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# Temporal and Spatial Distribution of Residual Film in Soil Profile under Continuous Film Mulching

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**Abstract:** Plastic pollution in farmland soil has become a significant concern for scientists studying farmland ecosystems. However, the current research focus on the environmental impacts of plastics in soil overlooks crucial factors such as sources, distribution, and persistence. In this study, we examined the distribution of residual film after eight years of film mulching in mid-April 2018. We also assessed changes in spatial distribution from 2018 to 2020. Our findings reveal that eight years of film mulching significantly increased the quantity of agricultural mulch film residues in the soil. The size of residual film fragments varied from 0.25 $cm^2$ to 109 $cm^2$, and the average size, number, and quantity of residues were influenced by soil depth. There was a noticeable downward trend in the quantity of agricultural mulch film residues, decreasing annually by 0.525 $kg{\cdot}ha^{-1}$. In contrast, the number of residual films showed an average annual growth rate of $2.13 \times 10^5$ $p{\cdot}ha^{-1}$. Importantly, we observed a substantial accumulation of residual film fragments below the 10 cm soil layer over time. Fragments ranging from 1–5 $cm^2$ were the most abundant and gradually accumulated in deeper soil layers, enhancing mulching film recovery efficiency. This study provides valuable insights into the influence of mulch cycles on farmland soil profiles, identifying the key locations and size-to-shape ratios of residual films. These findings serve as a theoretical foundation for implementing effective measures to control mulch film pollution in agricultural practices.

**Keywords:** plastic pollution; farmland soil; residual film; distribution characteristics; mulch cycle

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## 1. Introduction

China is the country with the highest amount of mulch film in the world [1], particularly in the arid and semi-arid regions of north and northwest China, such as Inner Mongolia, Shandong, Xinjiang, and Gansu, where mulch film covers a vast area of farmland [2]. According to data from the Ministry of Agriculture of China, China's main covered provinces have an average residual quantity of agricultural mulch film of 60 $kg{\cdot}ha^{-1}$. Among these provinces, the cotton-growing area in Xinjiang Province is the most polluted, with an average residue of 259 $kg{\cdot}ha^{-1}$ and the highest residual quantity of agricultural mulch film at 381 $kg{\cdot}ha^{-1}$ [3]. Residual film distribution in soil depends on several factors, including natural factors, the coverage period, human interference, and the ease of degradation [4–7]. The depth below the soil surface influences the service life of mulch films and residue distribution [8–10]. Ramos et al. analyzed medium and large polyethylene plastic film residues resulting from mulching, indicating high concentrations of polyethylene film in 10% of soil surface samples, with an average size of 28 $cm^2$ [11].

Mulch film has been instrumental in the development of modern agriculture. Mulching with plastic film increases soil moisture retention, improves soil surface temperature, enhances fertilizer use efficiency, and helps control weed growth [12]. In China, using

mulching on farmland increases grain and cash crop yields by 35% and 60%, respectively [2]. However, studies have shown that residual film impedes water, nutrient, and heat transfer in the soil, thereby impairing the crop root absorption of water and nutrients and reducing soil quality and crop productivity [13,14]. In recent years, microplastics in farmland soil have become a cause for concern. Studies have revealed that the content of microplastics in farmland soil may be higher than that in the ocean [15–17]. The sources include in situ differentiation and composting of agricultural mulch film, which bring microplastics directly into the soil [18,19]. Long-term use of mulch film may cause excessive microplastic accumulation in the soil, resulting in negative impacts on soil organic carbon (C) and nitrogen (N) circulation and nutrient migration, affecting the bulk density, water holding capacity, and water-stable aggregates of soil [5,20–24].

Currently, although many methods have been developed to address the issue of agricultural field film pollution, such as (1) the use of alternatives or agricultural management practices that can better replace conventional plastic film, such as biodegradable film and organic coverings; (2) enhancing the efficiency of film recycling; and (3) government implementation of management measures for film pollution, most of these methods are not as effective as conventional plastic film in terms of performance. They also involve increased workload and economic input, making them difficult to be widely adopted, especially considering the low recycling rate of conventional film. Therefore, it is still worthwhile to explore solutions to the environmental problems caused by conventional plastic film in the future. This study focuses on the representative semi-arid region of the Inner Mongolia Autonomous Region as the investigation area, with the residual film formed by widely used polyethylene film as the research object. By exploring the spatial and temporal distribution characteristics of agricultural soil residual film under known film covering time and input conditions, accurate and reliable data support can be provided for the evaluation of soil health after film pollution. Additionally, this provides a theoretical basis for the formulation of subsequent measures to remove soil residual film.

## 2. Materials and Methods

### *2.1. Site Description*

The study was conducted on a family farm located in Tumuji Town, Xing'an League, Inner Mongolia, China (Figure 1). The farm is situated in the transition zone between the Greater Khingan Mountains and arid grassland, with the latter being the predominant landform. The soil texture of this area is sandy. The surface thickness of the soil is 25–20 cm. It covers an area of 5.97 $km^2$ and was conventionally farmed using arid grassland till the 1990s, without employing mulch film. In 2010, the farm switched to a film-covered drip irrigation method for approximately 5.23 $km^2$ of the farmland, where 0.59 $t \cdot ha^{-1}$ of mulch film was used annually. The farm employed strip tillage with a depth of 10–15 cm to plant only corn for eight years. However, in the spring of 2018, the farm discontinued the use of mulch film due to its adverse impact on farming and planting. The mulch film used was purchased from cooperative manufacturers, and there was no change in its specifications during continuous mulching. The mulch film polymer type is low-density polyethylene (LDPE) with a thickness of 0.008 mm.

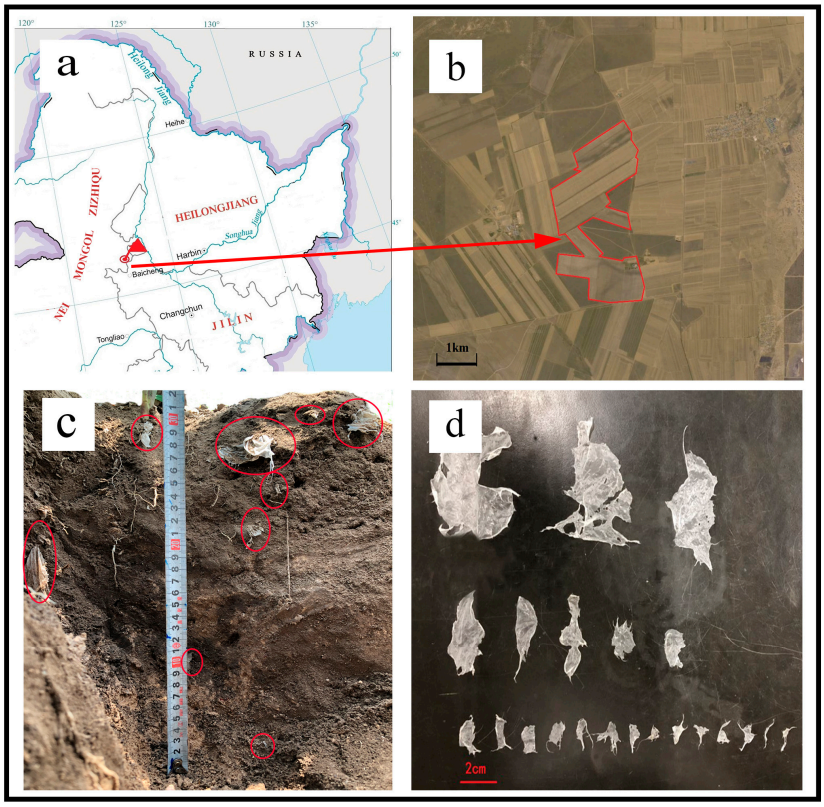



**Figure 1.** Location map and soil profile residual film in the study area: (**a**) farm location map; (**b**) satellite map of the residual mulch survey study area at the farm; (**c**) the presence of residual film in soil profiles; and (**d**) collected residual mulch of various sizes.

### *2.2. Experimental Design and Soil Sampling*

The experiment was conducted in mid-April 2018 to investigate the distribution characteristics of residual film in the soil area that had been continuously mulched for 8 years. To observe changes over time, we performed surveys from 2018 to 2020. The investigations were conducted after harvesting but before plowing. Our study area covered 61 ha. The survey depth was 0–40 cm, divided into four depth layers of 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. We collected residual film longer than 0.5 cm, cleaned it in the laboratory, air-dried it, and measured its weight and area. The residual film was classified into six gradient levels based on area: >20 $cm^2$, 20–15 $cm^2$, 15–10 $cm^2$, 10–5 $cm^2$, 5–1 $cm^2$, and <1 $cm^2$.

To conduct the survey, our sampling areas exceeded the standard of 100 m × 50 m, and we set up three rectangular sampling plots and divided the midline of each plot into four sections. We randomly selected two diagonal units from the four sections as the survey area. The 5-point sampling method was employed to select the measurement points. Starting from the diagonal points, we randomly chose four additional spots within a length of 1/4 to 1/8 of the diagonal length, totaling five sampling points. In total, we located 15 sampling points across the test area. The measuring points were standardized at 1 m × 1 m [8].

## 3. Results

### *3.1. Spatial Distribution of Residual Film in the Soil*

A total of 5349 residual membranes were collected in the study and their size was analyzed (Figure 2). The surface area of the collected residual film fragments ranged from 0.25 $cm^2$ to 109 $cm^2$. Among them, the residual film fragments with a surface area of 0.17–10 $cm^2$ showed the widest distribution range, visible in soil of 0–30 cm depth. Residual film fragments with a surface area of 10–20 $cm^2$ existed in the 0–20 cm soil layer, while those greater than 20 $cm^2$ occupied the 0–10 cm surface soil layer.

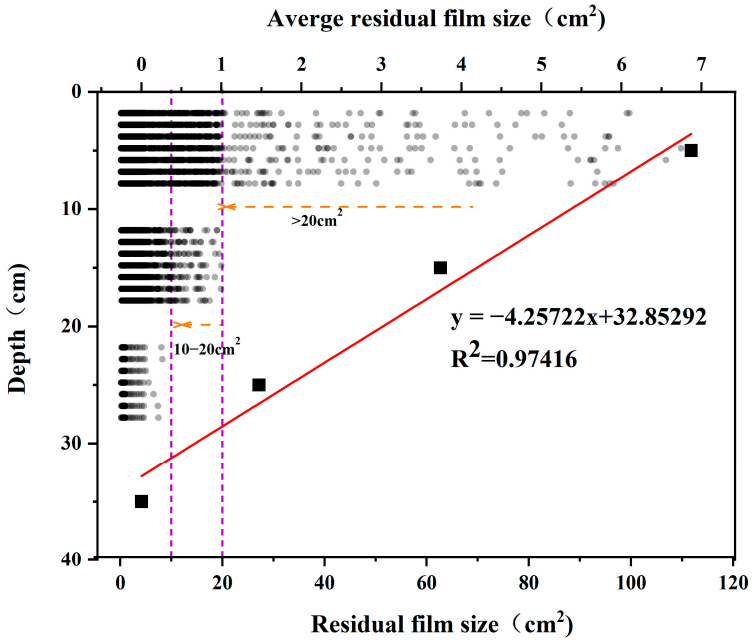



**Figure 2.** Characteristics of residual mulching film distribution in farmland soil after 8 consecutive years of mulching (note: The gray circle represents the residual film fragments. The square blocks are the average size of the residual film fragments in the soil layer at a depth of 10 cm).

The highest residual quantity of agricultural mulch film fragments was observed in the soil layer at a depth of 0–10 cm, with a value of 17.04 kg·ha$^{-1}$. As the soil depth increases, the residual quantity of agricultural mulch film drops sharply, with the residual quantity in the soil layer at a depth of 10–20 cm being 4.03 kg·ha$^{-1}$. This value is significantly lower than the residual quantity of agricultural mulch film at a depth of 0–10 cm. When the soil depth reaches 30 cm, the residual quantity of agricultural mulch film becomes negligible, with it measuring only 0.37 kg·ha$^{-1}$.

Furthermore, the study discovered that 61.89% of the residual film fragments were distributed in the soil layer at a depth of 0–10 cm, while 33.96% were distributed at a depth of 10–20 cm, and 4.43% were found at a depth of 20–30 cm. Short-term film mulching leads to a substantial accumulation of residual film in the topsoil. In the 0–10 cm soil layer, the number of residual film fragments can reach 2.176 ± 0.184 × 10$^6$ p·ha$^{-1}$ (pieces per hectare). Conversely, the number of residual film fragments in the 10–20 cm and 20–30 cm layers were significantly lower, measuring 1.194 ± 0.145 × 10$^6$ p·ha$^{-1}$ and 1.56 ± 0.181 × 10$^5$ p·ha$^{-1}$, respectively.

### *3.2. Temporal Distribution of Residual Film in the Soil*

The experiment, conducted over a period of 3 years, studied the changes in the residual quantity of different-sized film residues in the soil over time without adding new mulch film. Overall, the residual quantity of agricultural mulch film in the surface soil (0–40 cm) decreased from 21.44 kg·ha$^{-1}$ in 2018 to 20.39 kg·ha$^{-1}$ in 2020. The average annual decline rate of the residual quantity of agricultural mulch film was only 0.525 kg·ha$^{-1}$. The residual quantity of large-sized agricultural films (>20 cm$^2$) in the soil consistently decreased over time, from 7.96 kg·ha$^{-1}$ to 5.42 kg·ha$^{-1}$ (Figure 3). The residual quantity of films sized 10–15 cm$^2$ and 15–20 cm$^2$ displayed a consistent pattern of decrease followed by an increase. Among them, the residue of 10–15 cm$^2$ residual film showed no significant change, whereas the residue of 15–20 cm$^2$ film showed a significant decrease from 3.32 kg·ha$^{-1}$ in 2018 to 1.45 kg·ha$^{-1}$ in 2019. As for residual film fragments ranging from 5 to 10 cm$^2$ in size, their residual quantity increased initially and then decreased over time, showing a significant change ($p < 0.05$), and the residual quantity in 2020 increased by about 35% compared with 2018. It is worth noting the changes in the residual amount of smaller film residues over

time. As time goes on, there is a significant increasing trend ($p < 0.05$) in the small residual film fragments within the 1–5 $cm^2$ range, with an approximately 28% increase in residues in 2020 compared to 2018. However, the residue of the smallest film fragments (<1 $cm^2$) gradually decreases over time, and the change is not significant.

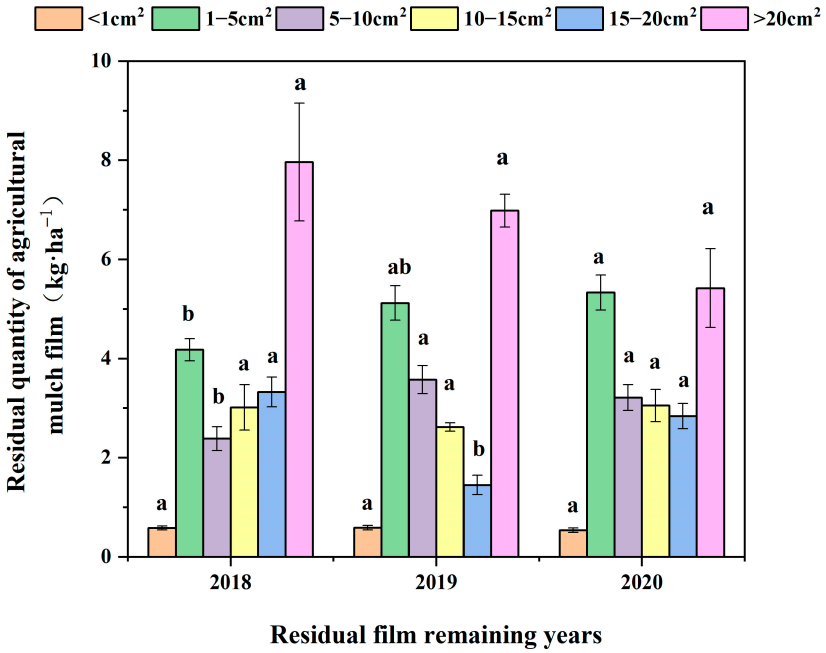



**Figure 3.** Distribution density of large and small residual film fragments in soil profiles over time (note: Different lowercase letters within the same column indicate significant differences at $p < 0.05$).

The number of residual film fragments exhibited a generally increasing trend from 2018 to 2020. Specifically, the average growth rate from 2018 to 2020 was $2.13 \times 10^5$ p·$ha^{-1}$. The research findings revealed that in the absence of new low-density polyethylene plastic mulch injection into the soil, the residual film of various sizes displayed a complex temporal pattern. However, the relative proportion of large residual film (>20 $cm^2$) (i.e., the occurrence frequency of residual film fragments relative to the total number of residual film fragments) increased annually (Figure 4). Its share increased from 3.7% in 2018 to 4.1% in 2020. The relative proportions of residual film fragments in the size ranges of 10–15 $cm^2$ and 15–20 $cm^2$ showed a trend of initially decreasing and then increasing. In 2020, they decreased by 4.50% and 1.01%, respectively. The pattern of variation for the 5–10 $cm^2$ range was the opposite, showing an initial increase followed by a decrease. In 2020, it increased by 2.29%. Among them, the relative proportion of residual film fragments in the 10–15 $cm^2$ size range exhibited a larger magnitude of change over time. The relative proportion of fragments in the 1–5 $cm^2$ size range constituted the highest percentage, accounting for 45–49% of the fragment count, and their number proportion continued to increase over time, eventually increasing by 4.23%. The relative proportion of residual film fragments in the size range of <1 $cm^2$ ranked second to the 1–5 $cm^2$ components, with a relative abundance of 25% to 29%. However, over time, the proportion showed a downward trend, eventually decreasing by 5.41%.

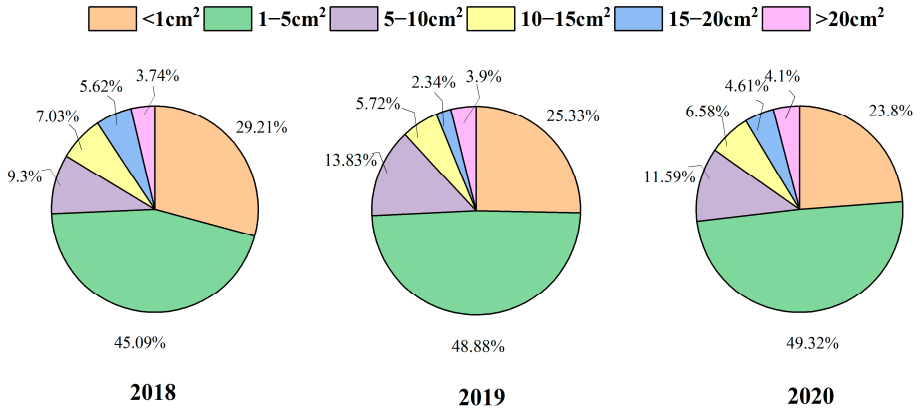



**Figure 4.** The change process of the number of residual film fragments over different years.

### *3.3. Temporal Variation in the Vertical Distribution of Residual Film in the Soil*

The spatial distribution characteristics of residual film fragments of different sizes are consistent, decreasing with increasing soil depth regardless of the variation over time (Figure 5). After continuous mulching for 8 years, the number of the two smaller residual film fragments (<1 $cm^2$, 1–5 $cm^2$) in the 0–10 cm soil layer reached 56.6 ± 4.73 × $10^4$ p·$ha^{-1}$ and 95.0 ± 6.46 × $10^4$ p·$ha^{-1}$, respectively. As the soil depth increased, the number of these two small fragments decreased exponentially. In the soil at a depth of 30 cm, the number decreased to 5.60 ± 0.75 × $10^4$ p·$ha^{-1}$ and 8.81 ± 0.73 × $10^4$ p·$ha^{-1}$, respectively. After the input of new plastic films into the soil was discontinued, the accumulation of these two smaller residual film fragments in the deep soil became more evident over time. By 2020, their number in the 30 cm soil layer accumulated to 8.4 ± 1.69 × $10^4$ p·$ha^{-1}$ and 14.2 ± 2.08 × $10^4$ p·$ha^{-1}$, respectively. This can be attributed to two reasons: the downward transport of small film fragments and the decomposition of larger fragments in deeper soil layers.

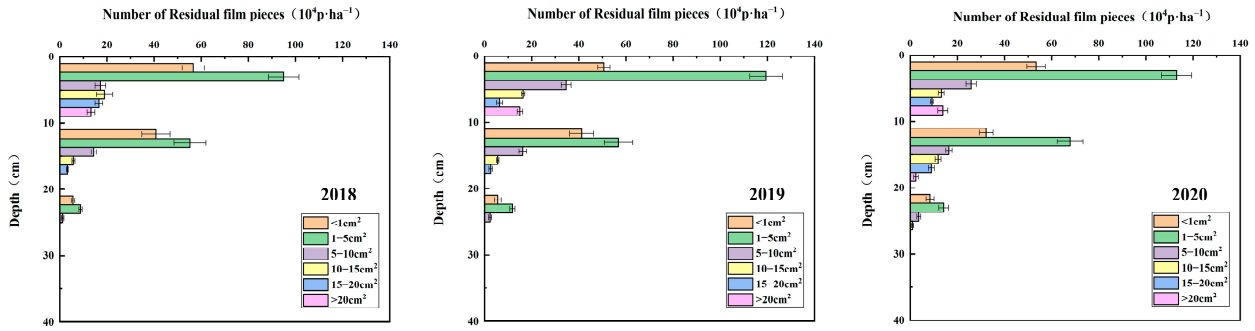



**Figure 5.** Distribution of the number of large and small residual film fragments in soil profiles over different years.

The number of medium-sized residual film fragments (5–10 $cm^2$ and 10–15 $cm^2$) in the 0–10 cm soil layer was 17.2 ± 2.27 × $10^4$ p·$ha^{-1}$ and 19.0 ± 3.41 × $10^4$ p·$ha^{-1}$, respectively. As the soil depth increased, the decrease in the number of these two groups of small fragments became more pronounced. In the soil at a depth of 30 cm, the number of residual film fragments of size 5–10 $cm^2$ decreased to 1.2 ± 0.58 × $10^4$ p·$ha^{-1}$, while fragments of 10–15 $cm^2$ in size did not appear in the 30 cm depth soil layer. The variation in these two medium-sized residual film fragments was more complex across different soil layers over time. However, over the entire time period, the quantity of 5–10 $cm^2$ fragments increased in the 0–30 cm soil layers, with the most stable increase observed in the 20–30 cm soil layer, from 1.2 ± 0.58 × $10^4$ p·$ha^{-1}$ in 2018 to 3.6 ± 0.81 × $10^4$ p·$ha^{-1}$ in 2020. Additionally, in 2019, there was a significant increase in the number of 5–10 $cm^2$ residual film fragments in the 0–10 cm soil layer, followed by a substantial decrease in 2020. However, in the 10–20 cm depth soil layer of the same year, there was no significant increase in the number

of fragments of the same size, indicating the occurrence of fragmentation and degradation of the 5–10 $cm^2$ fragments over a two-year period.

The quantity of 15–20 $cm^2$ residual film fragments showed a decreasing trend in the 0–10 cm soil layer and an increasing trend in the 10–20 cm soil layer over time. The increase in the 10–20 cm soil layer was more evident, from $5.8 \pm 0.66 \times 10^4$ p·$ha^{-1}$ in 2018 to $11.8 \pm 1.28 \times 10^4$ p·$ha^{-1}$ in 2020. It is noteworthy that in 2020, 15–20 $cm^2$ residual film fragments were found in the 20–30 cm soil layer. The decrease and increase in the quantity of medium-sized residual film fragments can be attributed to their downward migration and the replenishment of larger fragments. The accumulation of these fragments in the 10–20 cm soil layer over time indicates a certain degree of downward migration.

The larger groups of residual film fragments, 15–20 $cm^2$ and >20 $cm^2$, were mainly found in the 0–10 cm soil layer, with the numbers reaching $17.2 \pm 2.27 \times 10^4$ p·$ha^{-1}$ and $19.0 \pm 3.41 \times 10^4$ p·$ha^{-1}$, respectively. The quantity of 15–20 $cm^2$ residual film fragments in the 10–20 cm soil layer increased from $3.2 \pm 0.37 \times 10^4$ p·$ha^{-1}$ in 2018 to $9.0 \pm 1.22 \times 10^4$ p·$ha^{-1}$ in 2020. The quantity of >20 $cm^2$ fragments in the 0–10 cm soil layer showed a trend of initially increasing and then decreasing over time, with a small magnitude of change. Furthermore, it is worth noting that in 2020, residual film fragments (>20 $cm^2$) were found in the 10–20 cm soil layer, indicating a direct correlation with human tillage activities.

## 4. Discussion

According to the data from the 2010 National Pollution Source Census Bulletin, the average residue quantity of agricultural mulch film in China is 59.79 kg·$ha^{-1}$. In 2015, Bai et al. found that the average residual quantity of agricultural mulch film in the Inner Mongolia Autonomous Region was 84 kg·$ha^{-1}$ [25]. The Chinese national standard for limiting the residue quantity of agricultural mulch film is 75 kg·$ha^{-1}$ [10]. In 2018, our study found that the average residual quantity of agricultural mulch film in the experimental site was 21.44 kg·$ha^{-1}$, which is lower than the national and regional averages, as well as the standard limit. This could be attributed to the relatively short duration of continuous film covering in the experimental site, which was only 8 years. Investigation and research conducted by Jinzhou C in the southern plain, where the average film covering period was also 8 years, revealed a similar residue quantity of agricultural mulch film at 28 kg·$ha^{-1}$, validating our research findings [26]. Additionally, the investigation results of many studies show that a large proportion of the residue is distributed in the soil at depths of 0–10 cm, ranging from 70% to 90%, with the remaining residue distributed in the soil at depths of 10–30 cm [9,27], which is consistent with our research findings. It is worth noting that the residue levels in cotton fields investigated in Xinjiang are higher than in other regions. For example, the residue in the 20–30 cm soil layer in cotton fields in Shihhotze, Xinjiang, has reached 20.00 kg·$ha^{-1}$ [28], which is much higher than the residue quantity of agricultural mulch film at the same depth in our research area. This may be due to the longer duration of film covering in cotton fields in Shihhotze, Xinjiang, with an average covering history of over 20 years. Moreover, most of the research areas in Xinjiang adopt large-scale machinery operations, which can cause a deeper tillage depth during plowing, leading to easier direct infiltration of film fragments from shallow soil into deep soil. In contrast, the film covering history in our research area is shorter and the tillage depth is shallow (35–40 cm), with a plowing depth of only 10–15 cm, which can be achieved by ordinary small machinery for most agricultural operations.

The experiment tracked and investigated the temporal and spatial distribution characteristics of residual film fragments remaining in the soil after no new mulch film was input. The experimental results showed that over a period of two years, there was no significant change ($p < 0.05$) in the residual quantity and number of residual films in the soil. However, there were differences in the distribution residual quantity and number of residual films in the soil at depths of 10–30 cm in the second year. This indicates that the degradation of residual film at the molecular level or its decomposition into smaller fragments (such as microplastic fragments) is extremely slow over a period of two years.

This can be attributed to the fact that ordinary polyethylene materials have a degradation cycle of nearly a hundred years [29]. However, the splitting and vertical migration of film residues in the soil were more pronounced, especially the changes in the distribution residual quantity and number of medium and large residual film fragments, which were highly related to human tillage activities. This is because tillage and other cultivation activities can cause the inversion of surface soil and subsoil [30].

The research divides the size of the residue film into six ranges and refines the classification of residue film size. The main purpose is to explore and identify the decomposition degree of residue film in the soil under certain mulch duration conditions, as well as the distribution characteristics of the residue film after decomposition. Currently, most studies believe that in soil with abundant residue film, the dominant residue film occupies a size range of 0–25 $cm^2$ or close to 4 $cm^2$ [31–33]. The research results of Xi H showed that large- and medium-sized film residues predominated in the plow layer, while small-sized film residues were less common. The former study is more consistent with our experimental results, while the latter is inconsistent, which may be due to the length of the covering period, the depth of cultivation, the quality of the film, and the duration of coverage, all of which can affect the quantity and distribution of residue film fragments in the soil [10,27,34,35]. Further research is needed to investigate the distribution characteristics of residue film fragments under different agricultural management practices in different regions. In addition, contrary to our common understanding, the size range of film residues that predominate in terms of quantity in the soil is not <1 $cm^2$, but rather film fragments with a size range of 1–5 $cm^2$. In addition, contrary to our common understanding, our experimental results showed that film residues with a size range of <1 $cm^2$ did not dominate in terms of quantity. Instead, film residues with a size range of 1–5 $cm^2$ were predominant. During the experimental period (2018–2020), their quantity was higher than that of other sizes of film residues in both shallow and deep soil layers. This may be related to the material of the residue film itself, as its material determines the way it splits and degrades. The enrichment of film residues in surface soil (0–40 cm) may have a significant impact on soil properties and crop production [13]. Therefore, more measures must be taken to improve the recycling efficiency of mulch film covering and ensure the sustainable development of mulch film agriculture.

In current agricultural production, facing residual film pollution, people have explored two seemingly feasible methods: developing biodegradable films and using organic coverings as alternatives to plastic film. However, the results show that biodegradable films are more expensive than ordinary plastic films in terms of cost and sometimes have inferior performance [36]. Although organic coverings are environmentally friendly, they increase labor costs in practical production [37]. Therefore, the most common solution at present is still to strengthen the recycling of plastic film. However, the problem that arises from this approach is the low recovery rate of residual film, which is generally believed to be caused by the thinness of the film that hampers the recycling process [38]. In this study, a systematic analysis was conducted on the spatio-temporal distribution characteristics of residual film of different sizes in the soil. The focus of addressing residual film pollution was shifted from improving recycling methods to understanding the distribution patterns of pollutants themselves. It is hoped that the insights gained from adjusting the recycling process to enhance the recovery rate of plastic film can ultimately achieve effective control of residual film pollution. Additionally, a more important objective is to deepen the understanding of residual film pollution, help explain other hazards caused by residual film, and lay a theoretical foundation for further implementing sustainable agricultural development.

## 5. Conclusions

Using mulch film for 8 consecutive years results in increased accumulation of residual film fragments in farmland soil. The distribution depth of these fragments can reach up to 30 cm, with sizes ranging from 0.25 $cm^2$ to 109 $cm^2$. The average size, number, and residual quantity of these fragments decrease consistently with increasing soil depth. When mulch film usage is discontinued, the residual amount of film in the soil (0–40 cm) decreases at

an annual rate of only 0.525 kg·ha$^{-1}$, primarily driven by a decrease in larger fragments accompanied by smaller ones. This highlights the degradation process of residual film in the soil. The number of residual film fragments increases during this process, albeit not significantly, with an average growth rate of 2.13 × 10$^5$ p·ha$^{-1}$. Analyzing the vertical distribution characteristics over time, we observed a gradual decrease in the density of residual film in the 0–10 cm soil layer, though not significant. However, there is an increasing trend in the residual quantity of agricultural mulch film in the 10–20 cm and 20–30 cm soil layers. Over time, a significant accumulation of film fragments occurs in the 10–30 cm soil layer. Furthermore, in the 0–10 cm soil layer, the residual film is mainly distributed across all size ranges, with no significant change in quantitative advantages over the 2-year trial period. Among these, small residual membranes (<1 cm$^2$ and 1–5 cm$^2$) consistently dominate the study's time and space, with more pronounced accumulation in deeper soil layers (>20 cm depth).

**Author Contributions:** Conceptualization, validation, methodology, investigation, and writing—original draft preparation, X.Y. and W.F.; analysis of the data, Y.L.; experiments, W.Z.; resources, writing—review and editing, supervision, project administration, and funding acquisition, J.W. and H.C. All authors have read and agreed to the published version of the manuscript.

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## References

1. Gao, H.; Yan, C.; Liu, Q.; Ding, W.; Chen, B.; Li, Z. Effects of plastic mulching and plastic residue on agricultural production: A meta-analysis. *Sci. Total Environ.* **2019**, *651*, 484–492. [CrossRef] [PubMed]
2. Liu, E.K.; He, W.Q.; Yan, C.R. White revolution' to 'white pollution'—Agricultural plastic film mulch in China. *Environ. Res. Lett.* **2014**, *9*, 091001. [CrossRef]
3. Wang, X.F.; Shen, M.X. *Farmland Plastic Film-Hope and Dawn of Chinese Agricultural Development*; Countryside Science and Technology Department of Science of China: Beijing, China, 1998.
4. Jia, H.; Zhang, M.; Weng, Y.; Zhao, Y.; Li, C.; Kanwal, A. Degradation of poly (butylene adipate-co-terephthalate) by Stenotrophomonas sp. YCJ1 isolated from farmland soil. *J. Environ. Sci.* **2021**, *103*, 50–58. [CrossRef]
5. Rillig, M.C.; Ziersch, L.; Hempel, S. Microplastic transport in soil by earthworms. *Sci. Rep.* **2017**, *7*, 1362. [CrossRef] [PubMed]
6. Zhang, X.T.; Chen, Y.X.; Li, X.Y.; Zhang, Y.L.; Gao, W.; Jiang, J.; Mo, A.Y.; He, D.F. Size/shape-dependent migration of microplastics in agricultural soil under simulative and natural rainfall. *Sci. Total Environ.* **2022**, *815*, 152507. [CrossRef]
7. Picuno, P. Innovative material and improved technical design for a sustainable exploitation of agricultural plastic film. *Polym.-Plast. Technol. Eng.* **2014**, *53*, 1000–1011. [CrossRef]
8. He, H.; Wang, Z.; Guo, L.; Zheng, X.; Zhang, J.; Li, W.; Fan, B. Distribution characteristics of residual film over a cotton field under long-term film mulching and drip irrigation in an oasis agroecosystem. *Soil Tillage Res.* **2018**, *180*, 194–203. [CrossRef]
9. Ma, H.; Mei, X.R.; Yan, C.R.; He, W.Q.; Li, K. The residue of mulching plastic film of cotton field in North China. *J. Agro-Environ. Sci.* **2008**, *27*, 570–573.
10. Zhang, D.; Liu, H.B.; Hu, W.L.; Qin, X.H.; Yan, C.R.; Wang, H.Y. The status and distribution characteristics of residual mulching film in Xinjiang, China. *J. Integr. Agric.* **2016**, *15*, 2639–2646. [CrossRef]
11. Ramos, L.; Berenstein, G.; Hughes, E.A.; Zalts, A.; Montserrat, J.M. Polyethylene film incorporation into the horticultural soil of small periurban production units in Argentina. *Sci. Total Environ.* **2015**, *523*, 74–81. [CrossRef]
12. Menossi, M.; Cisneros, M.; Alvarez, V.A.; Casalongu´e, C. Current and emerging biodegradable mulch films based on polysaccharide bio-composites. A review. *Agron. Sustain. Dev.* **2021**, *41*, 53. [CrossRef]
13. Jiang, X.J.; Liu, W.; Wang, E.; Zhou, T.; Xin, P. Residual plastic mulch fragments effects on soil physical properties and water flow behmvior in the Minqin Oasis, northwestern China. *Soil Tillage Res.* **2017**, *166*, 100–107. [CrossRef]
14. Yang, N.; Sun, Z.X.; Feng, L.S.; Zheng, M.Z.; Chi, D.C.; Meng, W.Z.; Hou, Z.Y.; Bai, W.; Li, K.Y. Plastic film mulching for water-efficient agricultural applications and degradable films materials development research. *Mater. Manuf. Process.* **2015**, *30*, 143–154. [CrossRef]

15. Van Sebille, E.; Wilcox, C.; Lebreton, L.; Maximenko, N.; Hmrdesty, B.D.; Van Franeker, J.A.; Eriksen, M.; Siegel, D.; Galgani, F.; Law, K.L. A global inventory of small floating plastic debris. *Environ. Res. Lett.* **2015**, *10*, 124006. [CrossRef]
16. Nizzetto, L.; Futter, M.; Langaas, S. Are agricultural soils dumps for microplastics of urban origin? *Environ. Sci. Technol.* **2016**, *50*, 10777–10779. [CrossRef]
17. Nizzetto, L.; Langaas, S.; Futter, M. Pollution: Do microplastics spill on to farm soils? *Nature* **2016**, *537*, 488. [CrossRef] [PubMed]
18. Blasing, M.; Amelung, W. Plastics in soil: Analytical methods and possible sources. *Sci. Total Environ.* **2018**, *612*, 422–435. [CrossRef] [PubMed]
19. Hurley, R.R.; Nizzetto, L. Fate and occurrence of micro (nano) plastics in soils: Knowledge gaps and possible risks. *Curr. Opin. Environ. Sci. Health* **2018**, *1*, 6–11. [CrossRef]
20. De Souza Machado, A.A.; Lau, C.W.; Till, J.; Kloas, W.; Lehmann, A.; Becker, R.; Rillig, M.C. Impacts of microplastics on the soil biophysical environment. *Environ. Sci. Technol.* **2018**, *52*, 9656–9665. [CrossRef]
21. Zhang, G.S.; Zhang, F.X.; Li, X.T. Effects of polyester microfibers on soil physical properties: Perception from a field and a pot experiment. *Sci. Total Environ.* **2019**, *670*, 1–7. [CrossRef]
22. Cao, D.; Wang, X.; Luo, X.; Liu, G.; Zheng, H. Effects of polystyrene microplastics on the fitness of earthworms in an agricultural soil. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2017; Volume 61, p. 012148.
23. Liu, H.; Yang, X.; Liu, G.; Liang, C.; Xue, S.; Chen, H.; Ritsema, C.J.; Geissen, V. Response of soil dissolved organic matter to microplastic addition in Chinese loess soil. *Chemosphere* **2017**, *185*, 907–917. [CrossRef] [PubMed]
24. Rillig, M.C. Microplastic disguising as soil carbon storage. *Environ. Sci. Technol.* **2018**, *52*, 6079–6080. [CrossRef] [PubMed]
25. Bai, Y.; Li, X.; Zhang, S.; Bao, L.H.; Liu, L.P.; Lin, L.L.; Zhen, H.C. Study on the current situation of plastic film residue pollution and the countermeasures for the recovery and utilization of residual film in Inner Mongolia. *Soil Fertil. Sci. China* **2015**, *6*, 139–145.
26. Cai, J.; Zhang, F.; Fan, X. The status quo of film application and residue in the southern plains of China. *J. Agric. Resour. Environ.* **2013**, *30*, 23.
27. Hao, X.; Zhang, J.; Zang, X.W.; Yi, M.I.; Meng Wang, M.; Dong, W.Z. Analysis of the mulching film utilization and its residue pollution in peanut fields of henan province. *Soils Crops* **2019**, *8*, 43–49.
28. He, W.Q.; Yan, C.R.; Liu, S.; Chang, R.; Wang, X.; Cao, S.; Liu, Q. The use of plastic mulch film in typical cotton planting regions and the associated environmental pollution. *J. Agro-Environ. Sci.* **2009**, *28*, 1618–1622.
29. Möller, K.; Gevert, T.; Holmström, A. Arne holmstrom examination of a low-density polyethylene (LDPE) film after 15 years of service as an air and water vapour barrier. *Polym. Degrad. Stab.* **2001**, *73*, 69–74. [CrossRef]
30. Rillig, M.C.; Ingraffia, R.; de Souza Machmdo, A.A. Microplastic incorporation into soil in agroecosystems. *Front. Plant Sci.* **2017**, *8*, 1805. [CrossRef]
31. Liu, J.G.; Li, Y.B.; Zhang, W.; Sun, Y.Y. The distributing of the residue film and influence on cotton growth under continuous cropping in oasis of Xinjiang. *J. Agro-Environ. Sci.* **2010**, *29*, 246–250.
32. Yang, L.L.; Heng, T.; He, X.L.; Yang, G.; Zhao, L.; Li, Y.H.; Xu, Y. Spatial-temporal distribution and accumulation characteristics of residual film in cotton fields in arid oasis area and the effects on soil salt transport and crop growth. *Soil Tillage Res.* **2023**, *231*, 105737. [CrossRef]
33. Du, X.M.; Xu, G.; Xu, D.P.; Zhao, T.K.; Li, F.S. Mulch film residue contamination in typical areas of north China and countermeasures. *Trans. Chin. Soc. Agric. Eng.* **2005**, *21*, 225–227.
34. Manzano, V.; García, N.L.; Ramírez, C.R.; D'Accorso, N.; Goyanes, S. Mulch plastic systems: Recent advances and applications. *Polym. Agri-Food Appl.* **2019**, 265–290. [CrossRef]
35. Dong, H.G.; Liu, T.; Han, Z.Q.; Sun, Q.M.; Li, R. Determining time limits of continuous film mulching and examining residual effects on cotton yield and soil properties. *J. Environ. Biol.* **2015**, *36*, 677–684.
36. Wang, Y.; He, K.; Zhang, J.; Chang, H. Environmental knowledge, risk attitude, and households' willingness to accept compensation for the application of degradable agricultural mulch film: Evidence from rural China. *Sci. Total Environ.* **2020**, *744*, 140616. [CrossRef] [PubMed]
37. Zhao, Z.Y.; Wang, P.Y.; Xiong, X.B.; Zhou, R.; Zhu, Y.; Wang, Y.B.; Wang, N.; Wesly, K.; Xue, W.; Cao, J.; et al. Can shallow-incorporated organic mulching replace plastic film mulching for irrigated maize production systems in arid environments? *Field Crops Res.* **2023**, *297*, 108931. [CrossRef]
38. Zhang, Z.; Li, J.; Wang, X.; Zhao, Y.; Xue, S.; Su, Z.; Liang, J. Design and test of 1SMB-3600A type fragmented mulch film collector for sowing layer soil. *Soil Tillage Res.* **2023**, *225*, 105555. [CrossRef]


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