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Dynamics of residual film mass and microplastic abundance in long-term plastic-mulched cotton fields

Shufeng ZHANG[1,2,3], Xiaoqing LIAN[1,2,3], Xiao YANG[1,2,3], Yachuan ZHAO[1,2,3], Can HU (✉)[1,2,3], Haichun ZHANG (✉)[4], Xufeng WANG[1,2,3]

1 College of Mechanical and Electrical Engineering, Tarim University, Alaer 843300, China.
2 Modern Agricultural Engineering Key Laboratory at Universities of Education Department of Xinjiang Uygur Autonomous Region, Alaer 843300, China.
3 Xinjiang Production and Construction Corps (XPCC) Key Laboratory of Utilization and Equipment of Special Agricultural and Forestry Products in Southern Xinjiang, Alaer 843300, China.
4 Institute of Agricultural Mechanization, Xinjiang Academy of Agricultural Sciences, Urumqi 830091, China.

KEYWORDS

Long-term mulching, microplastic pollution, threshold effect, subsurface transport, arid agroecosystems

HIGHLIGHTS

- Residual film mass strongly links to microplastic abundance, accelerating above a threshold of 200 kg·ha^{-1}.
- Long-term mulching increase microplastics < 1 mm by nearly threefold, decreasing to 30 cm deep, revealing size dynamics.
- A 30-year field trial provided the first quantification of residual film (281 kg·ha^{-1}) and arid-zone microplastic vertical diffusion.

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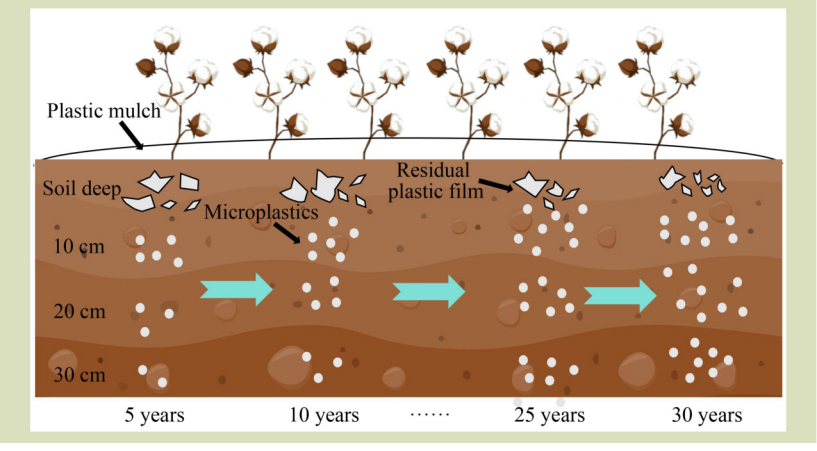
GRAPHICAL ABSTRACT



ABSTRACT

This study investigated the residual plastic film and microplastic (MP) dynamics in cotton fields of Xinjiang after 5–30 years of mulching. Long-term mulching not only caused continuous accumulation of residual films and MPs but also triggered nonlinear accumulation dynamics. When residual film mass exceeded the critical threshold of 160–200 kg·ha^{-1}, the MP generation rate increased significantly (by 85%), a phenomenon termed the critical effect. Residual films (manually collected) and MPs (extracted by density separation) had cumulative increases with mulching duration, reaching 127, 85.8 and 67.9 kg·ha^{-1} for films, and 10.8 × 10^3, 9.75 × 10^3 and 6.34 × 10^3 fragments kg^{-1} for MPs at depths of 0–1, 10–20, and 20–30 cm after 30 years. MPs had surface enrichment but also migrated downward, with < 1 mm fragments increasing from 7.9% to 22.6% to depth, while > 2 mm fragments declined

from 49.2% to 13.8%. A strong linear correlation (R^2 = 0.85–0.94) confirmed residual films as the primary MP source. Beyond the 200 kg·ha^{-1} threshold, MP accumulation rates accelerated sharply, highlighting fragmentation risks and vertical migration in arid soils. Timely residue removal before reaching critical thresholds is crucial to mitigate soil MP pollution. These findings provide actionable strategies for managing plastic-intensive agroecosystems, emphasizing proactive intervention to disrupt the critical effect and its cascading environmental impacts.

1 Introduction

Globally, China is the main consumer of agricultural plastic film[1], particularly in its northern and north-western regions. Mulching technology has significantly enhanced cotton yields and economic returns in arid and semiarid areas (e.g., Xinjiang) by improving soil moisture retention, temperature elevation and water use efficiency[2,3]. However, the long-term application of non-degradable plastic mulch has led to progressive residual plastic mulch film accumulation in soils, emerging as a critical source of soil pollution[4]. In Xinjiang, an extreme arid region (annual precipitation < 200 mm and evaporation > 1500 mm), film fragments rapidly disintegrate under high-temperature and low-humidity conditions[5], migrating to deeper soil layers and water bodies via wind and water erosion, thereby amplifying ecological risks. Microplastics (particle size < 5 mm) derived from residual plastic film degradation, owing to their small size and high specific surface area, influence soil physicochemical properties through two mechanisms: adsorption of heavy metals and pesticide residues, and pore structure modification that enhances their vertical migration deeper into the soil[6]. Recent studies emphasize that soil texture is a key regulating factor for microplastic migration. In typical sandy soils of arid regions, microplastics have stronger vertical migration due to large pore spaces and preferential flow paths, while clay-rich soils promote surface retention through strong adsorption[7]. Long-term field experiments in Mediterranean agricultural ecosystems further show that 20 years of continuous mulching increased microplastic abundance in sandy loam subsoil (30–50 cm) by 2.4 times, significantly higher than the 78% increase in clay soil under the same management conditions[8]. These processes disrupt soil physicochemical properties, threaten cotton root development and soil fertility, and pose risks to agricultural ecosystems and food safety. Investigating the relationship between residual film mass, microplastic abundance and their spatial distribution in soils is thus crucial for sustainable agroecosystem management.

Recently, there has been increasing research effort on residual film and microplastic pollution. International studies under controlled laboratory conditions have elucidated film degradation mechanisms. Horton et al.[9] demonstrated that ultraviolet radiation and mechanical abrasion fragment polyethylene films into microplastics (< 1 mm) within 6 months using accelerated aging experiments. Boots et al.[10] found that microplastics in moist soils rapidly migrate to depths of 50 cm through macropore preferential flow. However, these findings were primarily derived from short-term (< 3 years) controlled experiments, lacking field validation of residual film fragmentation and microplastic dynamics under long-term mulching. In Chia, researchers have conducted extensive empirical studies on residual film pollution. For example, Yang et al.[11] found an annual increase of 2.13 × 10^5 fragments ha^{-1} in residual film quantities over 8 years of continuous mulching. Li et al.[12], in a 32-year mulching trial, found that fertilization exacerbates plastic pollution; large plastic (> 5 mm) abundance in fertilized plots was 10-fold higher than in unfertilized areas, while microplastic (< 5 mm) quantities doubled, with polyethylene fragments constituting 33%–56% of microplastics and having downward migration.

The accumulation and distribution of microplastics represent core challenges in soil plastic pollution research. Long-term mulching not only intensifies residual film pollution but also provides a continuous source for microplastic generation[13]. Recent studies indicate that the ecological effects of

microplastics are soil type dependent. In arid sandy soils, < 100 μm polyethylene fragments physically disrupt the clay-organic matter bond, reducing the water-stable aggregates by 19%–33%, thus increasing wind erosion risks[14]. Microplastic size, abundance and vertical migration are likely influenced by soil depth and residual film mass[15]. Understanding the dynamic relationship between residual film and microplastics is essential for unraveling pollution mechanisms and formulating mitigation strategies. This study focuses on cotton-growing regions of Xinjiang, analyzing the spatiotemporal dynamics of residual film mass and microplastic abundance across varying mulching durations (5, 10, 15, 20, 25 and 30 years). Microplastics were extracted using density separation coupled with chemical digestion[16], followed by particle size classification and abundance analysis to investigate residual film accumulation patterns and their driving effects on microplastic distribution. This research aimed to (1) quantify the relationship between residual film mass and microplastic generation; (2) analyze microplastic size evolution and vertical distribution under long-term mulching; and (3) provide scientific foundations for precise assessment and management of agricultural microplastic pollution.

The innovations of this study were threefold: (1) it systematically quantified residual film contributions to microplastic generation across mulching durations using long-term field trials; (2) it refined microplastic size classification to reveal dynamic shifts in fragment distribution with mulching duration and soil depth; and (3) it identified a threshold effect characterized by accelerated microplastic accumulation under high residual film mass (> 200 kg·ha^{-1}), offering novel insights into plastic degradation mechanisms. These findings advance strategies for mitigating agricultural microplastic pollution and optimizing plastic film management practices.

2 Materials and methods

2.1 Study area

This study was conducted in the Alar City region of the First Division of Xinjiang Uygur autonomous region and its surrounding areas, a typical arid zone. The region has an annual precipitation of 50–150 mm, an annual evaporation exceeding 2000 mm and significant diurnal temperature fluctuations. The dominant soil type is brown desert soil, characterized by sandy loam texture, low organic matter content (< 1%) and a pH of 8.0–8.5. Cotton has been cultivated long-term in this area, with widespread adoption of plastic film mulching technology to enhance water-use efficiency and crop yields. Sampling sites included croplands with film-mulching durations of 5, 10, 15, 20, 25 and 30 years, representing distinct stages of film-mulching application.

2.2 Soil and plastic film sampling

This study selected a total of 60 independent sampling points, with 10 sampling points for each mulching duration (5, 10, 15, 20, 25 and 30 years). These sampling points were randomly distributed in independent fields to ensure sample independence. Each selected field was at least 500 m apart to minimize spatial overlap, thus avoiding pseudo replication. At each point, a five-point sampling method was employed to ensure representativeness and spatial homogeneity. A 100 cm × 100 cm quadrat was established at each sampling site, and soil samples were collected from three depths: 0–10, 10–20, and 20–30 cm. For each layer, soil was excavated onto a canvas sheet, and large plastic film fragments (> 5 mm) were manually sieved, separated from impurities (e.g., soil clods, cotton stalks and roots) and stored in labeled bags. About 1 kg of soil from each layer was sieved (5 mm), placed in cotton bags to avoid external plastic contamination and transported to the laboratory for residual film and microplastic extraction and analysis[17].

2.3 Residual film extraction and quantification

Fragments of plastic mulch film were separated manually from air-dried soil samples and rinsed with distilled water to remove adhered soil and organic matter, treated with 30% H_2O_2 for 24 h to eliminate residual organics and oven-dried at 50 °C to constant weight. The dried films were weighed using a high-precision electronic balance (accuracy 0.0001 g). Residual film mass was categorized into five ranges: < 10, 10–25, 25–50, 50–100, and > 100 mg, and recorded by soil depth and mulching duration.

The residual film mass per unit area M, (kg·ha^{-1}) was calculated according to the Chinese National Standard GB/T 25413-2010[18]:

$$M = \frac{W_1 + W_2 + W_3 + \cdots + W_n}{n} \times 10^4 \quad (1)$$

where, M is the average residual plastic film amount in the sampling plot (kg·ha^{-1}), W is the total weight of residual film in each quadrat (g·m^{-2}), and n is the number of sampling points, each with an area of 1 m^2.

2.4 Microplastic identification and quantification

Microplastics were extracted using density separation[19]. A 10-g subsample of air-dried soil was treated with 150 mL of Fenton's reagent (30% H_2O_2 and $FeSO_4$) for 3 h at room temperature to oxidize organic matter. The mixture was oven-dried at 50 °C for 12 h, resuspended in 200 mL saturated NaCl solution (P = 1.2 g·cm^{-3}), stirred for 30 min and allowed to settle for 24 h. The supernatant was vacuum-filtered through 500 and 1000 μm stainless steel sieves. Fragments < 20 μm were excluded due to limitations in Fourier transform infrared spectroscopy (FTIR) resolution. Retained microplastics (20–500 μm) were further treated with 30% H_2O_2 and ultrasonicated (40 kHz, 240 W) for 5 min, rinsed, dried and sieved into five size classes: 20–100, 100–250, 250–500, 500–1000, and > 1000 μm. Samples were stored at 0 °C for analysis.

Microplastic composition was identified by FTIR (wavenumber range 650–4000 cm^{-1}, resolution 4 cm^{-1} and 32 scans). Spectra were matched against a polymer library using OMNIC software (Thermo Fisher Scientific, Waltham, MA USA). Fragments with ⩾ 70% spectral match were confirmed as microplastics; others were discarded.

2.5 Data analysis

Data were analyzed using Origin 2023 and SPSS 26.0. ANOVA and linear regression were performed to assess relationships between mulching duration, soil depth, residual film mass, and microplastic abundance. Results are expressed as mean ± standard error, with significance set at $P < 0.05$.

2.6 Quality control

Blank controls (1 per 10 samples) were processed to monitor laboratory contamination. Reagents from the same batch were used and all equipment was thoroughly cleaned between samples. All extractions and analyses were conducted in triplicate, with mean values used for statistical analysis.

3 Results and discussion

3.1 Variation of residual film mass with mulching duration

The results (Fig. 1) showed that microplastic abundance increased significantly with film residual duration and this increase accelerated after 15 years of mulching. In fields mulched for 5 years, the film residue quality was 46 ± 5.0 kg·ha^{-1}; when the mulching duration was extended to 10 and 15 years, the residue quality reached 122 ± 6.1 and 134 ± 6.7 kg·ha^{-1}, respectively. Further extending the mulching duration to 20, 25 and 30 years led to a significant increase in residue quality, which reached 167 ± 8.3, 232 ± 11, and 281 ± 14 kg·ha^{-1}, respectively. The regression analysis revealed a significant positive correlation between residue quality and mulching duration (R^2 = 0.97) with a quadratic equation of $y = 0.2x^2 + 0.79x + 81.79$. By analyzing different stages, it was found that during the early mulching phase (5–10 years), the increase in residue quality was relatively small, with an increment of 28.5 kg·ha^{-1} and a growth rate of 28.4%; during the mid-phase (10–20 years), the increase was 99.8 kg·ha^{-1} with a growth rate of 77.4%; and in the long term mulching phase (20–30 years), the increment reached 168 kg·ha^{-1} with a growth rate of 73.6%. These results indicate that long-term mulching not only leads to a significant accumulation of residues but also accelerates the accumulation rate. The rapid accumulation of residues may adversely affect soil structure and permeability, thereby influencing the crop growth environment.

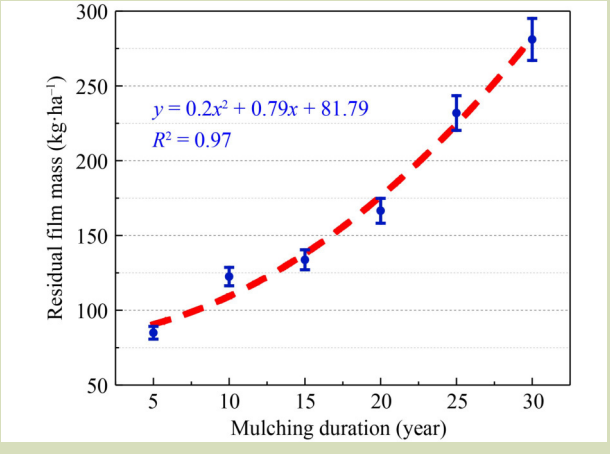


Fig. 1 Residual film mass dynamics over 30 years of film mulching.

Compared with previous studies, our findings confirmed the accelerating effect of mulching duration on the accumulation rate of film residues. For example, long-term observations in Gansu Province found a significant increase in accumulation rate after 15 years of mulching[20], which is consistent with our observations in southern Xinjiang farmland. However, related studies have pointed out that the changes in accumulation rate are also significantly influenced by soil texture and crop cultivation patterns, while this study further demonstrates that under arid climatic conditions, this accelerated accumulation trend is more pronounced. Notably, we also observed that the accumulation of film residue under long-term mulching conditions (> 10 years) has an exponential growth trend. This phenomenon has been confirmed in studies from other regions[21], with related analyses indicating that the accumulation rate of residues in the soil is not only related to mulching duration but also regulated by soil temperature and moisture conditions. This study has verified this pattern through field observations, particularly highlighting the critical role of the arid and high-temperature environment in accelerating residue accumulation.

3.2 Distribution characteristics of residual film fragments

The study investigated the distribution of residual film fragments across different mass ranges in farmlands with continuous mulching durations of 5, 10, 15, 20, 25 and 30 years (Fig. 2). Results revealed a significant increase in the total number of residual film fragments with prolonged mulching duration, rising from 88.5×10^4 to 216×10^4 ha^{-1} (an increase of 145%). When categorized by mass, smaller fragments (< 0.01 and 0.01–0.025 g) had a marked accumulation over time ($P < 0.05$), with their abundance increasing from 46×10^4 to 221.3×10^4 ha^{-1}. Their proportion also rose from 59.1% to 68.7%, indicating that the accumulation of small-mass fragments is a dominant feature of long-term mulching. These findings suggest a pronounced cumulative effect of residual films in topsoil with increasing mulching duration, accompanied by a gradual rise in the proportion of small-mass fragments. This trend reflects accelerated degradation and fragmentation of plastic films under prolonged mulching. In contrast, larger fragments (> 0.1 g) and medium-sized fragments (0.025–0.05 and 0.05–0.1 g, respectively) showed relatively stable proportional contributions. Although the absolute number of large fragments increased from 1.59×10^4 (5-year mulching) to 43.2×10^4 ha^{-1} (30-year mulching) (a 418.1% increase), their proportion declined from 6.3% to 5.6%. This implies slower decomposition and migration rates for large fragments compared to smaller ones, highlighting the potential role of small-mass fragments as indicators of soil ecological changes through their degradation, fragmentation and redistribution processes.

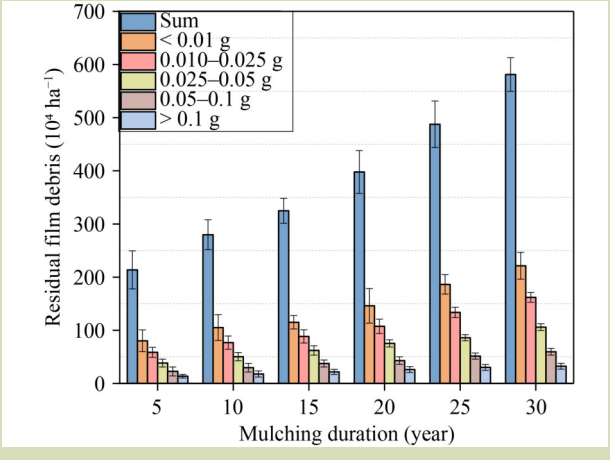


Fig. 2 Distribution of residual film fragment sizes under different periods of film mulching.

These results are consistent with earlier studies. The literature reports a positive correlation between the accumulation rate of small-mass fragments and mulching duration[22], particularly under long-term mulching, though their proportional contributions vary across studies, likely due to spatial heterogeneity in climatic conditions and soil properties[23]. Simulations in arid environments further demonstrate that extreme climate conditions promote mechanical fragmentation of plastic films, generating more small-sized fragments[24], consistent with the observed dominance of small-mass fragments in this study. Importantly, this study emphasizes that small fragments not only accumulate significantly in topsoil but may also migrate to deeper soil layers, suggesting their potential for multilayered cumulative impacts on soil ecosystems across varying mulching durations.

3.3 Vertical distribution characteristics of residual film

The results revealed significant variations in the vertical distribution of residual film mass across soil depths under

different mulching durations (Fig. 3). The topsoil (0–10 cm) was the primary accumulation zone for residual plastic films, with its mass increasing from 45 ± 1.9 to 127 ± 6.4 kg·ha^{-1}, representing a 185% increase. This growth trend significantly exceeds the accumulation rate in the deeper soil layers. In the middle layer (10–20 cm), residual film mass rose from 24.8 ± 1.2 to 85.8 ± 4.3 kg·ha^{-1}, showing a relatively stable accumulation trend. Although the residual film mass in the deep soil layer (20–30 cm) was lower than that in the upper layers, its accumulation rate increased significantly after 20 years of mulching, reaching 67.9 ± 3.4 kg·ha^{-1} at 30 years, with an increase of more than threefold.

The rapid accumulation in surface soil likely stems from direct contact with plastic film and its degradation dynamics, as the surface layer is the primary site for film fragmentation and degradation. In contrast, accumulation in middle and deep layers may be attributed to reduced particle size and vertical migration processes, particularly for small-sized fragments, which are more prone to downward movement under long-term mulching. This phenomenon indicates that the marked increase in residual films in deep soil layers could impose potential impacts on the physicochemical properties and ecosystems of subsoil environments.

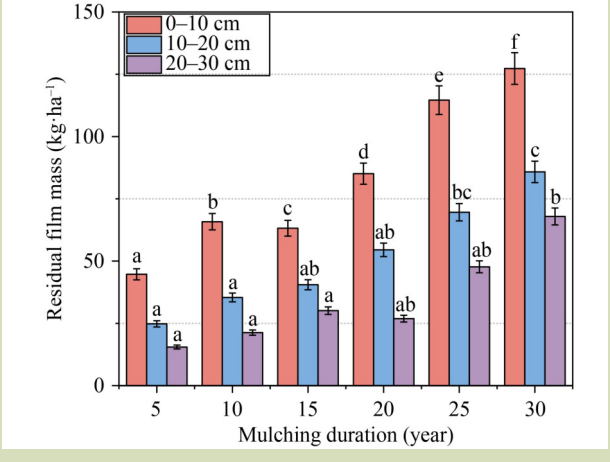


Fig. 3 Vertical distribution of residual film mass across soil depths under different mulching durations. Error bars indicate standard deviation (n = 10). The different lowercase letters above the error bars represent significant differences among treatments ($P < 0.05$)

3.4 Distribution characteristics of microplastic abundance

3.4.1 Temporal dynamics of microplastic abundance with mulching duration

The results indicated a significant increase in soil microplastic abundance with prolonged mulching duration, with distinct distribution patterns across soil layers (Fig. 4). In the 5-year mulching areas, microplastic abundances were 2292, 2158 and 1588 fragments kg^{-1} at depths of 0–10, 10–20, and 20–30 cm, respectively. With extension to 10 years of mulching, abundances increased to 3367, 3125 and 2657 fragments kg^{-1} at the respective depths. Further prolongation to 20 years resulted in abundances of 5241 fragments kg^{-1} (0–10 cm), 4118 fragments kg^{-1} (10–20 cm), and 3120 fragments kg^{-1} (20–30 cm). In areas with mulching durations exceeding 20 years, abundances continued to rise, reaching 10,084 fragments kg^{-1} (0–10 cm), 6909 fragments kg^{-1} (10–20 cm), and 4636 fragments kg^{-1} (20–30 cm).

The data revealed that surface soil (0–10 cm) consistently had the highest microplastic accumulation, with abundances significantly exceeding those in deeper layers. For example, during the 5–10 years mulching period, surface microplastic abundance increased by 1075 fragments kg^{-1} (46.9%), while middle and deep layers showed increases of 967 fragments kg^{-1} (44.8%) and 1069 fragments kg^{-1} (67.3%), respectively. Despite the highest concentration in the 20–30 cm layer for mulching durations beyond 20 years, absolute abundances remained substantially lower than those in surface soil. Overall, microplastics had pronounced surface enrichment, with accumulation gradually extending to middle and deep layers, providing critical evidence for understanding their distribution in long-term mulched farmland soils.

The observed trend aligns with previous studies highlighting that prolonged mulching enhances surface accumulation of microplastics, while their migration to deeper layers becomes more pronounced over time[25]. This indicates that arid climatic conditions have a significant regulatory effect on microplastic transport and redistribution. Additionally, simulation studies indicate that smaller microplastics are more susceptible to vertical migration via water infiltration[26], corroborating the synchronized increase in microplastic abundance across all depths observed here. These findings underscore the critical influence of particle size on microplastic distribution patterns. Collectively, this study revealed the

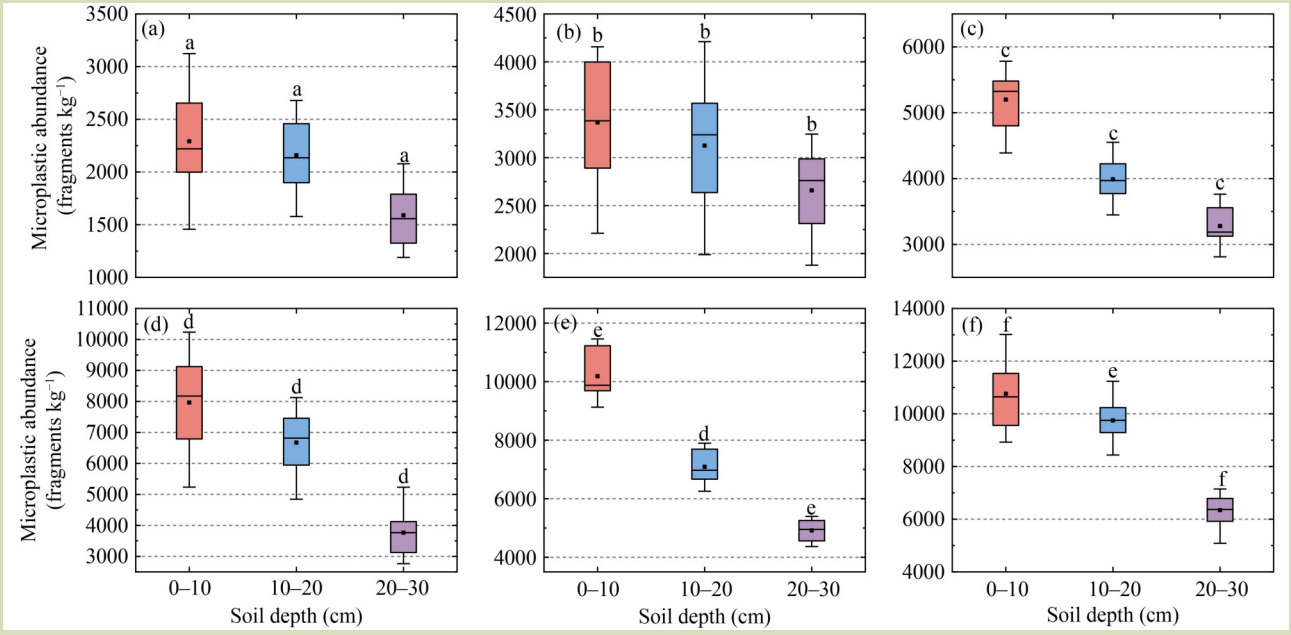


Fig. 4 Vertical distribution of microplastic abundance (fragments kg^{-1}) in the soil at three depths for six mulching durations: Temporal changes in microplastic abundance across soil depths under different mulching durations. (a–f) 5, 10, 15, 20, 25, and 30 years, respectively. Error bars indicate standard deviation (n = 10). The different lowercase letters above the error bars represent significant differences among treatments (P < 0.05).

cumulative effects of long-term mulching on vertical microplastic distribution, particularly in arid soils, where migration and stratification had distinct spatiotemporal dynamics.

3.4.2 Vertical distribution of microplastics across soil depths

Experimental results revealed distinct vertical distribution patterns of microplastic abundance under varying mulching durations (Fig. 5). Surface soil (0–10 cm) remained the primary enrichment zone for microplastics, though its proportional contribution decreased from 43.3% (5-year mulching) to 36.8% (30-year mulching). This decline indicates that while surface soil retains its role as the main site for microplastic generation (via film degradation and fragmentation), prolonged mulching promotes partial migration of microplastics to deeper layers.

In contrast, the middle soil layer (10–20 cm) had relatively stable proportions, fluctuating slightly from 33.1% to 30.6%. Conversely, the deep soil layer (20–30 cm) showed a gradual increase in microplastic proportion, rising from 23.6% (5-year) to 32.6% (30-year), indicating a pronounced accumulation trend in deep soil under long-term mulching. This shift likely reflects the downward migration of smaller microplastic fragments, further emphasizing the influence of mulching duration on vertical redistribution.

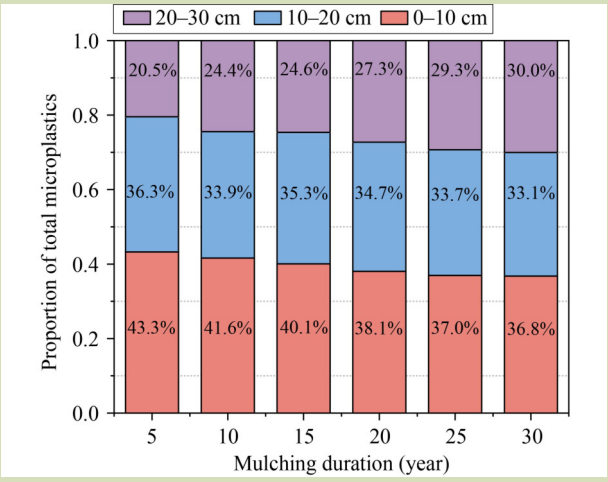


Fig. 5 Proportional distribution of microplastic abundance across soil depth intervals.

Overall, microplastic abundance had a surface-dominated yet depth-expanding distribution pattern[27]. These findings underscore that prolonged mulching may exacerbate both the accumulation and migration risks of microplastics in soil systems, providing critical insights for developing targeted recovery and management strategies.

3.4.3 Dynamics of microplastic particle size distribution

The results revealed significant shifts in microplastic particle size distribution with increasing mulching duration (Fig. 6). The proportion of small-sized microplastics (20–100 and 100–250 μm) increased annually, while the proportion of large-sized microplastics (1000–5000 μm) declined. In 5-year mulched areas, small-sized microplastics (20–100 μm) accounted for 7.9% of the total in surface soil (0–10 cm). With prolonged mulching to 30 years, this proportion rose markedly to 22.6%, representing an increase of 14.7 percentage points ($P < 0.05$). Conversely, the proportion of large-sized microplastics (1000–5000 μm) decreased from 49.2% to 13.8% over the same period. These findings indicate a progressive reduction in microplastic particle size, particularly pronounced in surface soil. Notably, this study was limited by the polymer identification capabilities of FTIR, and thus was unable to analyze the differential degradation patterns between different materials. Previous studies have confirmed that the carbonyl index of low-density polyethylene is positively correlated with its fragmentation rate, while linear low-density polyethylene has stronger resistance to UV degradation. This limitation may impact the in-depth understanding of the relationship between agricultural film additives (such as antioxidants) and fragmentation rates. Future research should incorporate thermal pyrolysis-gas chromatography-mass spectrometry to conduct polymer subtype analysis.

Earlier studies found that prolonged physical fragmentation and degradation of microplastics in soil can lead to gradual particle size reduction, with small-sized fragments accumulating at higher rates than larger ones[28]. The present study further demonstrates that the proportion of small-sized microplastics increased more significantly under the arid and high-temperature conditions of southern Xinjiang, indicating

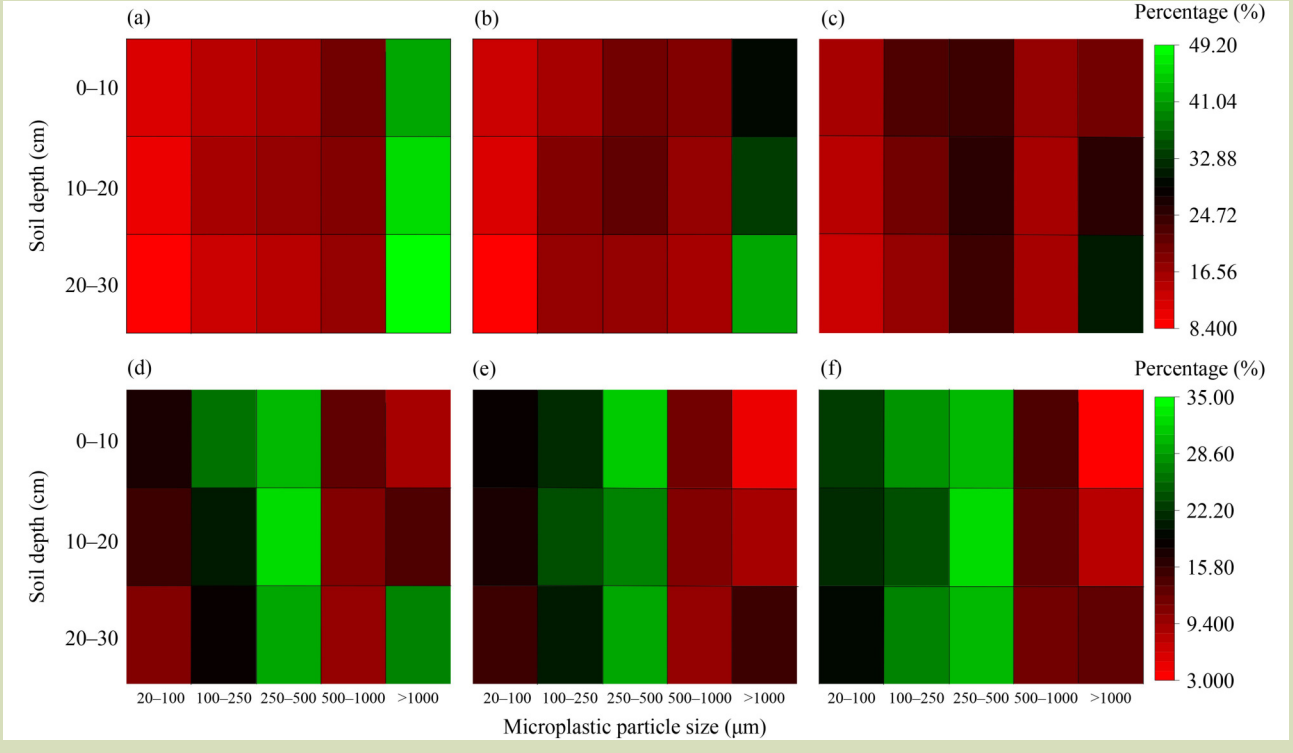


Fig. 6 Stratification of microplastic size fractions (indicated by the color scale) across soil depths under six mulching durations. (a–f) 5, 10, 15, 20, 25, and 30 years, respectively.

that climatic factors may accelerate film fragmentation and enhance the accumulation of smaller fragments. Additionally, agricultural practices, such as mechanical tillage, likely contributed to these trends. Research indicates that mechanical disturbance intensifies microplastic fragmentation, elevating the proportion of small-sized fragments[29]. Consistent with this, our results show that the accumulation of small-sized microplastics in surface soil (0–10 cm) was significantly higher than at a depth of 20–30 cm, reflecting combined effects of natural degradation, climate-driven processes, and mechanical agitation during farming activities.

Analysis of particle size distribution across soil depths revealed that small-sized microplastics predominantly accumulated in surface soil, whereas larger fragments were relatively more abundant in middle and deep layers[30]. Over time, small-sized microplastics gradually extended to deeper layers, though their accumulation rates remained lower than in surface soil[31]. This pattern highlights that the accumulation of small-sized microplastics under long-term mulching is driven not only by natural degradation and agricultural disturbance but also by soil water permeability. Collectively, this study elucidates the spatiotemporal dynamics of microplastic particle size distribution and confirms the progressive dominance of small-sized fragments over large-sized ones in long-term mulched soils.

3.5 Relationship between residual film mass and microplastic abundance under different mulching durations

The results revealed a significant linear correlation between residual plastic mulch film mass and microplastic abundance, with microplastic accumulation showing a consistent linear increase as residual film mass escalated (Fig. 7). Prolonged mulching facilitated the continuous accumulation of residual film in soils, establishing a persistent material basis for microplastic generation; an effect particularly pronounced in

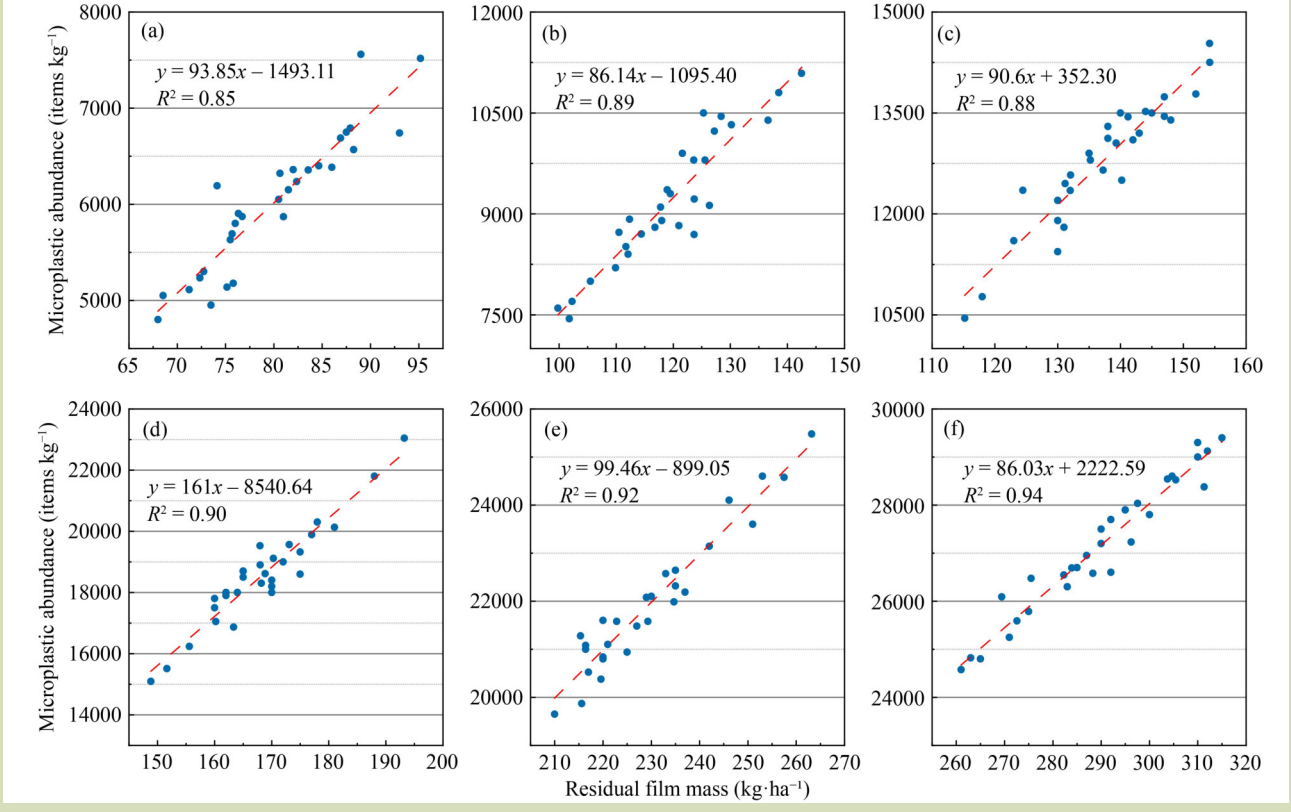


Fig. 7 Relationship between residual film mass and microplastic abundance for six mulching durations. (a–f) 5, 10, 15, 20, 25, and 30 years, respectively.

regions with high residual film mass (> 200 kg·ha^{-1}). Linear regression analysis shows that there is a highly significant linear relationship between residual plastic mulch films and microplastic abundance under different mulching durations ($P < 0.05$). The regression models for mulching durations of 5–30 years have R^2 values ranging from 0.85 to 0.94 (Fig. 7), with F-statistics ranging from 37.2 to 183 (corresponding degrees of freedom df = 28–58), indicating that the explanatory power of residual film mass on microplastic abundance is highly statistically significant. For every 1 kg·ha^{-1} increase in residual film mass, there was a corresponding average microplastic accumulation rate of 86–93 fragments kg^{-1}. Under high residual film mass conditions (Fig. 7(e,f)), this rate surged to 161 fragments kg^{-1}, indicating that residual film accumulation not only elevated total microplastic loads but also accelerated their generation kinetics.

A distinct threshold effect emerged, characterized by a sharp rise in microplastic accumulation rates followed by stabilization once residual film mass exceeded critical thresholds. Previous studies identified residual film accumulation as a primary precursor to soil microplastics, particularly in high-load regions (> 200 kg·ha^{-1}), where accelerated fragmentation and degradation of residual film directly drove microplastic proliferation. Our findings validated this mechanism and further uncovered a nonlinear enhancement in microplastic generation when residual film mass surpassed 160 kg·ha^{-1}, suggesting threshold-triggered acceleration in degradation dynamics. In addition, microplastic generation was critically modulated by soil environmental conditions. Soil temperature and moisture fluctuations, which are key regulators of film degradation kinetics, exerted significant control over microplastic formation[32]. Under arid climates, high-temperature, low-humidity soil environments exacerbated residual film degradation, leading to disproportionately rapid microplastic accumulation relative to film mass increases. This highlights the pivotal regulatory role of regional environmental conditions in the residual film-to-microplastic transformation process, with stronger environmental dependencies observed in climatically distinct zones.

Collectively, this study elucidates a linear mass-abundance relationship between residual films and microplastics, coupled with a threshold-governed acceleration in microplastic generation. Residual film accumulation was established as a dominant driver of soil microplastic pollution, with arid environments markedly amplifying this process. These insights advance mechanistic understanding of film degradation and microplastic generation across heterogeneous agroecosystems, providing a scientific foundation for optimizing region-specific plastic film management and recycling strategies.

4 Conclusions

This study systematically analyzed the dynamic relationship between residual film mass and microplastic abundance in desert cotton fields under varying mulching durations, revealing fundamental patterns of film degradation and microplastic accumulation. The results demonstrated that residual film mass increased significantly with prolonged mulching duration, having surface accumulation and gradual downward migration. The accumulation rate of residual film was relatively low during initial mulching stages but accelerated markedly under long-term mulching (> 20 years), with a more than threefold increase in the deeper soil (20–30 cm).

Microplastic abundance was predominantly enriched in surface soil, escalating progressively with mulching duration. The proportion of small-sized microplastics (20–250 μm) increased significantly over time, while large-sized microplastics (> 1000 μm) declined, reflecting a trend of progressive fragmentation and degradation of residual films into smaller fragments under long-term mulching. In addition, a robust linear relationship (R^2 = 0.85–0.94) was observed between residual film mass and microplastic abundance, indicating that residual film accumulation is a dominant driver of microplastic generation. In high residual film mass scenarios (> 200 kg·ha^{-1}), microplastic accumulation rates accelerated further, demonstrating a distinct threshold effect.

Overall, this study highlights the profound impacts of mulching duration on residual film degradation and microplastic generation, underscoring the urgency of enhancing film recovery and optimizing mulching practices in long-term agricultural management. However, the specific mechanisms of microplastic impacts on the soil ecosystem require further investigation. Future research should focus on microplastic-soil biota interaction mechanisms by establishing exposure experiments with different particle sizes and polymer types of microplastics, combined with metagenomics and metabolomics techniques, quantify the impact of microplastics on the expression of nitrogen cycle functional genes in soil

microbial communities. Also, it should address the cross-media migration flux by setting up contrasting observation areas around the 200 kg·ha^{-1} threshold, using stable isotope tracing technology combined with preferential flow tracer experiments, to construct a migration model of microplastics at the soil-groundwater interface.

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Compliance with ethics guidelines

Shufeng Zhang, Xiaoqing Lian, Xiao Yang, Yachuan Zhao, Can Hu, Haichun Zhang. and Xufeng Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Gao H H, Yan C R, Liu Q, Ding W L, Chen B Q, Li Z. Effects of plastic mulching and plastic residue on agricultural production: a meta-analysis. *Science of the Total Environment*, 2019, **651**(1): 484–492
2. He G, Wang Z H, Cao H B, Dai J, Li Q, Xue C. Year-round plastic film mulch to increase wheat yield and economic returns while reducing environmental risk in dryland of the Loess Plateau. *Field Crops Research*, 2018, **225**(1): 1–8
3. Dong H Z, Li W J, Tang W, Zhang D M. Early plastic mulching increases stand establishment and lint yield of cotton in saline fields. *Field Crops Research*, 2009, **111**(3): 269–275
4. Cui J, Bai R, Ding W, Liu Q, Liu Q, He W, Yan C, Li Z. Potential agricultural contamination and environmental risk of phthalate acid esters arrived from plastic film mulching. *Journal of Environmental Chemical Engineering*, 2024, **12**(1): 111785
5. Bai R H, Li Z, Liu Q, Liu Q, Cui J X, He W Q. The reciprocity principle in mulch film deterioration and microplastic generation. *Environmental Science. Processes & Impacts*, 2024, **26**(1): 8–15
6. Zhao S L, Zhang Z Q, Chen L, Cui Q L, Cui Y X, Song D X, Fang L C. Review on migration, transformation and ecological impacts of microplastics in soil. *Applied Soil Ecology*, 2022, **176**: 104486
7. Yang X Y, Zhang Z M, Guo X T. Impact of soil structure and texture on occurrence of microplastics in agricultural soils of karst areas. *Science of the Total Environment*, 2023, **902**: 166189
8. Luo H, Chang L, Ju T H, Li Y F. Factors influencing the vertical migration of microplastics up and down the soil profile. *ACS Omega*, 2024, **9**(51): 50064–50077
9. Horton A A, Walton A, Spurgeon D J, Lahive E, Svendsen C. Microplastics in freshwater and terrestrial environments: evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the Total Environment*, 2017, **586**: 127–141
10. Boots B, Russell C W, Green D S. Effects of microplastics in soil ecosystems: above and below ground. *Environmental Science & Technology*, 2019, **53**(19): 11496–11506
11. Yang X T, Fan W, Wu J G, Lv Y, Zhu W Y, Cai H G. Temporal and spatial distribution of residual film in soil profile under continuous film mulching. *Sustainability*, 2023, **15**(21): 15534
12. Li S, Ding F, Flury M, Wang Z, Xu L, Li S, Jones D L, Wang J. Macro- and microplastic accumulation in soil after 32 years of plastic film mulching. *Environmental Pollution*, 2022, **300**: 118945
13. Khalid N, Aqeel M, Noman A, Fatima Rizvi Z. Impact of plastic mulching as a major source of microplastics in agroecosystems. *Journal of Hazardous Materials*, 2023, **445**: 130455
14. Négyesi G, Szabó S, Buró B, Mohammed S, Lóki J, Rajkai K, Holb I J. Influence of soil moisture and crust formation on soil evaporation rate: a wind tunnel experiment in Hungary. *Agronomy*, 2021, **11**(5): 11050935
15. Gao J, Pan S Z, Li P F, Wang L W, Hou R J, Wu W M, Luo J, Hou D Y. Vertical migration of microplastics in porous media: multiple controlling factors under wet-dry cycling. *Journal of Hazardous Materials*, 2021, **419**(5): 126413
16. Cao J, Zhao X, Gao X, Zhang L, Hu Q, Siddique K H M. Extraction and identification methods of microplastics and nanoplastics in agricultural soil: a review. *Journal of*

Environmental Management, 2021, **294**: 112997

17. He H J, Wang Z H, Guo L, Zheng X R, Zhang J Z, Li W H, Fan B H. Distribution characteristics of residual film over a cotton field under long-term film mulching and drip irrigation in an oasis agroecosystem. *Soil & Tillage Research*, 2018, **180**: 194–203
18. National Standards of the People's Republic of China. GB/T25413–2010. Limit and test method for residual quantity of agricultural mulch film. Beijing: *National Public Service Platform for Standards Information*, 2011 (in Chinese)
19. Thompson R C, Olsen Y, Mitchell R P, Davis A, Rowland S J, John A W G, McGonigle D, Russell A E. Lost at sea: Where is all the plastic. *Science*, 2004, **304**(5672): 838
20. Zhao J J, Tang J R, Li C X, He H Q, Hang H. Distribution and influencing factors of plastic film residues in topsoil of farmland in Gansu Province. *Chinese Journal of Eco-Agriculture*, 2024, **32**(3): 456–467 (in Chinese)
21. Meng F R, Fan T L, Yang X M, Riksen M, Xu M, Geissen V. Effects of plastic mulching on the accumulation and distribution of macro and micro plastics in soils of two farming systems in Northwest China. *PeerJ*, 2020, **8**: e10375
22. Kang P D, Hu Q, Lu Y, Lei B K, He G Q, Wang C W. Study on residual plastic film in typical corn planting areas of Lijiang, Yunnan Province. *Hunan Agricultural Sciences*, 2013, **42**(3): 56–58 (in Chinese)
23. Yang L, Li W Y, Luo J, Zheng W, Zhang B Y, Wang Z, Yan T F. Effects of plastic film mulching and natural grass growing on soil nutrients, pH, water content and temperature in peach orchard. *Acta Agriculturae Zhejiangensis*, 2024, **36**(12): 2719-2726 (in Chinese)
24. Rowenczyk L, Jahandideh H, Lin N, Tufenkji N. Weathering of agricultural polyethylene films in cold climate regions: Which parameters influence fragmentation. *Environmental Science: Advances*, 2024, **3**(3): 470–479
25. Zhang Z M, Wu X L, Zhang J C, Huang X F. Distribution and migration characteristics of microplastics in farmland soils, surface water and sediments in Caohai Lake, southwestern plateau of China. *Journal of Cleaner Production*, 2022, **366**: 132912
26. Han N P, Zhao Q C, Wu C X. Threshold migration conditions of (micro) plastics under the action of overland flow. *Water Research*, 2023, **242**: 120253
27. Salehi Z, Hashemi S H, Flury M. Micro- and mesoplastics in farmlands with different irrigation water sources. *Water, Air, and Soil Pollution*, 2023, **234**(4): 267
28. Piehl S, Leibner A, Löder M G J, Dris R, Bogner C, Laforsch C. Identification and quantification of macro- and microplastics on an agricultural farmland. *Scientific Reports*, 2018, **8**(1): 17950
29. Liang R Q, Zhang L P, Jia R, Meng H W, Kan Z, Zhang B H, Li Y P. Study on friction characteristics between cotton stalk-residual film-external contact materials. *Industrial Crops and Products*, 2024, **209**: 118022
30. Zhang H, Yang X, Wang K, Cui J, Ritsema C J, Yan C, Liu X, Geissen V. Macro- and micro-plastic accumulation in soils under different intensive farming systems: a case study in Quzhou county, the North China Plain. *Environmental Pollution*, 2025, **364**: 125312
31. Jia W Q, Karapetrova A, Zhang M J, Xu L B, Li K, Huang M K, Wang J, Huang Y. Automated identification and quantification of invisible microplastics in agricultural soils. *Science of the Total Environment*, 2022, **844**: 156853
32. Zhang G X, Zhang S B, Xia Z Q, Bai J X, Wu M K, Lu H D. Integrated effects of polyethylene/biodegradable residual film on soil hydrothermal conditions and spring maize growth in rain-fed dryland. *Agricultural Water Management*, 2024, **305**: 109103