), fiber (solidity <0.2), and fragment (solidity >0.2 or circularity <0.8).

2.4. Assessment of microplastic pollution

The PLI model was used for assessing the overall pollution degree of microplastics in the farmland soil as it directly correlated with the abundance of microplastics [19,20]. The evaluation model is presented in the following equations.

$$CFi = \frac{Ci}{C0i} \tag{1}$$

$$PLIn = \sqrt{CFi} \tag{2}$$

$$PLIzone = \sqrt[n]{PLI1 \times PLI2 \times PLI3 \times \cdots\cdots \times PLIn} \tag{3}$$

where CF_i is the pollution coefficient of microplastics, C_i is the measured abundance of microplastics, and C_{0i} is the reference value of microplastic abundance. In this study, the lowest microplastic abundance of 1200 particles/kg detected in a non-mulched soil sample was used as the reference value [21]. PLI_n is the pollution load index of sampling point n, and PLI_{zone} is the pollution load index of the study area.

Currently, there is no standard method for evaluating the ecological risk of microplastic pollution in soil. However, the PHI model is a useful tool for assessing the environmental risk of microplastics and can be used to identify which types of microplastics pose the greatest risk to the environment based on their physical and chemical properties [22]. The model is presented in the following equation [20].

$$PHI = \sum Sn \times Pn \tag{4}$$

PHI is the microplastic-induced risk, S_n is the hazard score assigned to each polymer, and P_n is the proportion of each polymer type.

2.5. Statistical analysis

A combination of parametric and non-parametric statistical methods was utilized to analyze the differences based on the data's normality. The *t*-test, a well-established statistical method for comparing the means of two independent groups, was employed for normally distributed data, such as the abundances of microplastics in soils with and without plastic film mulching. The Mann-Whitney *U* test, a non-parametric statistical method suitable for comparing two independent samples, was employed to compare non-normally distributed data, such as the circularity and solidity of microplastics in soils with and without plastic film mulching. Additionally, the Kruskal-Wallis H test, a non-parametric method for comparing the medians of three or more independent samples, was applied to analyze non-normally distributed data, such as plastic film usage intensity and macroplastic residue in different study regions. A p-value less than 0.05 was considered to indicate a significant difference.

Given that the data did not follow a normal distribution, the Spearman rank correlation coefficient, a non-parametric test that measures the strength and direction of the association between two variables, was employed to analyze the relationships among mulch film usage intensity, macroplastic residue, and soil microplastics.

3. Results and discussion

3.1. Use and residue of plastic mulch film

Plastic mulch film was widely used in agricultural production in the study area (Fig. 1A), with an average usage intensity of 120.0 kg/ha, which is higher than in other provinces in China, such as Chongqing and Jilin [16]. This may be due to the high multi-plantation index in the study area. In order to achieve high agricultural productivity, farmers in the study area always cultivate different crops continuously within one year, which needs plastic film mulching more than once to allow crops to make full use of heat, water, light, and nutrients [23], and results in a high usage intensity of the plastic film.

The Kruskal-Wallis H test indicated that the usage intensity of plastic film varied in different study regions (Fig. 1B). Plastic film used in WG was significantly more than that in other regions. This result lay in the fact that different environmental and agricultural conditions in different regions might lead to variations in the usage intensity of mulch film as the WG region is an important production base for vegetables. Some farmlands in WG need to be covered with black film to keep water and prevent weeds due to lack of water and easy for grass growth [24]. The results provide important information for identifying key areas for the use and recovery of plastic film.

Macroplastic residues were found in the farmland soils across the study area (Fig. 1C), with an average abundance of 35.7 kg/ha, which is lower than that of 19 provinces across China by 47.9 kg/ha [16]. It can be explained by the relatively short period of time that plastic mulching has been used in Guangdong province, where 69.2% of the farmers used plastic film for the first time after the year

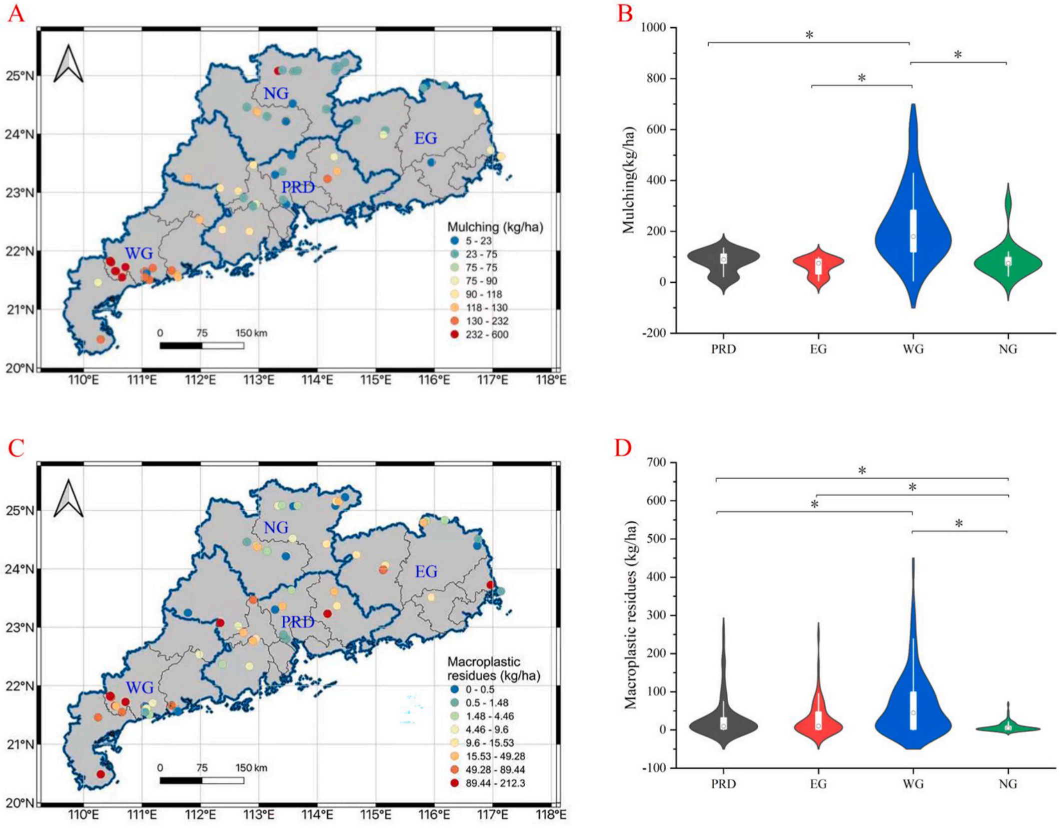

Fig. 1. Plastic mulch film usage and residue. (A) Usage intensity of plastic mulch film in 64 sampling sites. (B) Differences in usage intensity across various regions. (C) Macroplastic residues detected in agricultural soils of 64 sampling sites. (D) Differences in macroplastic residues across various regions.

2011. In comparison to the limit for the residual quantity of agricultural mulch film specified by the China National Standard (GB/T 25413-2010), the average macroplastic residue is still below the standard limit of 75 kg/ha, indicating that macroplastic residue pollution is not a severe environmental problem in the study area.

The Kruskal-Wallis H test indicated that macroplastic residues varied considerably in different study regions (Fig. 1D). The macroplastic residue was the least in the farmland soil of NG, with an average abundance of 7.8 kg/ha. The result underscores the fact that macroplastic residue pollution is a complex and multifaceted problem that could vary depending on many factors, such as geographic location. It also highlights the need for localized solutions and targeted interventions to address the issue. The macroplastic residue in the soil would negatively impact soil health and crop yield [25,26]. It was shown that crop yield would decrease by 3% for every additional 100 kg/ha of film residue [27]. The abundance of macroplastic residues in the soils of some farmlands exceeded the limit standard, ever reaching 432.8 kg/ha, demonstrating the need for ongoing research and action to understand better the sources, distribution, and impacts of macroplastic pollution in different regions. This will help inform effective strategies for preventing and mitigating the harmful effects of macroplastic residue pollution on the agroecosystem.

The Spearman rank correlation coefficient suggested that the macroplastic residues in the soils were positively correlated with the plastic film usage intensity in the study area (Fig. 2), indicating plastic film mulching contributed to the accumulation of macroplastic residue in the farmland soils. It could be explained that the plastic film used in the study area was always made of polyethylene, which is difficult to degrade under natural conditions because of its high physical, chemical, and biological stability [28]. If the plastic film was not completely removed after use, macroplastic residue in the soil would accumulate. This finding had significant implications for agricultural practices and waste management strategies. It highlighted the need for alternative solutions to plastic film usage in agriculture, as well as improved waste management practices to prevent macroplastic residue pollution from accumulating in the farmland soils. Moreover, this result emphasized the importance of addressing the root causes of macroplastic residue pollution rather than just focusing on its symptoms. By reducing the use of plastic film and promoting more sustainable agricultural practices, we can reduce the amount of plastic film that enters the environment and help protect agroecosystem health.

3.2. *Abundance of microplastics*

Microplastics were found in all soil samples of the study area with an average abundance of 22,675 particles/kg, generally higher than that in the global majority of the prospected agricultural and horticultural sites [29]. Compared to the abundance of microplastic in the farmland and grassland soils of the Qinghai-Tibet plateau, the abundance of microplastic in this study area exceeded by 3 orders of magnitude [30]. It could be explained by the intensity of anthropogenic activities as population density in the study area is more than that in the Qinghai-Tibet plateau [31]. In addition, the method for microplastic identification might also result in the difference as the laser direct infrared chemical imaging system used in this study had a higher resolution than the stereo microscope.

The *t*-test suggested that the average abundance of microplastics in mulched soil was significantly higher than that in non-mulched soil, which appeared to be consistent with previous studies carried out in southwest China [32]. However, more information was needed to conclude that plastic film mulching directly increased the number of microplastics as multiple sources accounted for the accumulation of microplastics in farmland soils [33]. As microplastics could have negative impacts on soil health and ecosystem functioning, it is important to investigate sources of microplastics in the soil and develop strategies to reduce this impact.

3.3. *Polymers composition of microplastics*

The polymers of microplastics provided information essential for determining their sources and risks. A total of 25 polymers were detected in the soil samples, including PU, SR, PB, PET, PVC, PE, which accounted for 76.8% of the microplastics. In addition, other

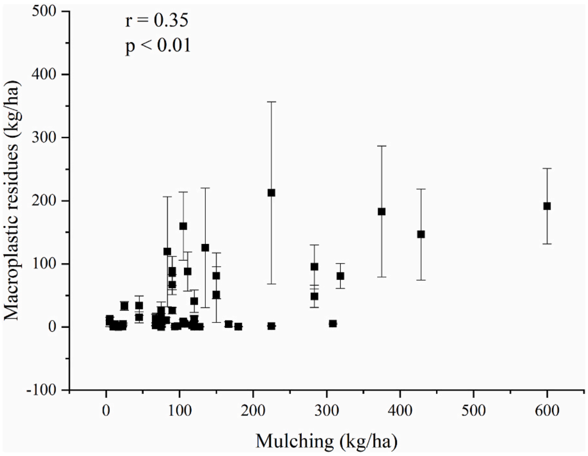

Fig. 2. Correlation between plastic mulch film usage intensity and macroplastic residue amounts in farmland soils.

common polymers were also found, such as PP, PLA, PC, POM, PS. The diversity of polymers indicated that the sources of soil microplastics were diverse. Hence, more comprehensive waste management practices are needed to prevent microplastic pollution from accumulating in the environment.

The diversity of the polymers was generally the same in the plastic film mulched soils and non-mulched soils, but the percentage of the polymer was different (Table 1). PU and SR accounted for 66.4% of the microplastics in the plastic film mulched soils, and they accounted for 58.9% of the microplastics in the non-mulched soils. PB was the third most abundant microplastic in the plastic film mulched soils, while PET was the third most abundant in the non-mulched soils. As human activity intensity differed in the plastic film mulched and non-mulched farmland soils, the results suggested that human activity introduced considerable PU, SR, and PB into farmland soils.

3.4. *Size of the microplastics*

The microplastics in the farmland soils had an average diameter of 47.7 μm, and nearly half of the microplastics (49.0%) had a diameter of less than 30 μm. With the increase of the microplastic diameter, the number of microplastics decreased (Fig. 3A). This result differed from the study conducted in southwest China [34]. It might be caused by different identifying methods for microplastics as the laser direct infrared chemical imaging system used in this study had the minimum detection limit of 10 μm and could characterize smaller microplastics than the stereo microscope.

The average diameter of microplastics in the soils with film mulching was significantly larger than that in the non-mulched farmland soils. The result was in line with a previous study that showed a high percentage of large-sized microplastics in mulched soil [32]. It could be explained by the short time of plastic input and slow weathering under environmental conditions, such as solar radiation and climate conditions [35]. The result indicated that more plastics were newly input and degraded into smaller microplastics in the farmland with film mulching. The diameter of the polymers differed in the mulched farmland and non-mulched farmland (Fig. 3B). Particle size is an essential property of microplastic that can influence surface area and environmental behavior [36]. Smaller microplastics always have a greater potential for surface chemical interactions [37], but more information is needed to assess the ecological effects of microplastics in the mulched soil and non-mulched soil as they could be impacted by other factors.

3.5. *Shape of the microplastics*

Circularity and solidity are essential characteristics that could be used to classify microplastics into fibers, microspheres, and fragments. The average circularity of microplastics was 0.29 and 99.0% of the microplastics had a circularity of less than 0.8. PU had larger circularity than other microplastics, such as PB (Fig. 4A). The average solidity of microplastics was 0.60 and 92.0% of the microplastics had a solidity of more than 0.2. PVC had the largest solidity, while PB had the smallest solidity (Fig. 4B). These findings suggest that circularity and solidity can be useful indicators for identifying and classifying different types of microplastics.

The Mann-Whitney *U* test indicated that circularity and solidity were different in mulched soil and non-mulched soil. As for circularity, it was significantly less in the mulched farmland soil than in the non-mulched soil. PET had the largest circularity in the film-mulched soil (Fig. 4C), whereas PB had the smallest circularity. PET had the smallest circularity in the non-mulched soil, and it was also smaller than that in the mulched soil. The solidity of microplastics in the mulched soil was significantly less than that in the non-mulched soil (Fig. 4D). PVC had the largest solidity in the soil with film mulching, whereas PB had the smallest solidity. The solidity of PB in the soil without film mulching was larger than that in the soil with film mulching, while the solidity of PET was smaller in the soil without film mulching than that in the soil with film mulching. The differences in the circularity and solidity of microplastics in the mulched and non-mulched soils indicated that their formations were different.

Diverse microplastic were found in the farmland soils (Fig. 5A), including fragments (Fig. 5B), fibers (Fig. 5C), and microspheres (Fig. 5D). Fragments accounted for 91.2% of the microplastics, while microspheres accounted for only 0.9%. The result was different from that of a study carried out in southwest China [34], which showed that fiber was the most abundant microplastic. PU was the most abundant in fiber, microsphere, and fragment, accounting for 31.4, 56.5, and 50.2%, respectively. PE mainly existed in the form of fragments, accounting for 77.1%, and the rest existed in the form of fiber. There was no microsphere PE, PET, PB, or fibrous PVC. The polymers of fibers, microspheres, and fragments were different in the soils with and without film mulching (Fig. 6). PU was the most abundant polymer in fibers in the soil with film mulching, while PET was the most abundant polymer in fibers in the soil without film

Table 1
The abundance of different microplastics in the plastic film mulched and non-mulched farmland soils.

Microplastics	Plastic film mulching		Non-plastic film mulching	
	Abundance (particles/kg)	Percentage	Abundance (particles/kg)	Percentage
PU	17646 ± 20626	39.6 ± 10.4	4447 ± 6759	37.6 ± 13.6
SR	9050 ± 6301	26.8 ± 6.0	2690 ± 4848	21.3 ± 12.1
PB	1602 ± 1711	4.4 ± 2.1	103 ± 252	0.4 ± 0.4
PET	1147 ± 1073	3.1 ± 0.9	352 ± 367	6.3 ± 3.5
PVC	1164 ± 1672	4.3 ± 3.1	285 ± 467	4.4 ± 3.9
PE	829 ± 617	2.5 ± 0.5	306 ± 515	2.9 ± 2.0
Others	4952 ± 3304	19.3 ± 7.3	778 ± 400	27.1 ± 15

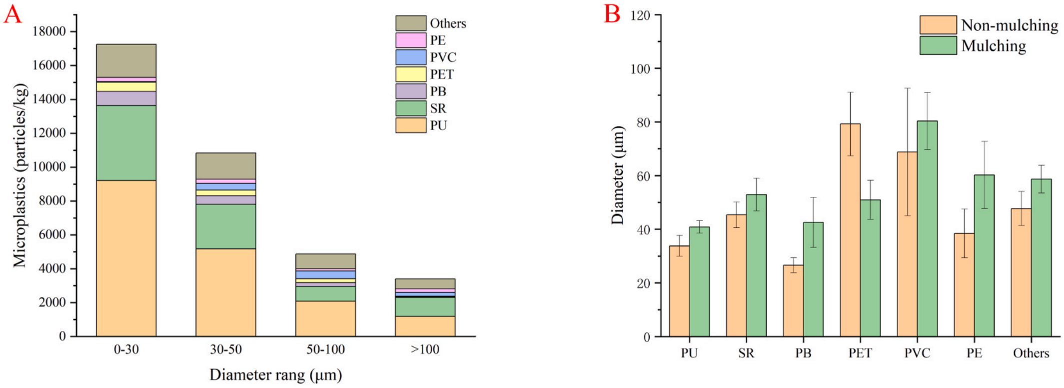

Fig. 3. Microplastic diameters in farmland soils. (A) Abundance and polymer composition of microplastics across different diameters. (B) Diameters of polymers in mulched and non-mulched farmland soils.

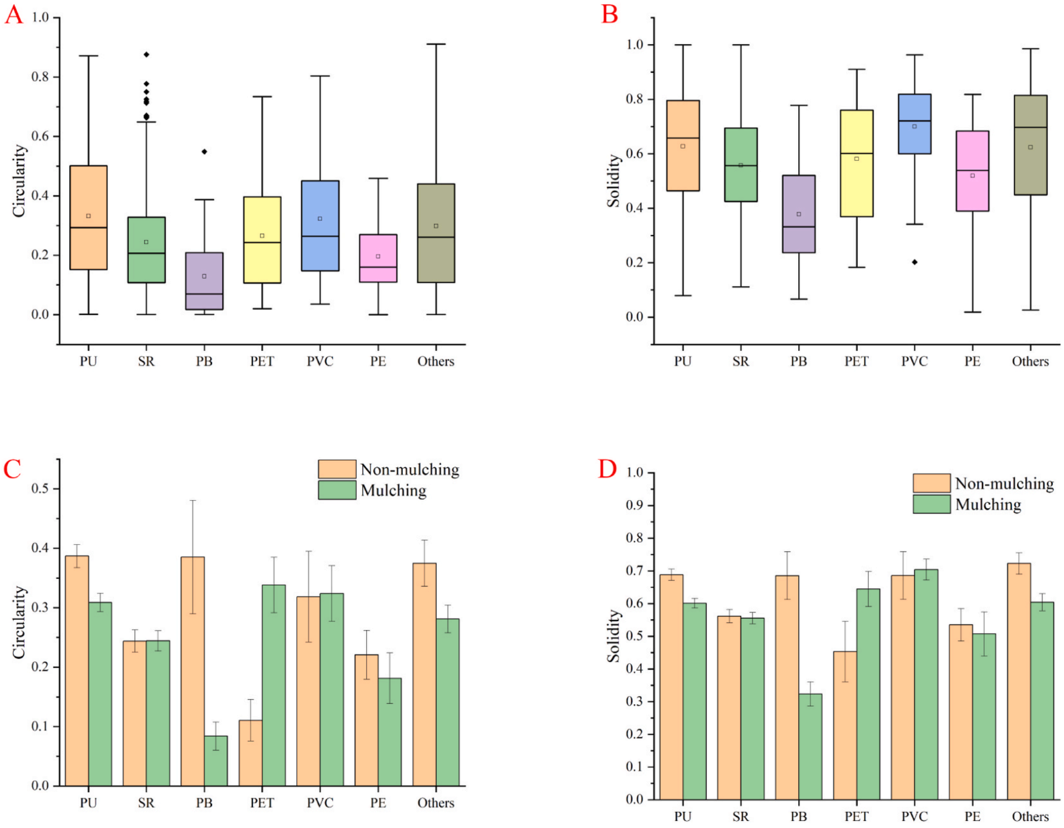

Fig. 4. Shape characteristics of microplastics in farmland soils. (A) Circularity and (B) solidity of different polymers. (C) Circularity and (D) solidity of polymers in soils with and without film mulching.

mulching. The microsphere in the soil with film mulching contained PU, PVC, and SR, while PU was the only polymer of the microsphere in the soil without film mulching. The difference in the polymer of microplastic shapes in the soils with and without film mulching indicated that they had different sources, which would provide critical information for controlling microplastic pollution in the farmland soil.

3.6. Microplastic pollution assessment

The PLI model was used to assess the level of microplastic pollution in the farmland soil. When *PLI* is less than 10, the area is classified as category I pollution. If $10 < PLI < 20$, it is classified as Category II pollution. When $20 < PLI < 30$, it is classified as Category

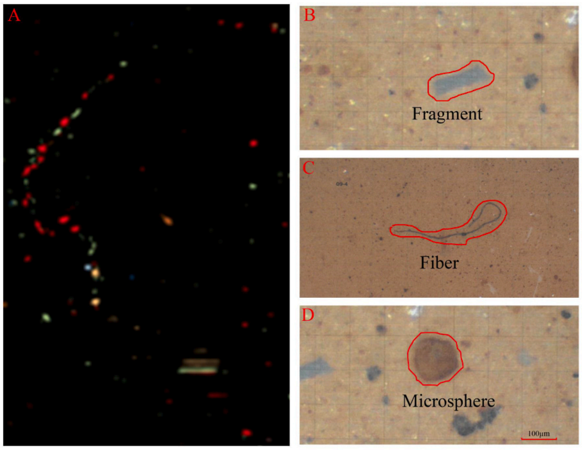

Fig. 5. Diverse microplastic shapes found in farmland soils. (A) Image of microplastics captured using a laser direct infrared chemical imaging system. (B) Fragment, (C) fiber, and (D) microsphere shapes.

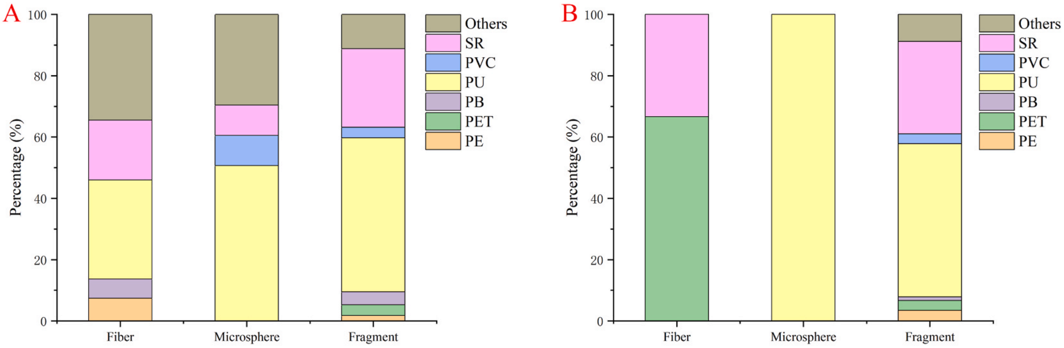

Fig. 6. Proportion of polymers in various microplastic shapes found in soils from (A) plastic film mulched farmlands and (B) non-mulched farmlands.

III pollution. PLI greater than 30 is classified as Category IV pollution [20]. Employing Equations (1)–(3), a relatively low overall PLI was computed for the study area, with a PLI_{zone} value of 3.3. All sampling points are classified as category I, with PLI values ranging from 1.53 to 8.03. The average PLI value of mulched farmland soils was 5.27, higher than that of non-mulched farmland soils, which was 2.44. The result suggested that the degree of microplastic pollution is relatively higher in soil covered with plastic film. It was noteworthy that basic data and background values for microplastic pollution were lacking in the study area, so the PLI model evaluated the degree of microplastic pollution in the farmland soil using the minimum detected abundance value (1200 particles/kg) in place of the background value, which would lead to an underestimation of the degree of microplastic pollution.

The PHI model was used to evaluate the potential hazards of microplastics based on their physical and chemical properties [22]. PU posed the greatest risk according to the PHI computed by Equation (4), and it was 13,775 times more than PE. It could be explained that PU has a higher risk value (hazard score = 10,599) than PE (hazard score = 11) and a larger proportion of the overall microplastic content. Both in plastic film mulched soils and non-mulched soils, the environmental risk posed by PU was significantly higher compared to PE, with a ratio of 12,493 and 15,262, respectively. These findings suggested that the presence of PU microplastics in farmland soils should be a concern regardless of plastic film mulching. The PHI model is effective in identifying polymers with relatively high environmental risk, but it has limitations and cannot provide an accurate risk assessment of microplastic pollution. One of the limitations of the PHI model is that it only considers the proportion of microplastics in a sample and not their absolute abundance. This means that the model cannot provide an accurate assessment of the total amount of microplastics in an environment. This is important because even if a particular type of microplastic has a low proportion if it is present in large quantities, it could still pose a significant risk. Another limitation of the PHI model is that it does not consider other factors, such as the size and shape of the microplastics or the environmental conditions, which would affect the environmental effects. Hence, the tools and approaches are necessary to fully assess the environmental risk of microplastics.

3.7. Environmental implications

The concentration of microplastics in the farmland soil showed no significant correlation with the usage intensity of the agricultural film and the macroplastic residue in the soil. The result was consistent with a previous study carried out in the coastal plain of Hangzhou Bay, east China [33], which showed multiple sources other than plastic film mulching contributed directly to the accumulation of microplastics in the agricultural soils, while it was different from another study which showed a significant positive correlation between the concentration of microplastics in soil and the usage intensity and age of agricultural film [16]. The abundance of microplastics in the mulched soil was significantly higher than that in the non-mulched soil, which was in line with the intensity of human activities, implying that human activities significantly impacted the accumulation of microplastics in agricultural soil. The results suggested that multiple sources other than plastic film mulching were primarily responsible for microplastics in the farmland soil of Guangdong province.

The diversity of polymers in the farmland soil also suggested that plastic film mulching has a limited direct impact on microplastics. PE was the primary polymer of the agricultural film [38], while it only accounted for 2.7% of the microplastics in the farmland soil. The result differed from a previous study showing that PES and PE were the two primary polymers representing 82.1% of microplastics in the soils of southwest China [32]. In addition, although the abundance of PE in the farmland soil with film mulching was more than that in the farmland soil without film mulching, the percentage of PE in microplastics was not significantly different. The results indicated that plastic film mulching directly contributed little to the accumulation of microplastics in the agricultural soil.

PU was the most abundant microplastic in the soil and has a high-risk value (hazard score = 10,599), much greater than that of common polymers such as PE (hazard score = 11), PET (hazard score = 4), PP (hazard score = 4), and PS (hazard score = 30) [22,39]. Hence, PU microplastics in farmland soil should be a cause for concern as they could have significant negative impacts on soil quality, as well as the organisms that rely on it for survival. The presence of PU microplastics in the farmland soil may result from agricultural practices, waste disposal, and atmospheric transport [40]. To address this issue, it may be necessary to implement policies and regulations that limit the use and disposal of PU, as well as promote sustainable farming practices. Additionally, further research is needed to better understand the impacts of microplastic pollution on soil ecosystems and to develop effective strategies for mitigating these risks.

4. Conclusions

In conclusion, our study highlights the importance of considering multiple sources of microplastic pollution in farmland soils, as plastic film mulching was found to have a limited direct impact on microplastic accumulation. The research revealed a positive correlation between macroplastic residues and mulch film usage intensity but no significant correlation between macroplastic residues and microplastics. Moreover, polyethylene accounted for a small proportion of microplastics and posed a low environmental risk in both mulched and non-mulched soils. These findings emphasize the need for further research to better understand the sources of microplastics in farmland soils and develop effective mitigation strategies to minimize the potential risks they pose to the agroecosystem.

Author contribution statement

Conceived and designed the experiments: Bibo Long and Dong Xie.
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Analyzed and interpreted the data: Bibo Long, Fayong Li, and Ke Wang.
Contributed reagents, materials, analysis tools or data: Bibo Long, Fayong Li, and Dong Xie.
Wrote the paper: Bibo Long.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the GDAS' Project of Science and Technology Development (2020GDASYL-20200103055) and the National Natural Science Foundation of China (52103336), We want to express our great gratitude to our colleagues for helping with the sampling. In addition, we would like to thank the staff members of Shanghai Microspectrum Testing Technology Group Co., Ltd for their support in data collection.

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