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Experiment on Cultivation Performance of Plant Fiber-Based Degradable Film in Paddy Field

Xianglan Ming [1,*] and Haitao Chen [2]

1 College of Mechanical and Electrical Engineering, Lingnan Normal University, Zhanjiang 524048, China
2 College of Engineering, Northeast Agricultural University, Harbin 150030, China; htchen@neau.edu.cn
* Correspondence: mingxianglan521@126.com; Tel.: +86-1884-683-3842

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Abstract: To solve the problems of the damage of weed in paddy field on crop yield and quality, the impact of chemical herbicides on the ecological environment, and the soil pollution caused by plastic film mulching, the field-positioning test was carried out in 2015 to 2017. Taking Daohuaxiang 2 as the test material, three treatments (plant fiber-based degradable film, plastic film, and CK) were setup to investigate the effects of plant fiber-based degradable film on the weed inhibition, warming effect under mulching cultivation, rice yield, rice quality, and economic benefit. The results showed that compared with CK, the plant fiber-based degradable film and plastic film reduced the weed by 85.5% to 87.7% and 78.7% to 81.7%, respectively. Plant fiber-based degradable film mulching cultivation can increase the soil temperature of soil layer 0 to 0.1 m depth. In 2015 to 2017, rice yield with plant fiber-based degradable film increased by 8.71%, 7.53%, and 9.02%, respectively. Plant fiber-based degradable film can significantly reduce the hardness, increase its adhesion, and improve the eating quality of rice. Different films mulching had a certain impact on crop economic benefit. During the developmental stage of the panicle, the plant fiber-based degradable film began to crack, and by the blossom fruit period, the degradation rate reached the grade of 3 or 4. Therefore, the use of plant fiber-based degradable film instead of plastic film can reduce the amount of weed under the membrane and create a more suitable soil temperature, which was conducive to rice yield and quality.

Keywords: plant fiber-based degradable film; paddy mulching cultivation; weed inhibition; warming effect; economic benefit

1. Introduction

The rice productivity in China is the highest around the world. Rice plantings accounted for 30% of arable land, and production accounted for 40% to 50% of total national grain production. The yield reduction of rice due to diseases and weed was up to 100% and 66%, with an average of 24% [1]. In 2010, global paddy field pesticide sales accounted for 9.9% of the entire pesticide market, of which herbicides reached 43.2% [2]. Herbicides played an important role in weed inhibition in the paddy field and stable production of rice. However, long term application of herbicides also had negative effects, such as the increase of herbicide-tolerant weed biotypes, the residues and accumulation of herbicide, and the issues of ecological balance, environmental governance, and human and animal health [3]. Therefore, the study of paddy mulching cultivation had been researched by domestic and foreign scholars [4–6].

The weed under the membrane grew seriously at plastic film mulching cultivation, thus seriously competing for the nutrients and moisture needed for crops. In order to inhibit weed, it was necessary to apply herbicides before the film mulching, which was easy to pollute the soil and groundwater, worsen the ecological environment, and lead to a decline in yield and quality. At the same time, plastic film was difficult to degrade and remained in the soil, which not only destroyed the soil structure, inhibited the normal absorption of water and nutrients by plant roots, reduced the yield and quality of crops, but also hindered the sustainable development of agriculture [7,8]. So as to solve the negative effects caused by plastic film mulching, new environmental-friendly films such as biodegradable film, photodegradable film, photo-biodegradable film, and plant fiber-based degradable film had been successively launched [9–12]. The photo-biodegradable film can be degraded due to the synergistic effect of photo-degradation and biodegradation without substantial residual film damage. However, due to the high cost of photo-biodegradable film, the degree of industrialization was not enough. At present, its application was still in the stage of small-scale experiment, and further research was needed. The plant fiber-based degradable film had no significant difference with plastic film in terms of increasing soil temperature, inhibiting weed, promoting crop growth and development, improving crop yield and water use efficiency, which can replace plastic film for agricultural production [13–16].

Regarding plant fiber-based degradable film, the current research focus was on the raw material composition, degradation properties and the comparison of different types of plant fiber-based degradable film, but lack of systematic research on the application of plant fiber-based degradable film in the field [17,18]. In addition, the effects of temperature increasing, water retention and yield increasing of mulching cultivation techniques had been studied in depth, and the research fields included different regions, different soil types, and different crop types [19–22]. For rice cultivation, most studies were limited to film mulching aerobic cultivation, and there were few studies on the waterlogged cultivation of plant fiber-based degradable film, which was lack of the research of the effect of paddy mulching cultivation on weed growth, soil temperature, rice yield, rice quality, and economic benefit. In order to provide a theoretical basis for the large-scale application of plant fiber-based degradable film, the research systematically studied the effects of plant fiber-based degradable film on the weed inhibition, warming effect under mulching cultivation, rice yield, rice quality, and economic benefit.

2. Materials and Methods

2.1. Experimental Field

The experiment was conducted in the Experimental Field of Biomass Material Technology Equipment Laboratory of Northeast Agricultural University (Harbin, China) in May 2015 to 2017. The area is located at 45°74′ north latitude, 126°72′ east longitude, and 145.1 m above sea level, which belongs to the mid-temperate continental monsoon climate. The annual average precipitation is 420.1 mm, and the precipitation is mainly concentrated in May to August, accounting for more than 70% of the annual precipitation. The annual average temperature, the highest monthly average temperature, and the lowest monthly average temperature are 5.6, 23.6, and −15.8 °C, respectively. The frost-free period is 168 days. The sunshine hours are 2090.7 h. Moreover, the soil is dominated by black soil and meadow black soil [23].

The water holding capacity and the dry weight of the soil in the experimental field that is meadow black soil are 21% (mass moisture content) and 1.146 g/cm^3. The basic physical and chemical properties of the soil before sowing were: Organic matter 14.63, ammonia nitrogen 129.49, available phosphorus 57.52, available potassium 357 mg/kg, pH 7.98 [23].

2.2. Materials

Plant fiber-based degradable film (ZM), plastic film (SM), and CK were repeated three times with a random incomplete block design. ZM was developed by the Northeast Agricultural University and produced by Mudanjiang Paper Research Institute, which was manufactured by using plant pulp as the basic raw material and adding environmental-friendly functional additives to the pulp. The conventional characteristics required for ZM were satisfied, with a thickness of 0.328 mm and a width of 700 mm. SM was a commercially available ordinary polyethylene plastic film. The experimental field was 6 m long, 10 m wide, and 60 m^2 in area.

The main stem, the plant height, the spike length, the number of grains per panicle, and the thousand-grain weight of the test material (Daohuaxiang 2) are 15 leaves, 1.05 and 0.216 m, 120 and 26.8 g, respectively. In the adaptation area, the days from emergence to maturity are 147, and the accumulated temperature of activity is about 2800 °C [23].

450 kg/hm^2 rice compound fertilizer (15:15:15) was applied as a base fertilizer to experimental field in late May each year. Rice seedlings were transplanted to experimental field in early June with the transplanting density of 0.3 × 0.15 m (about 2 to 4 strains per hole) and no herbicides. In late June and mid-July, 100 kg/hm^2 urea (46.2% nitrogen) was applied as a re-fertilizer and tiller fertilizer to the experimental field, which was harvested in the beginning of October.

2.3. Methods

Weed inhibition: Refer to the Chinese Standard GB 7172 - 1987 to calculate the weed dry weight of each treatment. The number of repetitions is three.

$$\text{Weed inhibition rate } = \frac{\text{weed dry weight of CK } - \text{ weed dry weight of film}}{\text{weed dry weight of CK}} \times 100\%$$

Soil temperature: The temperature sensors had been installed at the same location on each treatment. Monitor the soil temperature changes of 0, 0.05, 0.1 m depth during the whole growth period of rice, and record the data every 10 min [24].

Rice yield: Measure the thousand-grain weight and the actual yield of rice (measured area of 60 m^2) in maturity. The number of repetitions is three [24].

Texture characteristics: Use the TA-XT plus physical property analyzer to determine the texture characteristics of cooked rice of each treatment, and objectively reflect the edible quality of rice [25]. Randomly place three completely steaming rice grains at the same distance from each other and evenly distribute on a P/50 probe. Characterize the hardness and adhesion with the average of eight repeats.

$$\text{Economic benefit : Film cos t} \left(\text{yuan} \cdot \text{hm}^{-2}\right) = \text{film consumption} \times \text{film unit price}$$
$$\text{Output value} \left(\text{yuan} \cdot \text{hm}^{-2}\right) = \text{crop yield} \times \text{crop unit price}$$

Film degradation: Observe every 10 days after film mulching. Refer to the method of Yang Huidi [26] to express the classification index of film degradation: 0: No crack; 1: Cracks begin to appear; 2: Hairline cracks appear in 25% of the film; 3: Film appears 0.02 to 0.025 m cracks; 4: Film cracks become uniform mesh, no large pieces of film existing; 5: Basically, no film exists in ridge surface.

2.4. Statistical Analysis

The experimental results were processed with Microsoft Excel 2010, Design—Expert 6.0.10, and Origin pro 9 software [27]. LSD test at 5% level was used to test for significant differences between each year's results.

3. Results and Analysis

3.1. Effect of Different Films Mulching on Weed Inhibition

It can be seen from Figure 1 that the main weed population was barn grass in 2015 to 2017. Under different types of film mulching conditions, the weed dry weight is shown in Figure 2, in which ZM had the best effect on weed inhibition. The three year results showed that the weed inhibition rate of ZM and SM was 85.5% to 87.7% and 78.7% to 81.7%, which were significantly better than that of CK. In the study, the number of weed in paddy field can be significantly reduced, and artificial weeding and the use of herbicides can be avoided. The soil structure can be protected from damage after film mulching cultivation. The reason is mainly the low light transmittance of the plant fiber-based degradable film that was the primary color film that could block the photosynthesis of the weed under the membrane, thus inhibiting the weed. The rice seedlings were transplanted after mulching film so it can grow normally. Paddy mulching cultivation destroyed the living environment of weed and inhibited the breeding of weed, indicating that the paddy mulching cultivation techniques had certain control effects on common weed and dominant weed in paddy field. The ZM and SM without spraying herbicide had significant weed inhibition effect, and the herbicide could be reduced or not used in the mulching cultivation.

(**a**) ZM (**b**) CK

Figure 1. Comparison of weed for ZM and CK. Note: ZM: Plant fiber-based degradable film.

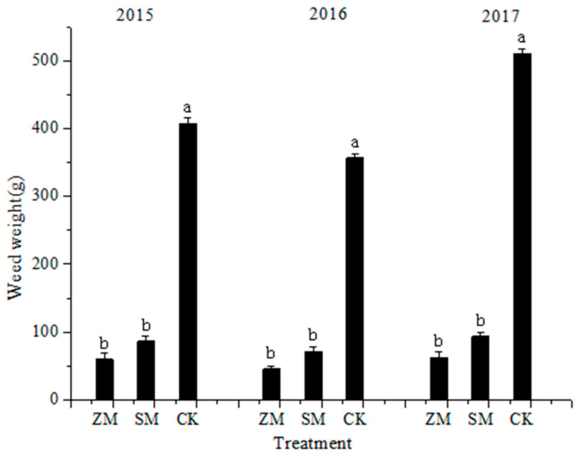

Figure 2. Effect of different films mulching on weed inhibition. Note: Different letters are significantly different within the same year among treatments at the 0.05 probability level.

3.2. Effect of Different Films Mulching on Soil Temperature

The changes of ZM, SM, and CK in surface soil temperature are shown in Figure 3. It can be seen from Figure 3 that the surface soil temperature of SM and ZM was higher than that of CK in different growth stages of rice, and SM was significantly higher than ZM in the panicle developmental stage in 2017. The warming effect of ZM during the whole growth period was not significantly different from that of SM. Due to the continuously rising atmospheric temperature, the temperature-increasing extent of SM, ZM, and CK gradually decreased after the blossom fruit period. During the whole growth period, the average surface soil temperature of ZM and SM was 0.74 and 2.14 °C higher than that of CK in 2015 to 2017.

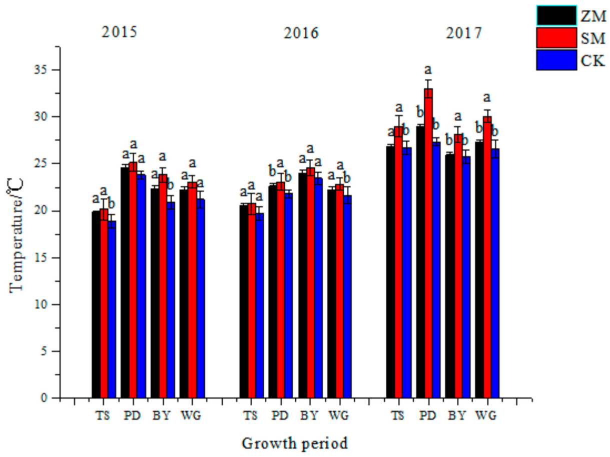

Figure 3. Changes of surface soil temperature under different treatments. Note: TS: Tillering stage; PD: Panicle developmental stage; BY: Blossom fruit period; WG: Whole growth period.

The changes of soil temperature of ZM, SM, and CK in 0.05 m depth are shown in Figure 4. It can be seen from Figure 4 that the soil temperature of SM and ZM in 5 cm depth was higher than that of CK in different growth stages of rice. The temperature during the blossom fruit period was higher than panicle developmental stage in 2016. The warming effect of ZM was comparable to that of SM. During the blossom fruit period, the temperature-increasing extent of SM, ZM, and CK gradually narrowed due to the rising ambient temperature. During the whole growth period, the average soil temperature of ZM and SM in 0.05 m depth was 0.84 and 2.16 °C higher than that of CK in 2015 to 2017.

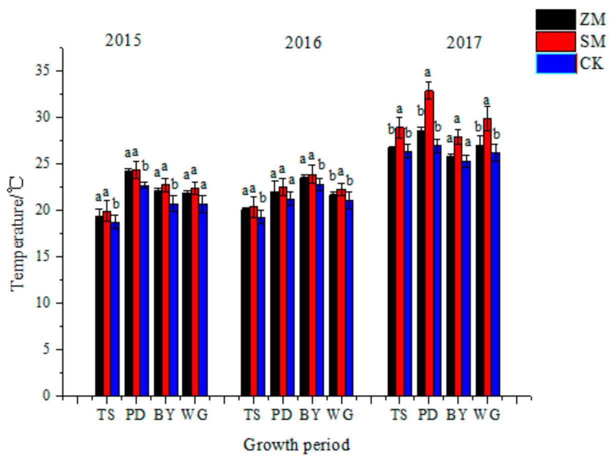

Figure 4. Changes of soil temperature in 0.05 m depth under different treatments.

The changes of soil temperature of ZM, SM, and CK in 0.1 m depth are shown in Figure 5. It can be seen from Figure 5 that the soil temperature of SM and ZM in 10 cm depth was higher than that of CK in different growth stages of rice, and the SM was significantly higher than ZM in panicle developmental stage in 2017. The warming effect of ZM in 0.1 m depth was not as good as that of SM. During the blossom fruit period, the temperature-increasing extent of SM, ZM, and CK gradually reduced mainly due to the continuous increase of surrounding temperature. During the whole growth period, the average soil temperature of ZM and SM in 0.1 m depth was 0.95 and 2.26 °C higher than that of CK in 2015 to 2017.

The study found that plant fiber-based degradable film mulching cultivation had a certain effect of increasing soil temperature through preliminary experiments. The average soil temperature of ZM in 0 to 0.1 m depth during the whole growth period was 0.81 °C higher than that of CK, slightly lower than that of SM probably due to the low light transmittance and high gas permeability of ZM compared to the SM. In the blossom fruit period, ZM had the smallest temperature-increasing extent and even the temperature-dropping trend, which might be related to the degradation performance of ZM and the decrease of external temperature. Rice planting by the plant fiber-based degradable film mulching cultivation was equivalent to plastic film in improving soil hydrothermal conditions and promoting crop growth and development.

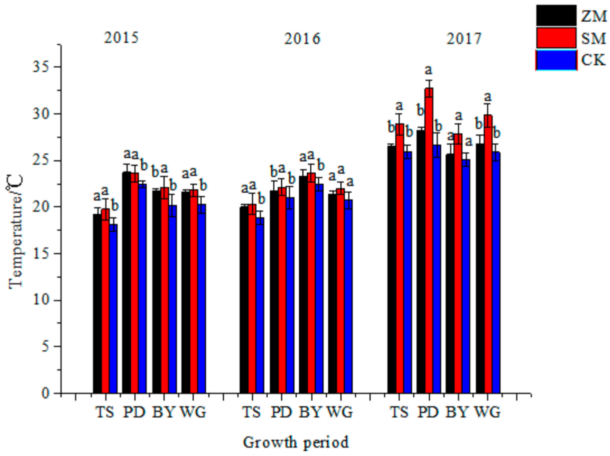

Figure 5. Changes of soil temperature in 0.1 m depth under different treatments.

3.3. Effect of Different Films Mulching on Rice Yield and Quality

As can be shown in Figure 6, compared with CK, ZM increased yield by 8.71%, 7.53%, and 9.02% in 2015, 2016, and 2017, respectively. The main reason is that the significant weed inhibition effect of ZM can effectively inhibit weed on the competition for crop moisture and nutrients, thereby increasing yield. There was no significant difference of the yield between each treatment in 2017, and the rice yield in 2017 was significantly reduced than that in 2015 and 2016. The phased low temperature in the spring of 2017 and the cold damage in the middle and late August of 2017 caused the slow seedling time longer and tillering delay, which finally affected the rice yield. The thousand-grain weight of ZM, SM, and CK were 18.99, 16.43, and 15.41 g, respectively in 2015 to 2017. The effect of different films mulching on rice quality is shown in Table 1. Compared with CK, the hardness of ZM decreased by 26.30% to 41.78%, and the adhesion of ZM increased by 9.39% to 12.39%, which was significantly different. The study showed that ZM had a certain yield increase effect, but there was no significant difference between ZM and SM, which was significantly higher than CK. The order of rice yield and thousand-grain weight were ZM > SM > CK. The rice hardness in plant fiber-based degradable film mulching cultivation was significantly lower than SM and CK. The adhesion of ZM was significantly higher than that of CK, and there was no significant difference between ZM and SM.

Table 1. Effect of different films mulching on rice quality.

Year	Treatment	Hardness (kg)	Adhesion (kg)
2015	ZM	1.53697b	0.26125a
	SM	1.84726a	0.23714a
	CK	2.17923a	0.22889b
2016	ZM	2.49404b	0.80321a
	SM	2.67785a	0.79208a
	CK	3.15009a	0.72782b
2017	ZM	2.13075b	0.24702a
	SM	2.55093a	0.23126a
	CK	2.87674a	0.21680b

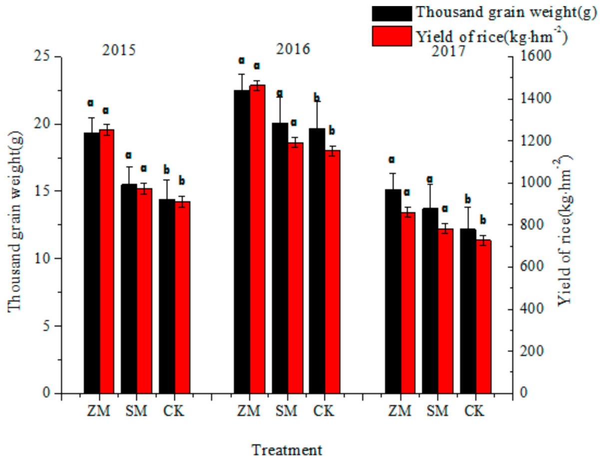

Figure 6. Effect of different films mulching on rice yield.

3.4. Effect of Different Films Mulching on Economic Benefit

The economic benefit of different films mulching is shown in Table 2. The cost of ZM was three times to that of SM. The output value of ZM in 2015 to 2017 was similar to that of SM and CK. However, the plant fiber-based degradable film mulching cultivation can improve soil fertility and agricultural labor productivity without the need to recycle residual film, spray herbicides, or artificial weeding, which can reduce the cost of topdressing and field management. The production cost, the reference price, and the profit of ZM was 2942.92 to 3169.73, 4500 to 5000, and 1330.27 to 2057.08 yuan/ton referring to the price of recycled paper film 5500 yuan/ton in the current market. If plant fiber-based degradable film mulching cultivation accounted for 50% of the China's rice planting area with plastic film mulching cultivation that reached 657,000 hectares in 2011, the consumption of ZM can reach 246,000 tons and the profit was 32.72464 to 50.60417 million [28]. The market price of rice produced by ZM is more than 10 times higher than that of ordinary rice. It can be seen that ZM had huge market potential and economic benefit.

Table 2. Effect of different films mulching on rice quality.

Year	Treatment	Yield ($kg{\cdot}hm^{-2}$)	Film Dosage [a] ($kg{\cdot}hm^{-2}$)	Film Cost [b] ($yuan{\cdot}hm^{-2}$)	Output Value [c] ($yuan{\cdot}hm^{-2}$)
2015	ZM	1251.62a	750	3750	4255.508a
	SM	1173.93a	90	1080	3991.362b
	CK	1142.67b	0	0	3885.078b
2016	ZM	1462.55a	750	3750	5001.921a
	SM	1390.89a	90	1080	4756.8438b
	CK	1352.37b	0	0	4625.1054b
2017	ZM	859.87a	750	3750	2665.597a
	SM	812.61a	90	1080	2519.091a
	CK	782.34b	0	0	2425.254a

[a] The basis weight of plant fiber-based film and plastic film mulching was 75 and 9 g/m^2, respectively; [b] The unit price of plant fiber-based film and plastic film mulching was 5.0 and 12.0 yuan·kg^{-1}, respectively; [c] The unit price of rice in 2015, 2016, and 2017 was 3.4, 3.42, and 3.1 yuan·kg^{-1}, respectively.

3.5. Film Degradation

It can be seen from Table 3 that the cracks of SM began to appear during the blossom fruit period. ZM began to crack in the panicle development stage, but there were significant differences in degradation rates in different years. The degradation rate of ZM in 2016 was faster than that in 2015 and 2017. Moreover, the degradation rate of ZM in the blossom fruit period in 2015 to 2017 reached the grade of 3, 4, and 3, respectively. The ZM had begun to show a small area crack at the position of transplanting rice seedlings in the panicle development stage after paddy mulching cultivation. At the blossom fruit period, most of the ZM had been degraded into fragments without large film existing, which reached the grade of film degradation rates 3 and 4. Although the degradation rate and degradation cycle of various degradable films are different due to the differences in raw material composition, additives, manufacturers, production requirements, and induction period design, the degradation process is basically similar mainly due to the influences of meteorological factors and soil environment [29–31].

Table 3. Effect of different films mulching on rice quality.

Year	Treatment	Tillering Stage	Panicle Development Stage	Blossom Fruit Period
2015	ZM	0 [a]	1 [b]	3 [d]
	SM	0 [a]	0 [a]	1 [b]
	CK	0 [a]	0 [a]	0 [a]
2016	ZM	0 [a]	2 [c]	4 [e]
	SM	0 [a]	0 [a]	1 [b]
	CK	0 [a]	0 [a]	0 [a]
2017	ZM	0 [a]	2 [c]	3 [c]
	SM	0 [a]	0 [a]	1 [b]
	CK	0 [a]	0 [a]	0 [a]

[a] 0: No crack; [b] 1: Cracks begin to appear; [c] 2: Hairline cracks appear in 25% of the film; [d] 3: Film appears 2.0–2.5 cm cracks.

4. Discussion and Conclusions

Compared with CK, the plant fiber-based degradable film and plastic film reduced the weed by 85.5% to 87.7% and 78.7% to 81.7%, respectively. After the rice field is covered with film, the number of weeds is significantly reduced, thereby eliminating the weeding workers and medicines in the rice field and reducing the soil nutrient consumption. The main reason is that the low light transmittance of the plant fiber-based degradable film blocked the photosynthesis of the weeds. Rice mulching cultivation has changed the living space of weeds and inhibited the occurrence of many weeds. It indicates that mulching cultivation of rice cultivation technology has a certain control effect on common weeds and dominant weeds in rice fields. In this study, no herbicide was sprayed in each treatment, and the plant fiber-based degradable film and plastic film had a significant herbicidal effect, and the herbicide could be reduced or not used in the cover cultivation [32].

Plant fiber-based degradable film mulching cultivation can increase the soil temperature of soil layer 0 to 0.1 m depth. In 2015 to 2017, rice yield with plant fiber-based degradable film increased by 8.71%, 7.53%, and 9.02%, respectively. However, the overall warming effect of the plant fiber-based degradable film is slightly lower than that of the plastic film, which may be related to the poor transmittance of the plant fiber-based degradable film to the plastic film. During the blossom fruit period of rice, the temperature increase of plant fiber-based degradable film was the lowest or even decreased, which may be related to the degradation performance of plant fiber-based degradable film and the decrease of external temperature [33].

Plant fiber-based degradable film can significantly reduce the hardness, increase its adhesion, and improve the eating quality of rice. Different films mulching had a certain impact on crop economic benefit. During the panicle developmental stage, the plant fiber-based degradable film began to crack, and by the blossom fruit period, the degradation rate reached the grade of 3 or 4. Although the degradation rate and intensity of various degradable mulch films are different, the degradation processes are basically similar.

Plant fiber-based degradable film mulching cultivation is equivalent to plastic film mulching cultivation in improving soil temperature. Plant fiber-based degradable film can not only exert the weed inhibition performance of plastic film, promote crop growth and development, accelerate the growth process, increase rice yield, improve rice quality, but also completely biodegrade without pesticides and residual pollution in the soil. Therefore, in order to alleviate the white pollution of plastic film, solve the problem of weed removal in paddy field, create a more suitable ecological environment, and improve the yield and quality of rice, it is extremely important and environmentally significant to replace the plastic film with plant fiber-based degradable film for practical production, especially for organic rice production. However, further research is needed on the economic cost and agronomic characteristics.

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