Field-Based Experimental Evaluation of Mulch Film Recyclability via Physical Property Dynamics in Tobacco Cultivation

W. Gao[1], X. Yin[1,2], Sh. Wang[3], Z. Tu[1,2], Sh. Ming[1,2], K. Cai[1], H. Cai[4], Ch. Xu[5*]

1- Guizhou Academy of Tobacco Science, Guiyang, Guizhou, 550081, China
2- College of Tobacco Science, Guizhou University, Guiyang, Guizhou, 550025, China
3- Guizhou Academy of Forestry, Guiyang, Guizhou, 550001, China
4- Bijie Tobacco Company of Guizhou Province, Bijie, Guizhou, 551700, China
5- Fuling Branch of Chongqing Tobacco Company, China National Tobacco Corporation, Fuling, Chongqing 408107, China
(*- Corresponding Author Email: cqxuchen@139.com)
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Abstract

Residual plastic mulch film pollution in agricultural fields threatens soil health and sustainable agriculture due to structural degradation and inefficient recovery. To address this, this study investigated the effects of mulch film thickness (0.006-0.014 mm), mulching duration (0-120 days), and two contrasting ecological regions in the Guizhou Province of China: Longgang Town (Kaiyang County) and Linquan Town (Qianxi County), on physical properties and recyclability in tobacco cultivation. Analyses of mechanical, optical, and recycling efficiency revealed that tensile, tear, and puncture strengths increase proportionally with thickness across identical durations, while elongation rates initially increase and then decline. Prolonged mulching reduces mechanical performance at fixed thicknesses, with longitudinal tensile and tear strengths consistently exceeding transverse values. Optical properties vary significantly: unused films exhibit peak light transmittance and haze, while 0.008 mm films achieve maximum transmittance, and thicker films (0.010-0.014 mm) show higher haze. Recycling efficiency correlates positively with thickness and inversely with mulching duration. After 120 days, recycling efficiency strongly correlates with longitudinal and transverse tear loads. Regional variations significantly affect the mechanical properties of 0.010 mm films, suggesting that 0.010 mm films may adapt better to diverse environments. Thicker films show higher recyclability after 120 days of mulching due to retained structural integrity. These findings systematically link physical degradation patterns to recyclability under field conditions, offering actionable insights for optimizing mulch film use, designing durable products, and improving recovery machinery. The study supports sustainable agricultural practices by balancing film performance, environmental adaptability, and end-of-life recovery efficiency.

Keywords: Mechanical properties, Mulch film recyclability, Optical properties, Recycling efficiency, Tobacco cultivation conditions

Introduction

Mulch cover planting technology, originating from Japan, has been widely used in China since the 1970s (Zhao *et al.*, 2012). Mulching improves soil temperature and moisture, enhances fertilizer efficiency, suppresses weeds, and increases crop yield (Gao *et al.*, 2019; Lin *et al.*, 2024; Steinmetz *et al.*, 2016; Zhao *et al.*, 2012). It is widely applied in various crops such as vegetables, fruits, and medicinal herbs. It ranks as the fourth most important agricultural input after seeds, pesticides, and fertilizers (Kasirajan & Ngouajio, 2012; D. Sun *et al.*, 2020; H. Zhang, Miles, Gerdeman, LaHue, & DeVetter, 2021). As indicated in the “China Rural Statistical Yearbook”, the area of China's agricultural plastic mulch film has increased from 4.91 million hectares in 1991 to 17.47 million hectares in 2022, representing the largest area in the world (Xu *et al.*, 2024). Tobacco is a significant commercial crop in China, with currently producing approximately 1 million hectares of flue-cured tobacco annually. Of this total, the proportion of mulch film planting remains relatively stable at approximately 90% (Yan, Kong, Wang, Wang, & Li, 2021). Polyethylene is the most widely used mulch film in China's tobacco farming, noted for its consistent physicochemical properties and durability against natural degradation. Although plastic mulch film provides significant agronomic benefits, its non-degradable nature combined with current recycling limitations has created an urgent environmental crisis in fields. In China, several factors contribute to the low efficiency of mulch films recycling. These include the thinness of mulch films, the presence of soil, stalks, and other residues in wasted mulch films, which complicate mechanical recycling, as well as farmers' limited environmental awareness (Liang *et al.*, 2024; Yu, Zhao, & Ma, 2021). Over time, the residue mulch film accumulates in the soil, impeding the movement of nutrients, water, and gases essential for tobacco growth (Shen, Wang, & Zhang, 2012; Wu *et al.*, 2022). Additionally, the residue hinders the development of the root system and the accumulation of biomass in the plant (Gao *et al.*, 2020), posing challenges to the agricultural environment and ecological security. Furthermore, it threatens the sustainable development of tobacco.

Currently, the primary methods for managing wasted mulch films residues in China include on-site landfilling, incineration, and recycling. Farmers typically either plow the residual film directly into the soil or dispose of it alongside straw in the fields. However, due to the absence of effective recycling and treatment options, these residual films tend to accumulate in the fields over extended periods or are burned on-site, leading to significant environmental pollution. Recycled mulch films can be repurposed as valuable resources; for instance, they can be reprocessed into recycled plastic particles, which can then be manufactured into products such as seedling trays and manhole covers. Alternatively, these films can be incinerated to generate electricity, contributing to a reduction in environmental pollution. It can be reasonably deduced that the most cost-effective and environmentally friendly solution to address pollution caused by wasted tobacco mulch films is recycling (Yan *et al.*, 2017).

The physical properties of mulch films significantly influence the recycling process (Gao *et al.*, 2020). These properties can vary due to factors such as mulching duration, film thickness, and the soil and climate conditions of different planting regions (Tang, Zhao, Wang, & Wang, 2020). A stronger tensile force in mulch films significantly enhances the efficiency of the recovery process during machinery operation. Similarly, variations in climate, temperature, sunlight duration, and other factors across different geographical regions can affect the tensile force of mulch films, thereby influencing the overall recycling efficiency (Zhang, Liu, Zhang, Chen, & Xu, 2024). The current research on mulch film technology in tobacco cultivation is primarily concerned with the impact of mulching on soil physicochemical properties in regions (Wang *et al.*, 2024), as well as the effect on the quality of the tobacco leaf (Tang *et al.*, 2024). Nevertheless, there is not much literature focusing on the dynamic monitoring and analysis of physical properties and their recycling efficiency. Monitoring the spatiotemporal dynamics of mulch film physical properties informs targeted recycling operations, addresses plastic pollution at its source, and advances sustainable agricultural systems.

To bridge the critical gap in spatiotemporal monitoring of physical degradation-recyclability linkages, this study: (1) Quantifies dynamic effects of mulching duration (0-120 d) and film thickness (0.006-0.014 mm) on mechanical/optical properties and recycling efficiency; (2) Evaluates regional impacts on performance decay thresholds to establish environment-adaptive recovery protocols. Findings provide a theoretical foundation for data-driven agricultural machinery design and mulch film specification optimization, ultimately reducing residual pollution and promoting soil health in tobacco ecosystems.

Materials and Methods

Overview of the experimental area

The Longgang experimental site is located in Longgang Town, Kaiyang County, Guiyang City, Guizhou Province, China. Its geographical coordinates are 26°52′49″ (N) longitude and 107°6′32″ (E) latitude. The site is situated at an elevation of 1537.3 meters, with an average annual temperature of 14°C. The highest recorded temperature is 37.3°C, while the lowest is -8.0°C. The frost-free period exceeds 300 d, and the average annual precipitation is 1139 mm. The Linquan experimental site is located in Linquan Town, Qianxi County, Bijie City, Guizhou Province, China, with geographical coordinates of 27°2′30″ (N) longitude and 105°51′43″ (E) latitude. The elevation here is 1200 meters, and the average annual temperature is 13.8°C. The highest recorded temperature is 32.0°C, while the lowest is 2.0°C. The mean annual precipitation is 1030 mm, with a frost-free period of 264 d. The selected plots featured flat terrain (< 2° slope gradient) and visually homogeneous surface soil properties with no apparent fertility variations observed during site inspection.

Experimental materials and design

In accordance with the specifications set forth in the agricultural film standard GB 13735—2017 "Polyethylene Blown Mulch Film for Agricultural uses" and the requirements for tobacco cultivation, four types of polyethylene mulch films with thicknesses of 0.006, 0.008, 0.010, and 0.014 mm, were selected in a Longgang plot experiment. A randomized block design was implemented to control field heterogeneity, with blocks partitioned based on topography. Each treatment was replicated three times, with replicates distributed across homogeneous plots, resulting in a total of 12 experimental plots. Each area was 50 m^2. Mulching is undertaken when the soil moisture content reaches 60% of soil field capacity. A well cellar method is employed for the tobacco planting, with a plant spacing of 0.5 m. When the growing point of the tobacco plant reaches 2-3 cm above the wellhead, the well is filled with fine soil, and the mulch film is securely compacted around the wellhead. Samples with 50 cm × 50 cm of the mulch film are collected from each plot at 0, 30, 60, 90, and 120 d after mulching for testing the mechanical and optical properties. Furthermore, samples are collected at 45 d and 120 d after mulching to determine the recovery rates of each type of mulch film.

Given that 0.010 mm is the predominant mulch film thickness in China, only this thickness was tested at Linquan. Using an identical randomized block design (3 replicates, 50 m^2/plot) and mulching/planting protocols as Longgang. Determined by tobacco phenology, samples were collected at 30 d and 120 d for mechanical property assessment to evaluate cross-regional environmental effects.

Measurement parameters and methods

Mechanical properties

In accordance with the requirements of GB/T 1040.3—2006, "Determination of Tensile Properties of Plastics - Part 3: Test Conditions for Films and Sheets" and GB/T 10004—2008, "Plastic Composite Films and Bags for Packaging - Dry and Extrusion Laminating", the mulch films were subjected to tensile, right-angle tear, and puncture tests using a CMT 6103 electronic universal testing machine. Each sample was tested on five repetitions. Furthermore, the relative error of the mechanical properties of the mulch films was calculated using Equation (1), thus facilitating a comparison of the variations in mechanical properties between the two regions.

$$\text{Relative error} = \frac{A-B}{B} \times 100\% \quad (1)$$

where, A and B represent the mechanical properties of the mulch film from Linquan and Longgang, respectively. The relative error (RE) shows how much values from Linquan differ from Longgang. For example, a positive RE (%) indicates that Linquan outperforms Longgang, while a negative RE (%) suggests Linquan underperforms compared to Longgang. Additionally, a larger |RE| signifies a more significant regional influence.

Optical properties

In accordance with the requirements of GB/T 2410-2008 "Determination of Light

Transmittance and Haze of Transparent Plastics", the light transmittance and haze were measured using a light transmittance/haze meter. Each sample was tested three times.

Mulch film recovery rate

The recovery rate (%) of the mulch film is defined as the ratio between the amount of mulch film removed from the field and the amount used. Field measurements were conducted to survey each type of mulch film before and after use at the Longgang site. The initial mulch film mass for each treatment was measured using a balance with a precision of one thousandth, recorded as M0. At 45 and 120 days post-mulching, the mulch film for each treatment was collected, cleaned, and air-dried to measure the mulch film mass (amount removed from the field), recorded as M1. The protocol for cleaning mulch films involved subjecting the recovered films to ultrasonication in deionized water for 30 minutes (KQ-500DE, 40 kHz), effectively eliminating any loosely bound soil. Samples were then immersed in 75% ethanol and manually wiped with ethanol-moistened gauze under gloved handling. This two-stage process eliminated soil contaminants while preserving film integrity. Cleaned films were air-dried at 25°C for 24 h before mass measurement. The mulch film recovery rate was calculated using the following formula:

$$\text{Recovery rate} = \frac{\text{M1}}{\text{M0}} \times 100\% \qquad (2)$$

Data analysis

Statistical analysis of the collected data was performed using Excel. Graphs were created using OriginPro. Statistical analysis was performed using IBM SPSS Statistics 22 (2013 release). Prior to ANOVA, data normality and homogeneity of variances were verified by the Shapiro-Wilk test ($P > 0.05$) and Levene's test ($P > 0.05$), respectively. One-way ANOVA with Duncan's post hoc test ($\alpha = 0.05$) was applied only when assumptions were satisfied.

Results and analysis

Dynamic changes in the mechanical properties of mulch film

Dynamic changes in tensile properties

The dynamic changes in the longitudinal and transverse maximum tensile force of mulch films with different mulching durations and thicknesses are shown in Fig. 1. At any given mulching duration, the maximum tensile force increased with film thickness, in the following order: 0.014 mm > 0.010 mm > 0.008 mm > 0.006 mm. At 120 d, significant differences ($P < 0.05$) were observed among the four film thicknesses, confirming that maximum tensile force increases with thickness. At a constant film thickness, the maximum tensile force generally decreased over time. The rate of decline was faster during 0–30 d and slowed between 30 and 120 d. At the same mulching duration and thickness, the maximum longitudinal tensile force consistently exceeded the transverse tensile force, except for the 0.014 mm film at 60 d and 90 d.

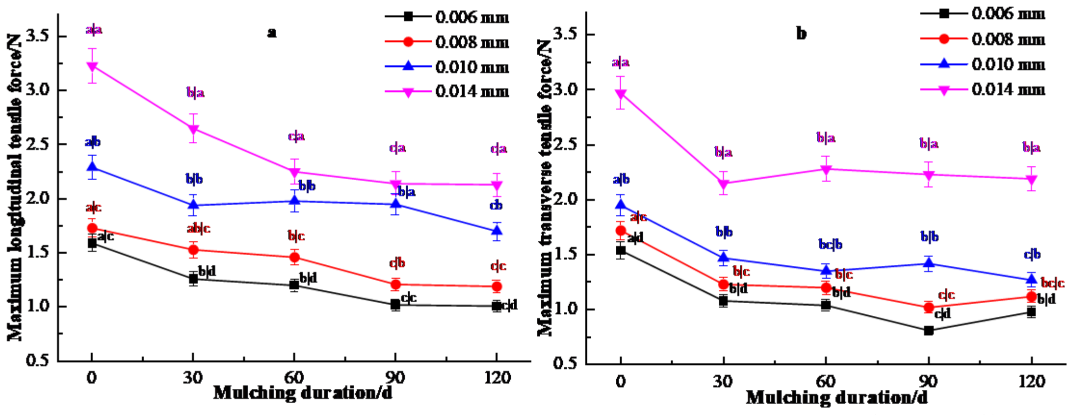

Fig. 1. The dynamic changes in the maximum: (a) longitudinal and (b) transverse tensile force at different mulching

durations and thicknesses

Note. In this and the following figures, the lowercase letters to the left of the '|' indicate differences in the same film thickness over time ($P < 0.05$), and those on the right indicate differences in the film thickness at the same time ($P < 0.05$).

The dynamic changes in the longitudinal and transverse elongation at break with varying mulching durations and thicknesses are depicted in Fig. 2. For the same mulching duration, the elongation at break followed the pattern: 0.014 mm > 0.010 mm > 0.008 mm > 0.006 mm. The elongation at break of the mulch film increased with thickness. When the mulch film thickness remained constant, the elongation at break exhibited an overall decreasing trend as the mulching duration increased. Notably, the decline rate in elongation accelerated after 60 d for the 0.014 mm thick film. For the same mulching duration and thickness, except for the 0.006 mm and 0.008 mm films at 0 d, where the longitudinal elongation at break was lower than the transverse, the longitudinal elongation at break for all other films was consistently greater than the transverse elongation at break.

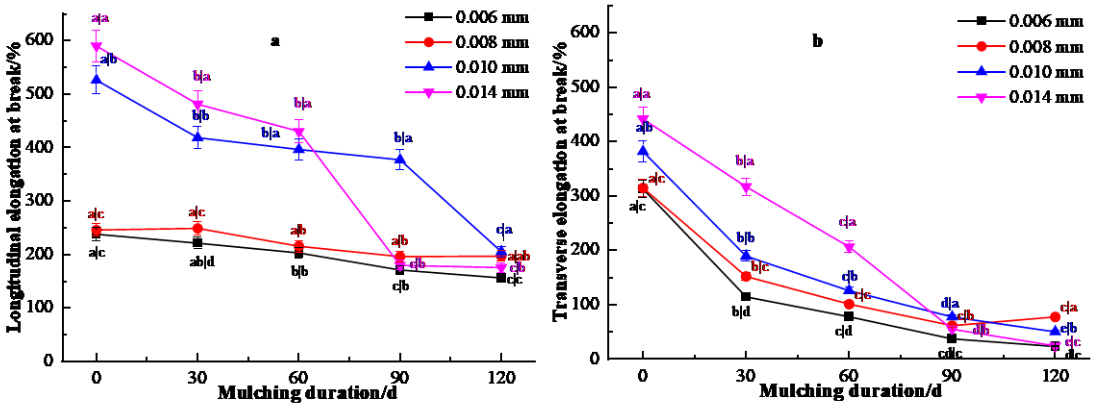

Fig. 2. Dynamic change of: (a) longitudinal and (b) transverse tensile elongation at break for different mulching durations and thicknesses

Dynamic changes in right-angle tear load

The dynamic changes in the longitudinal and transverse maximum right-angle tear load for mulch films with varying mulching durations and thicknesses are illustrated in Fig. 3. For the same mulching duration, the maximum right-angle tear load increased with film thickness. The maximum right-angle tear load for the 0.014 mm film was significantly higher than that of the other thicknesses. During the initial 30 days after mulching, the rate of change in the maximum right-angle tear load was relatively high, while from 30 d to 120 d, this rate of change slowed. For the same thickness, the maximum right-angle tearing load of the mulch film varies with the mulching duration but generally shows a decreasing trend. When both mulching duration and thickness are the same, except for the 0.006 mm mulch film, where the longitudinal right-angle tearing load is lower than the transverse load at 30 d and 90 d, the maximum longitudinal right-angle tearing load of all other mulch films is greater than the transverse load.

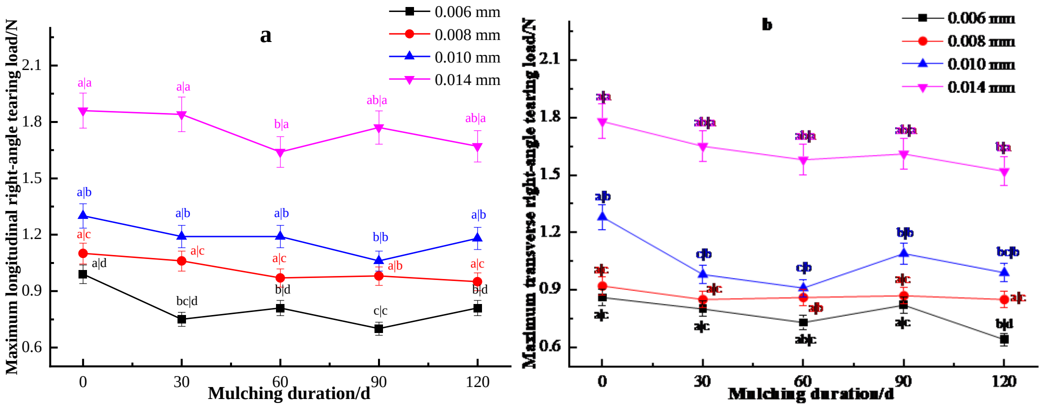

Fig. 3. The dynamic changes in maximum: (a) longitudinal and (b) transverse right-angle tearing load

Dynamic changes in puncture resistance

The dynamic changes in the maximum puncture force of mulch films with varying mulching durations and thicknesses are illustrated in Fig. 4. For the same mulching duration, the maximum puncture force exhibited a consistent trend of 0.014 mm > 0.010 mm > 0.008 mm > 0.006 mm, with the differences being statistically significant. This indicates that the maximum puncture force of the mulch film increases as the film thickness increases. When the thickness remains constant, the maximum puncture force generally displayed a decreasing trend over the mulching duration; however, at 120 d, the maximum puncture strength was greater than that observed at 90 d. Notably, the puncture resistance of the 0.014 mm and 0.006 mm thick films showed a significant decline between 60 d and 90 d.

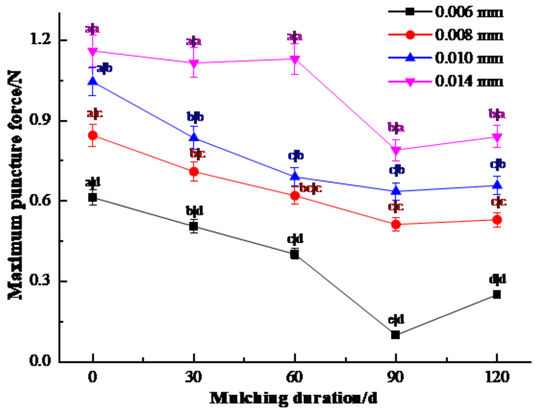

Fig. 4. The dynamic changes in maximum puncture force for different mulching durations and thicknesses

Dynamic changes in optical properties of mulch film

Table 1 presents the light transmittance of mulch films with varying mulching durations and thicknesses. Under the same light source conditions and at equivalent mulching durations, no significant differences in light transmittance were observed among the different thicknesses of mulch film at 60 d and 120 d. However, at 0 d of mulching, the light transmittance of the 0.008 mm and 0.010 mm films was significantly higher than that of the 0.006 mm film. After 30 d of mulching, the light transmittance of the 0.008 mm film was significantly greater than that of the other thicknesses. At 90 d, the light transmittance of the 0.006 mm and 0.008 mm films was significantly higher than that of the 0.014 mm film, with the 0.008 mm film exhibiting the highest transmittance. When the thickness was held constant, the light transmittance of the

0.006 mm mulch film exhibited no significant differences as the mulching duration increased. For the 0.008 mm mulch film, the transmittance at 0 d was significantly higher than that at 30 d, 60 d, and 120 d. Similarly, for the 0.010 mm mulch film, the transmittance at 0 d was significantly greater than at any other mulching duration. In the case of the 0.014 mm film, the transmittance at both zero and 120 d was significantly higher than at 30 d and 90 d, with the highest transmittance recorded at zero day.

Table 1- Transmittance (%) of different mulching durations and thicknesses

Mulching duration (d)	**Film thickness (mm)**			
	0.006	**0.008**	**0.010**	**0.014**
0	90.0±3.42**a**|b	91.93±1.02**a**|a	91.80±1.12**a**|a	90.90±1.03**a**|ab
30	88.6±2.18**a**|b	89.73±0.81**b**|a	88.67±1.45**b**|b	88.33±1.88**b**|b
60	87.83±3.55**a**|a	89.25±1.01**b**|a	90.13±1.26**b**|a	89.60±0.91**ab**|a
90	89.93±2.36**a**|a	90.20±0.95**a**|a	89.37±1.44**b**|ab	88.23±1.25**b**|b
120	90.67±3.84**a**|a	89.47±1.11**b**|a	89.90±1.37**b**|a	90.6±1.44**a**|a

Note: In this and the following tables, the lowercase letters to the left of the '|' indicate differences in the same film thickness over time ($P < 0.05$), and those on the right indicate differences in the film thickness at the same time ($P < 0.05$).

The haze values of mulch films with different mulching durations and thicknesses are shown in Table 2. Under the same light source conditions and mulching duration, no significant differences in haze were observed among films of varying thicknesses at 60 d and 90 d. However, at 0 d, the haze of the 0.014 mm film was significantly higher than that of the other thicknesses. At 30 d, the haze of both the 0.014 mm and 0.010 mm films was significantly greater than that of the 0.006 mm and 0.008 mm films. At 120 d, the haze of the 0.010 mm film was significantly higher than that of the 0.006 mm film, with both the 0.010 mm and 0.014 mm films displaying relatively high haze values. When comparing different mulching durations within the same thickness, the haze of the 0.006 mm film at 0 d was significantly higher than at 120 d. For the 0.008 mm film, the haze at 0 d was significantly greater than that at 60 d. For the 0.010 mm film, the haze at 30 d was significantly higher than at 60 d and 90 d. In the case of the 0.014 mm film, the haze at 0 d was significantly higher than at any other mulching duration.

Table 2- The haze value of different mulching durations and thicknesses (%)

Time of mulching (d)	**Film thickness (mm)**			
	0.006	**0.008**	**0.010**	**0.014**
0	34.43±5.85**a**|b	32.12±4.32**a**|b	34.46±4.50**ab**|b	49.72±6.10**a**|a
30	27.04±3.65**ab**|b	27.47±3.88**ab**|b	39.32±5.05**a**|a	37.44±4.75**b**|a
60	26.51±3.28**ab**|a	24.45±3.44**b**|a	28.56±4.02**b**|a	31.30±4.25**b**|a
90	26.37±3.42**ab**|a	28.67±3.68**ab**|a	26.57±3.80**b**|a	30.19±4.12**b**|a
120	23.88±3.10**b**|b	29.48±3.92**ab**|ab	35.58±5.02**ab**|a	31.02±4.30**b**|ab

Differences in mulch film recovery rate over time

Fig. 5 shows the recovery rates of mulch films with different thicknesses at 45 d and 120 d of mulching. At 45 d, the recovery rates with highest to lowest, were as follows: 0.014 mm > 0.008 mm > 0.010 mm > 0.006 mm. At 120 d, the order was: 0.014 mm > 0.010 mm > 0.008 mm > 0.006 mm. This indicates that the recovery rate increases with the thickness of the mulch film, with the 0.014 mm mulch film exhibiting a significantly higher recovery rate. When the mulching duration is shorter (45 d), the recovery rate difference between 0.008 mm and 0.01 mm thick films is minimal. However, after a longer mulching period (120 d), the recovery rate of the 0.01 mm film outperformed that of the 0.008 mm film. At the same thickness, the recovery rate at 45 d is significantly higher than at 120 d for all films except the 0.010 mm thickness, indicating that recovery efficiency decreases as mulching duration increases.

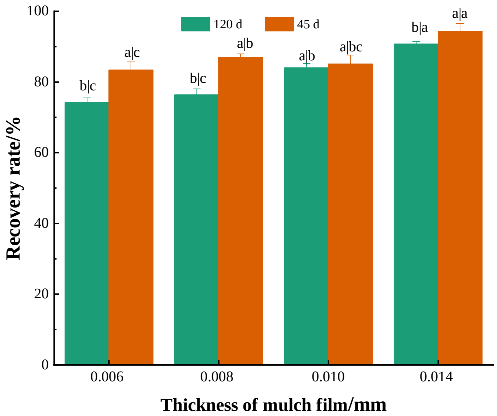

Fig. 5. Effect of different thicknesses and mulching durations on mulch film recovery rate

Correlation analysis between mulch film rate and physical properties

A correlation analysis between the recovery rate of mulch films at 120 d and their physical properties is presented in Fig. 6. The recovery rate exhibited a highly significant positive correlation (P < 0.01) with the longitudinal maximum right-angle tearing load, transverse maximum right-angle tearing load, longitudinal maximum tensile force, transverse maximum tensile force, and maximum puncture force. These findings suggest that the recovery rate of mulch films is strongly correlated with their mechanical properties, implying that enhancing these characteristics could significantly improve the films' recyclability.

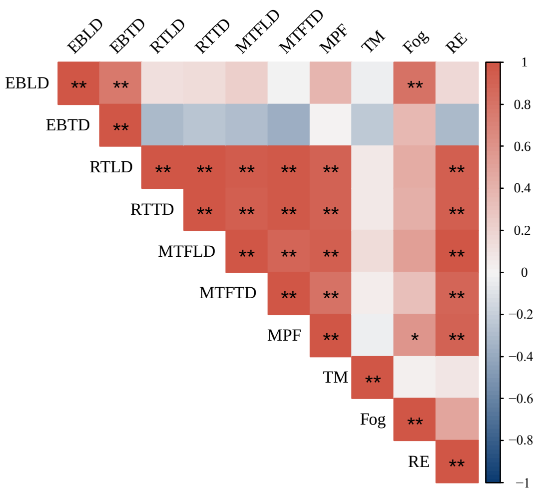

Fig. 6. Correlation analysis between mulch film recovery rate and physical properties

Note. In the figure, EBLD, EBTD, RTLD, RTTD, MTFLD, MTFTD, MPF, TM, Fog, and RE represent the longitudinal elongation at break, transverse elongation at break, longitudinal maximum right-angle tearing load, transverse maximum right-angle tearing load, longitudinal maximum tensile force, transverse maximum tensile force, maximum puncture force, transmittance, haze, and recovery rate, respectively. The symbols “*” and “**” indicate significance levels of P < 0.05 and P < 0.01, respectively.

Differences in mechanical properties of mulch films across different regions

Table 3 presents the mechanical properties of the 0.010 mm mulch film at the Longgang and Linquan sites after 30 d and 120 d of mulching. Following a period of 30 d, the relative error in the longitudinal tensile breaking elongation rate between the Linquan and Longgang mulch films was -5.24, while the relative error in the transverse maximum right-angle tear load was 9.18. After 120 d of mulching, the longitudinal maximum right-angle tear load, longitudinal tensile breaking elongation rate, and maximum puncture force of the mulch film from the Linquan site were significantly greater than those from the Longgang region, with relative errors of 9.30, 40.61, and 15.50, respectively. This suggests that the discrepancies in environmental circumstances between regions may result in variations in the performance characteristics of the mulch films.

Table 3- Mechanical properties of mulch film in different flue-cured tobacco planting areas

Mechanical properties of film		Mulching for 30 d			Mulching for 60 d		
		Longgang	**Linquan**	**Relative error (%)**	**Longgang**	**Linquan**	**Relative error (%)**
Longitudinal	Maximum tensile force (N)	1.94	1.92	-1.03	1.70	1.73	1.76
	Maximum right-angle tear load (N)	1.19	1.22	2.52	1.18	1.29	9.30
	Tensile breaking elongation rate (%)	418.85	396.90	-5.24	205.30	288.67	40.61
Transverse	Maximum tensile force (N)	1.47	1.46	-0.68	1.27	1.28	0.79
	Maximum right-angle tear load (N)	0.98	1.07	9.18	0.99	1.00	1.01
	Tensile breaking elongation rate (%)	189.46	188.00	-0.77	50.22	51.65	2.85
	Maximum puncture force (N)	0.84	0.83	-1.20	0.658	0.76	15.50

Discussion

In developed countries where the use of mulch films is extensive, such as the USA and Japan, the typical film thickness is generally 0.200 mm or 0.015 mm (Madrid *et al.*, 2022). In the Chinese context, due to cost-saving considerations, farmers tend to use mulch films with a reduced thickness, approximately 0.008 mm. Furthermore, the majority of mulch film recovery machinery is characterized by relatively simple functionality. Consequently, these factors contribute to the absence of effective mulch film recovery processes, particularly after harvesting the crops, when issues such as severe film fragmentation and inadequate mechanical strength exacerbate the problem, leading to an escalation in mulch film residue pollution (Jambeck *et al.*, 2015; Khalid, Aqeel, Noman, & Fatima Rizvi, 2023; Liu, He, & Yan, 2014). Although various biodegradable mulch films have been developed, these films still face issues such as high usage costs, poor performance, and incomplete degradation (Huang, Zhang, Wang, Zhang, & Zhang, 2023). Recycling is still one of the key measures to effectively mitigate the pollution caused by wasted mulch films in tobacco fields, playing a crucial role in promoting the green health of soil in tobacco-growing areas and ensuring the sustainable development of tobacco leaf production. Good mechanical properties are fundamental to the higher recycling rate (Jiang, Chen, Yan, Yang, & Li, 2023). The maximum tensile force, tensile breaking elongation rate, maximum right-angle tearing load and maximum puncture force are significant indices for reflecting the mechanical properties of mulch film (Bulati, Zhan, Xu, & Yang, 2025). For example, during mechanical recovery of mulch films in the field, the films are subjected to stretching, which causes the molecular chains to break, resulting in surface cracks or even direct tearing. This hinders the smooth progress of the recovery process (Han *et al.*, 2020). Therefore, enhancing the maximum tensile force and elongation at break can improve the ductility of the mulch film, reducing the likelihood of rupture during the mechanical recovery process, preserving its integrity, and decreasing the probability of fragmentation, ultimately increasing the recovery rate. In this experiment, when the mulching duration remained constant, the maximum tensile force, maximum right-angle tearing load, and maximum puncture force of the mulch film increased in proportion to the thickness of the film. However, when the film thickness was maintained at a constant level, the mechanical properties generally demonstrated a declining trend as the mulching duration increased. Furthermore, the mulch film recovery rate demonstrated a highly significant positive correlation with the longitudinal maximum right-angle tearing load, transverse maximum right-angle tearing load, longitudinal maximum tensile force, transverse maximum tensile force, and maximum puncture force. This suggests that the mechanical properties are of paramount importance for higher recovery rates. It is therefore imperative that the role of mechanical properties in improving recovery efficiency is fully considered when designing mulch film products and planning mechanical recovery methods.

Mulch films are polymer compounds, and as the mulching duration is extended, the phases of plastic flow and necking expansion gradually cease to be observable. Once the mulch film has been applied, the environmental factors, including light, heat, and moisture, cause the oxidation and subsequent breakage of C-C bonds. These results in a gradual decline in the mechanical properties (Ainali, Bikiaris, & Lambropoulou, 2021; Chen *et al.*, 2021; Qiang *et al.*, 2023; Wang, Ma, & Ji, 2021). Due to the high crystallinity and molecular weight of polyethylene molecules, as well as their strong hydrophobicity and intermolecular forces, the arrangement of polyethylene molecules is not completely regular or orderly. This irregularity results in an uneven rate of oxidation and bond breakage (Antunes, Agnelli, Babetto, Bonse, & Bettini, 2018; Cuadri & Martín-Alfonso, 2017; Wang, Pan, Zhao, Li, & Guo, 2024). Similarly, the rate of change in the mechanical properties of the mulch films from 30 d to 120 d was slower and exhibited greater fluctuations compared to the duration from 0 d to 30 d. The greater the thickness, the stronger the bond energy of the C-C covalent bonds that constitute the polyethylene molecules, and a greater force is required to break these molecular bonds. Accordingly, the maximum tensile force, maximum right-angle tearing load, and maximum puncture resistance increase with its thickness (Beltrán-Sanahuja, Benito-Kaesbach, Sánchez-García, & Sanz-Lázaro, 2021). However, once the mulch film reaches a critical thickness, it becomes susceptible to premature rupture during tensile tests. Consequently, the tensile breaking elongation rate initially increases with thickness but then declines (Sun *et al.*, 2024). In longitudinal tensile and tearing tests, the load required for the mulch film demonstrates a gradual increase with displacement. Initially, the film thins slowly before ultimately breaking, with the maximum load point occurring in close proximity to the fracture point. In contrast, the load does not exhibit significant changes with displacement during transverse tensile and tearing tests. This results in the rapid tearing or localized thinning of the material before rupture occurs (Singh & Sharma, 2008; Song *et al.*, 2018). These results demonstrate that the longitudinal tensile and tearing force of the mulch films exceed those observed in the transverse direction, when the mulching duration and thickness are maintained at consistent levels. This finding is consistent with previous research. The mechanical properties are susceptible to alteration by environmental factors, including ultraviolet radiation and wind (Liu *et al.*, 2020). At 30 d of mulching duration, the relative error for the longitudinal tensile breaking elongation rate between the Linquan and Longgang sites was -5.24, while the relative error for the transverse maximum right-angle tearing load was 9.18. At 120 d of mulching, the longitudinal maximum right-angle tearing load, longitudinal tensile breaking elongation rate, and maximum puncture force of the Linquan film exhibited significantly higher values than those of the Longgang film. Previous studies have shown that higher ultraviolet (UV) intensity and temperature can accelerate the degradation of polyethylene mulch film (Briassoulis, Babou, Hiskakis, & Kyrikou, 2015; Chiellini, Corti, D'Antone, & Baciu, 2006). Due to its higher elevation, the UV intensity in Longgang is also greater than that in Linquan, and Longgang experiences higher maximum temperatures than Linquan. Therefore, after 120 d of mulching, the mechanical properties of the mulch film in Linquan are superior to those in Longgang. This further demonstrates that the mechanical properties of the mulch film exhibit significant variation under different ecological conditions.

The optical properties of mulch films can be effectively evaluated through the analysis of two key indicators: transmittance and haze. Transmittance is defined as the ratio of the luminous flux that passes through a material to the incident luminous flux. Upon striking the surface or penetrating the interior of the material, light undergoes scattering, resulting in a relative lack of clarity on the material's surface. The extent of this lack of clarity is quantified by the parameter known as haze (Xie *et al.*, 2022). The present study reveals that there are notable differences in transmittance and haze among mulch films with varying mulching duration and thicknesses. Such discrepancies may be ascribed to disparate extents of contamination, abrasion, and scratches on the film's surface. Furthermore, environmental factors like light, heat, and moisture can cause molecular chains to break and reorganize, resulting in structural changes. Such alterations can affect the spectral energy of the mulch film, thereby influencing its transmittance and haze under identical lighting conditions. Commonly, the higher the transmittance of the mulch film, the less solar energy it absorbs, allowing most of the radiant energy to pass through the film and causing a rapid temperature increase within the planting hole. Additionally, higher transmittance facilitates earlier growth of tobacco plants, leading to a higher root-to-crown ratio, as well as increased height, stem circumference, and lengths of the largest leaves. On the other hand, lower transmittance can improve the visual quality, chemical composition, and overall harmony of the tobacco leaves (Feng *et al.*, 2020). Therefore, it is essential to consider local natural conditions and comprehensively select mulch films with appropriate transmittance levels.

Conclusion

This study demonstrates that mulch film thickness fundamentally governs the mechanical and optical performance of polyethylene films, with thicker films exhibiting superior tensile, tear, and puncture resistance. Mulching duration accelerates property deterioration, most markedly within the initial 30 days, followed by decelerated degradation. Critically, ecological conditions modulate degradation kinetics, driving divergent mechanical retention and recyclability across regions. These findings reveal synergistic interactions among thickness, mulching duration, and environment in determining film recyclability. To enhance recovery efficiency and reduce soil pollution, we recommend prioritizing films thicker than 0.010 mm. Future work should integrate environmentally adaptive high-strength recyclable materials with region-specific mechanized recovery systems.

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Authors Contribution

Weichang Gao Supervision, Project administration. Oversaw research design, coordinated field experiments across Longgang and Linquan regions, and finalized manuscript revisions.

Xie Yin Conceptualization, Methodology. Designed the experimental framework for evaluating mulch film thickness and mulching durations, and formulated recycling efficiency metrics.

Shasha Wang Data acquisition, Data pre- and post-processing. Conducted field data collection on mechanical properties and managed dataset standardization.

Zugui Tu Statistical analysis, Software services. Performed regression analysis on physical property correlations and developed computational models for optical property evaluation.

Shuang Ming Validation, Visualization. Verified experimental reproducibility across ecological regions and generated graphical representations of degradation trends.

Kai Cai Methodology, Technical advice. Optimized mechanical testing protocols and provided expertise on agricultural film recycling technologies.

Heqing Cai Review & editing, Text mining. Synthesized literature on mulch film recyclability and critically revised the manuscript for technical clarity.

Chen Xu Numerical simulation, Resources. Simulated light transmittance/haze variations using finite element analysis and secured access to regional field sites.

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ارزیابی میدانی قابلیت بازیافت مالچ‌های پلاستیکی به روش بررسی پویایی خواص فیزیکی آن‌ها تحت کشت تنباکو

وی‌چانگ گائو[1]، شیه یین[1،2]، شاشا وانگ[3]، زوگویی تو[1،2]، شوانگ مینگ[1،2]، کای کای[1]، هچینگ کای[4]، چن شو[5]*

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چکیده

مالچ های پلاستیکی باقی‌مانده در مزارع کشاورزی به دلیل تخریب ساختاری و بازیابی ناکارآمد، سلامت خاک و کشاورزی پایدار را تهدید می‌کنند. برای پرداختن به این موضوع در این مطالعه، اثرات ضخامت فیلم مالچ (۰/۰۰۶-۰/۰۱۴ میلی‌متر)، زمان ماندگاری فیلم مالچ (تا ۱۲۰ روز) و دو منطقه مختلف از لحاظ اکولوژیکی در استان گوئیژو چین: شهر لانگگانگ (شهرستان کایانگ) و شهر لینکوان (شهرستان کیانشی) را بر خواص فیزیکی و قابلیت بازیافت در کشت تنباکو بررسی کرد. تحلیل مکانیکی، نوری و راندمان بازیافت نشان داد که مقاومت کششی، گسیختگی (پارگی) و سوراخ شدن به‌طور متناسب با ضخامت در مدت زمان‌های یکسان افزایش می‌یابد، در حالی‌که نرخ ازدیاد طول در ابتدا افزایش و سپس کاهش می‌یابد. ماندگاری مالچ ها در طولانی مدت عملکرد مکانیکی را در ضخامت‌های ثابت کاهش می‌دهد، به‌طوری‌که مقاومت کششی و پارگی طولی به‌طور مداوم از مقادیر عرضی بیشتر می‌شود. خواص نوری به‌طور قابل‌توجهی دچار تغییر می شود: فیلم‌های نو و استفاده‌نشده، بهترین عبور نور و کدورت را نشان می‌دهند، در حالی‌که فیلم‌های ۰/۰۰۸ میلی‌متری حداکثر عبور نور را داشته و فیلم‌های ضخیم‌تر (۰/۰۱۰-۰/۰۱۴ میلی‌متر) کدورت بیشتری دارند. راندمان بازیافت با ضخامت همبستگی مثبت و با مدت ماندگاری مالچ همبستگی معکوس دارد. پس از ۱۲۰ روز، راندمان بازیافت همبستگی زیادی با بارهای پارگی طولی و عرضی دارد. تغییرات منطقه‌ای به‌طور قابل‌توجهی بر خواص مکانیکی فیلم‌های ۰/۰۱۰ میلی‌متری تاثیر می‌گذارند، که نشان می‌دهد این ضخامت ممکن است با محیط‌های متنوع جغرافیایی بهتر سازگار شود. فیلم‌های ضخیم‌تر پس از گذشت ۱۲۰ روز از استقرار مالچ، به دلیل حفظ یکپارچگی ساختاری، قابلیت بازیافت بالاتری را نشان می‌دهند. این یافته‌ها به‌طور سیستماتیک الگوهای تخریب فیزیکی را به قابلیت بازیافت در شرایط مزرعه مرتبط می‌کنند و بینش‌های عملی برای بهینه‌سازی استفاده از مالچ پلاستیکی، طراحی محصولات بادوام و بهبود ماشین‌آلات بازیابی ارائه می‌دهند. این مطالعه با متعادل کردن عملکرد پلاستیک، سازگاری با محیط‌زیست و راندمان بازیابی در پایان عمر، از شیوه‌های کشاورزی پایدار حمایت می‌کند.

واژه‌های کلیدی: خواص مکانیکی، خواص نوری، راندمان بازیافت، شرایط کشت تنباکو، قابلیت بازیافت فیلم مالچ

۱ـ آکادمی علوم تنباکوی گویژو، گوی‌یانگ، گویژو، ۵۵۰۰۸۱، چین
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(*- نویسنده مسئول: Email: cqxuchen@139.com)

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