Degradability of biodegradable plastic films and its mulching effects on soil temperature and maize yield in northeastern China

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Abstract: Plastic film is an important resource in agricultural production, but it takes hundreds of years to degrade completely in natural environment. The large-scale use of plastic film will inevitably lead to serious environmental pollution. One way to solve the problem is to develop a substitutable mulching film, such as a biodegradable film that can ultimately be decomposed to water, carbon dioxide, and soil organic matter by micro-organisms. In this study, a 2-year experiment was conducted to determine the degradation properties of a biodegradable plastic film, including degradation rate, surface microstructure, tensile strength and elongation at break, and the effects of different mulching treatments on soil temperature and maize yield. The mulching experiment was conducted with three different biodegradable plastic films with different degradation rates, using a common plastic film and a non-mulched treatment as control. With the addition of the additives for degradation in the biodegradable plastic films, the degradation rates increased significantly, which were 7.2%-17.8% in 2017 and 18.1%-35.2% in 2018 after maize harvesting. However, the degradation occurred mainly on the ridge side. The decrease in tensile strength and elongation was proportional to the degradation rate of the degradable film. The SEM results indicated that the surface microstructures of the biodegradable films were loose and heterogeneous after maize harvesting. Biodegradable plastic film mulching increased the soil temperature at soil depths of 5 cm, 15 cm, and 25 cm, over the maize's entire growth period, by 3.1°C-3.2°C in 2017 and 1.2°C-2.1°C in 2018 compared with the non-mulched treatment. The biodegradable plastic film increased the maize yield by 10.4%-14.3% in 2017 and 11.6%-24.7% in 2018. The soil temperature and maize yield increases were statistically significant; however, with respect to maize qualities, there were no statistically significant increases among the five treatments. This study shows that biodegradable plastic film can be used as a substitute for common plastic film. However, the ingredients in biodegradable plastic films should be improved further to ensure that they can be degraded completely after crop harvest.

Keywords: biodegradable plastic film, film mulching, degradation properties, soil temperature, maize yield

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1 Introduction

Northeast China is the most important maize-producing area in China. The maize planting area and yield in Northeast China account for 31% and 34% of the entire country's maize planting area and yield, respectively[1]. However, chilling damage and frost in spring in some parts of Northeast China[2], plus the lack of precipitation or an uneven distribution of precipitation during the year in most parts of the region, cause a reduction in maize yield. Numerous studies had shown that plastic film mulching had significant effects on soil temperature and moisture[3,4]. Film mulching can also help crops reach maturity earlier and increase yields[5-7]. Polyethylene, a synthetic polymer material that is synthesized mainly from petroleum[8], is the main component of common plastic film. In nature, it takes hundreds of years to be completely degraded[9]. Such large-scale use, coupled with recycling difficulties, leads to a massive amount of residual film remaining in the field, which pollutes the landscape and causes soil hardening that ultimately affects crop root growth and results in a yield reduction[10]. In Xinjiang, China, where the used amount of film is relatively high, the maximum residual amount of plastic film has reached 502.2 kg/hm^2, which is 6.7 times higher than the national standard (75 kg/hm^2)[11]. Therefore, there is an urgent need to solve the plastic film residue problem. At present, there are mainly two ways to solve this problem: one is to increase the amount of recycled plastic film; the other is to develop and popularize degradable plastic film[12]. The plastic film recycling process is time and labor consuming, which faces the problem of high difficulty in recycling broken plastic film and low recycling rate. Therefore, developing degradable plastic film as a substitute for common plastic film is an important means to reduce pollution from common plastic film[13].

Degradable plastic film degrades under the effects of sunlight (ultraviolet rays) and soil micro-organisms. It eventually decomposes into water and carbon dioxide, which are harmless to the environment. After crop harvesting, degradable plastic films do not rely on manual recycling, which means the saving on time and labor[14]. A degradable plastic film's degradation process is

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influenced by environmental factors, and its degradation degree varies with different climates[15]. In addition, a plastic film's degradation rate could also be controlled by changing its ingredients or thickness[16]. Degradable plastic films were widely used to crops, including strawberry, millet, and maize[17-19]. The Mater-Bi biodegradable film, which was used in southern France, had the same initial characteristics as common film; however, its near-infrared (NIR) transmittance was higher than that of common film. Therefore, even if the biodegradable film was partly degraded, its covering effect, which could sufficiently meet the heat needs of crops during the growing period, was still better than that of common film[20]. In Spain, biodegradable plastic film was found to be rapidly degraded, and its soil-temperature-increasing effect was found to basically disappear during tomato's late growth stage with no effort on the yield and quality of tomato[21]. In Xinjiang, China, degradable plastic film was found to have the same heating effect as common plastic film, which mainly acts in the 0-15 cm soil layer. The variation in soil temperature decreased as the soil depth increased and was relatively stable at a depth of 25 cm[7]. In northwest China, the length and density of taproot and the lateral root of winter rape treated with degradable plastic film were found to be significantly higher than those treated with common plastic film, although there was no significant difference in yield and water use efficiency between them. Furthermore, degradable plastic film significantly reduced the amount of erucic acid and glucosinolate, which were harmful to human[22]. Biodegradable plastic film has been developed in recent years which combines the advantages of oxidative degradation and biodegradation[23]. Liu et al.[24] showed that the average soil temperature in the 0-25 cm layer and the soil water storage in the 0-60 cm layer with biodegradable film mulching were significantly higher than those without mulching in a maize field. The maize seedling rate and yield were increased by 16.2% and 35.2%, respectively, compared to the maize field without mulching.

At present, most of the studies on the degradation process of biodegradable plastic film have been based on qualitative observations[25-27]. Few studies have considered quantitative changes in the mechanical properties of biodegradable plastic film at different mulching times. Mechanical properties are important physical characteristics in the film degradation process, as their changes are closely related to the degree of degradation. In this study, three kinds of biodegradable plastic film with different degradation rates were tested, to: (1) study their mulching effect in the field and their degradation performance through testing the mechanical properties at different mulching times; and (2) select the biodegradable plastic film with the appropriate degradation rate by comprehensively evaluating the films' mulching effect and degradation performance.

2 Materials and methods

2.1 Experimental site

A 2-year field experiment (from May 2017 to October 2018) was conducted at the Shenyang Agricultural University experimental station in Liaoning, Shenyang (41°44'N, 123°27'E, 44.7 m + mean sea level (MSL)), China. The soil in the experimental field is a humid loam that equally distributed and typical of this area. The average soil bulk density of the 0-100 cm soil layer is 1.41 g/cm^3. The average water-holding capacity is 0.38 cm^3/cm^3. The permanent wilting is 0.18 cm^3/cm^3. During the experiment, the average depth to groundwater was 4.5 m.

2.2 Experimental design and field management

Five treatments were established in 2017 and 2018: (1) a biodegradable film with a fast degradation rate treatment (DM1); (2) a biodegradable film with a moderate degradation rate treatment (DM2); (3) a biodegradable film with a slow degradation rate treatment (DM3); (4) a common plastic film treatment (PE); and (5) a non-mulching treatment as a control (CK). Different degradation rates of biodegradable film were achieved by adding different proportion of degradation masterbatch in the process of plastic film production, more masterbatch led to faster degradation rate. The three kinds of biodegradable plastic film and the common film were manufactured by Shandong Tianzhuang Eco-Benign Plastics Technology Co., Ltd, and were 120 cm wide and 0.008 mm thick. Since the degradation performance did not meet the expectations in 2017, additional additives were added to the biodegradable film in 2018 for better degradation. The five treatments were repeated three times and arranged in a randomized block design. The area of each individual plot was 44.8 m^2 (14 m×3.2 m), with three ridges. Traditional large-ridge double-lines planting method (a ridge platform width of 80 cm and a furrow width of 40 cm) was applied. The theoretical planting density of maize (cv. Liangyu 777) was 82 500 plants/hm^2.

Maize was planted on 3 May 2017 and 28 April 2018 using a small seeder. The crop was only fertilized with compound fertilizer, which contained 243 kg/hm^2 N, 135 kg/hm^2 P, and 117 kg/hm^2 K. Then, the crop was sprayed with herbicides and covered with film (using new film in each season) on the same day. Rainfall was the crop's only source of water during the entire experiment. The field management measures were consistent with local farming practices.

2.3 Sampling and measurements

2.3.1 Degradability

In this study, weight loss rate was used to describe the degradation process of biodegradable film. First, new film samples (1 m×1.2 m) were cut from the four kinds of film, and the operation was repeated three times before mulching. Then, a ridge (1 m in length) was randomly selected from a fixed ridge (to prevent the damage the film caused to a large area from affecting the experiment) of each individual plot. All of the film in the area, including the buried film, was gathered every 30 days after sowing (DAS). The samples were cleaned with an ultrasonic cleaner, dried, and weighed. Finally, the weight loss rate of the film was calculated.

2.3.2 Mechanical properties

Samples (30 cm × 40 cm), with three replicates, were cut from the four kinds of film before mulching. Then, samples were randomly selected from the top of a fixed ridge (the same as above) of each plot after 90 and 120 DAS. The same operation was performed on the side of the fixed ridge after 120 DAS. All of the samples were cleaned using an ultrasonic cleaner. After drying, their tensile strength and elongation at break were tested using an American Instron-5567A. According to the method for testing the tensile properties of plastic film (GB-13022, China), the tensile strength of plastic film is expressed as σ_t (MPa). The formula for calculating tensile strength is as follows:

$$\sigma_t = p/b\times d \quad (1)$$

where, p is the breaking load (N); b is the width of the sample, mm; and d is the thickness of the sample, mm.

The elongation at break of a film is expressed as ε_t (%). The formula for calculating elongation at break is as follows:

$$\varepsilon_t = (L-L_0)/L_0 \quad (2)$$

where, L_0 is the primitive marking distance, mm; and L is the marking distance when the sample breaks, mm.

2.3.3 Soil temperature

Soil temperature was measured by a group of curved tube geothermometers, which were placed on the top of the ridge in each plot. The measurement depths were 5 cm, 15 cm, and 25 cm. The measurement times were 07:00, 14:00, and 18:00 with an interval of 3-5 DAS.

2.3.4 Yield and seed quality

The yield of each individual plot was determined when the maize was ripe. The maize's seed quality was determined using an Infratec TM 1241 from Denmark.

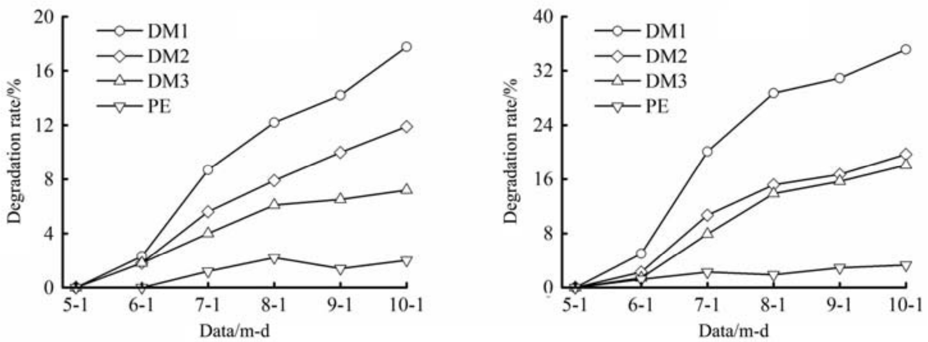
3 Results

3.1 Degradation rate of biodegradable film

The degradation rate of the biodegradable film increased significantly from 30 to 60 DAS (Figure 1). In 2017, the degradation rates of DM1, DM2, and DM3 were 17.8%, 11.9%, and 7.2%, respectively. In 2018, the degradation rates of DM1, DM2, and DM3 were 35.2%, 19.7%, and 18.1%, respectively. At the end of the growth period, the maximum degradation rate increased by 17.4% in 2018 compared with that in 2017. The degradation rate of the plastic film was effectively improved by increasing the content of additives for degradation. The common plastic film had nearly no degradation during the 5 months growth period of maize. The decrease in its weight was caused mainly by seedling holes and human factors.

3.2 Surface microstructure

The common plastic film and biodegradable film had a complete and uniform surface microstructure before use, which indicated that the components of the film had good compatibility (Figure 2). In 2017, the change in the microstructure of the biodegradable film before and after use was small because the degradation degree of the three kinds of biodegradable film was low. With faster degradation rate of the film, the surface microstructure became rougher.



a. 2017 b. 2018

Note: DM1: biodegradable film with a fast degradation rate; DM2; biodegradable film with a moderate degradation rate; DM3: biodegradable film with a slow degradation rate; PE: common plastic film.

Figure 1 Degradation rate of film at different mulching times in 2017 and 2018

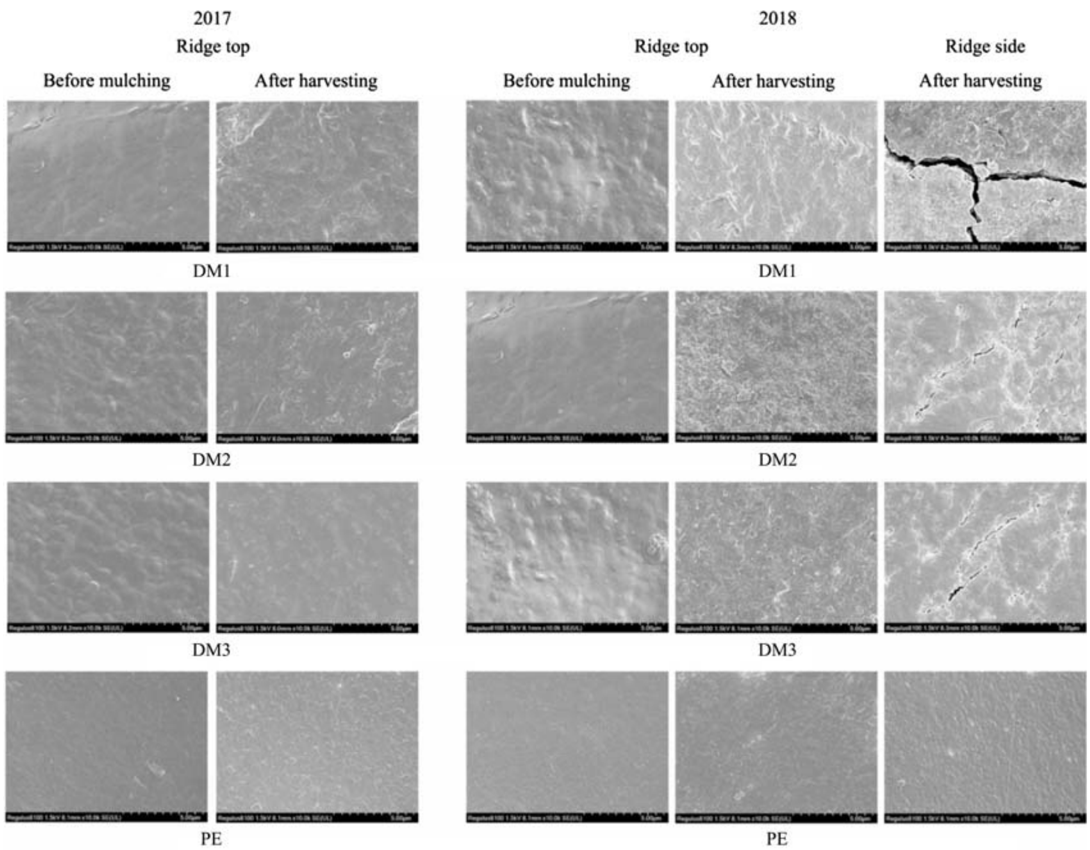


Figure 2 Surface microstructure of the film at different mulching times in 2017 and 2018 (6000X)

In 2018, the surface microstructure of the film after use became rougher than that in 2017 due to the increase in additives for degradation. In addition, the microstructure of the ridge-side film, in which there were some cracks, had changed more obviously than that of the ridge-top film. This was particularly the case for DM1, where the ridge-side film had completely degraded after the end of the growing period because of its fast degradation rate. Due to the slow degradation rates of DM2 and DM3, there were many small cracks on the surface of the film, and the microstructure of the film was more complete than that of DM1.

The common plastic film did not crack after the 2-year experiment, which was different from the biodegradable film. However, the surface of the common plastic film changed from smooth to rough, which was mainly caused by external pulling and UV irradiation during the experiment.

3.3 Mechanical properties

In 2017, the loss rates of tensile strength in DM1 were 25.6% and 30.4% after 90 and 120 DAS, respectively, on the ridge-top film. In 2018, the loss rates of tensile strength in DM1 were 32.3% and 38.6% after 90 and 120 DAS, respectively, on the ridge-top film (Table 1). In 2017, the loss rate on the ridge-side film of DM1 was 59.0% after 120 DAS. In 2018, the loss rate on the ridge-side film of DM1 was 100% after 120 DAS. The loss rate of the film's tensile strength on the ridge side was significantly higher than that on the ridge top. For the same mulching period, the tensile strength loss rates in DM2 were 16.5%, 20.3%, and 50.7% respectively in 2017 and 20.1%, 26.2%, and 55.0% respectively in 2018, while the tensile strength loss rates in DM3 were 9.8%, 19.1%, and 45.6% respectively in 2017 and 19.2%, 26.2%, and 54.1% respectively in 2018. Overall, DM1 showed the maximum loss rate because it had the fastest degradation rate, and DM3 showed the minimum loss rate because of its lowest degradation rate.

The change in elongation at break of the three kinds of biodegradable film was consistent with the tensile strength. After 120 DAS, the elongation at break of the ridge-top film in DM1, DM2, and DM3 decreased by 10.4%, 13.5%, and 5.0% respectively in 2017, and decreased by 21.0%, 13.4%, and 12.5% respectively in 2018. The elongation at break of the ridge-side film decreased by 71.7%, 55.6%, and 51.0% respectively in 2017, and decreased by 100%, 68.8%, and 66.0% respectively in 2018. The loss rate of the ridge-side film was higher than that of the ridge-top film. Overall, the loss rate was highest in DM1 and the lowest in DM3, which was consistent with the results on tensile strength.

Table 1 Changes of tensile strength and elongation at break of different biodegradable plastic films at different mulching times in 2017 and 2018

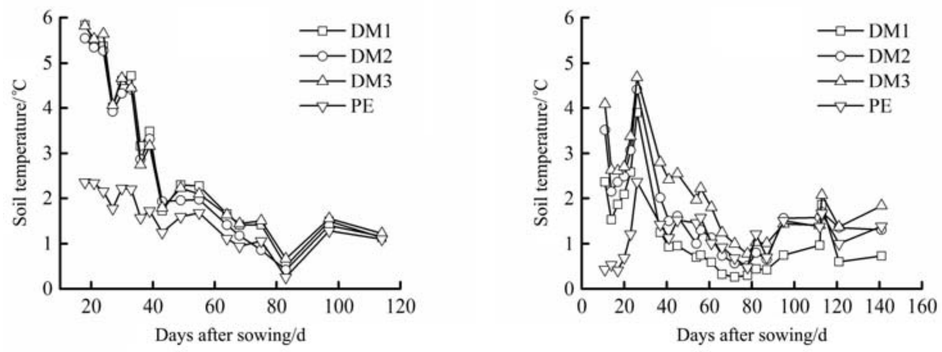
Years	Mechanical property	Treatment	Top of ridge			Side of ridge
			Before mulching	90 DAS	120 DAS	120 DAS
2017	Tensile strength/MPa	DM1	29.66±1.53b	22.06±1.50b	20.64±0.85c	12.17±0.85c
		DM2	30.81±0.58ab	25.72±1.19a	24.56±0.93b	15.20±0.52b
		DM3	29.12±1.24b	26.28±1.71a	23.57±0.73b	15.84±0.50b
		PE	32.16±0.56a	—	31.49±0.85a	30.38±0.48a
	Elongation/%	DM1	385±5b	370±9b	345±13b	109±17c
		DM2	414±8a	400±9a	358±11ab	184±9b
		DM3	400±13ab	390±5a	380±15a	196±16b
		PE	400±9ab	—	380±9a	380±10a
2018	Tensile strength/MPa	DM1	29.12±0.81b	19.72±0.80b	17.87±0.83c	0±0.00d
		DM2	29.50±0.54b	23.56±0.70a	21.76±0.47b	13.28±0.63c
		DM3	30.25±0.91ab	24.45±0.55a	22.32±0.47b	13.87±0.47b
		PE	31.58±1.13a	—	31.02±0.39a	30.47±0.26a
	Elongation/%	DM1	405±13a	350±10b	320±10c	0±0c
		DM2	410±10a	370±9a	355±9b	120±20b
		DM3	400±14a	375±10a	350±5b	140±18b
		PE	415±5a	—	400±13a	390±10a

3.4 Safety period of film mulching

The crop safety period through plastic film mulching refers to the appropriate number of DAS of film mulching for a crop in a certain area. It is used to estimate the amount of plastic film mulching time and avoid a negative effect on the farmland environment and the crop. In the field of degradable plastic film, the crop safety period through plastic film mulching means that the structure of the degradable film remains basically intact during the safety period to maintain a good soil-temperature-increasing effect. When the safety period is over, the degradable film begins to crack, so that it will not have a negative effect on the subsequent growth of the crop.

The temperature-increasing effect is an important property of plastic film mulching, and the effect of temperature on crops is much greater than other environmental factors. Therefore, plastic film mulching's function is considered to be basically disappeared when its temperature-increasing effect disappears or almost disappears.

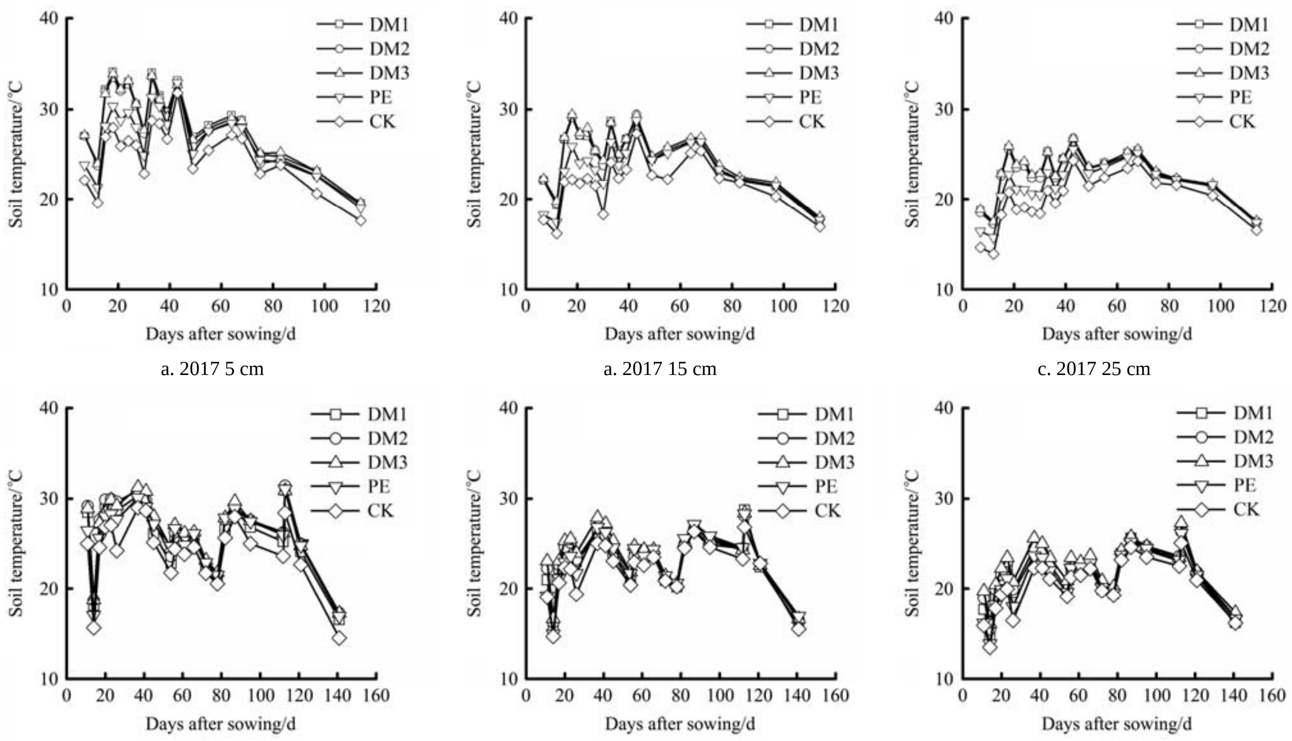
The temperature increase value gradually decreased with time and reached the minimum value at 83 DAS in 2017 and 78 DAS in 2018 (Figure 3). The temperature increase values in DM1, DM2, DM3, and PE were 0.5°C, 0.4°C, 0.7°C, and 0.3°C higher than that in CK respectively in 2017, and 0.3°C, 0.5°C, 0.8°C, and 0.5°C higher than that in CK respectively in 2018. In conclusion, it was determined that the crop safety period through film mulching of maize was approximately 80 DAS in this area.



a. 2017 b. 2018

Note: DM1: biodegradable film with a fast degradation rate; DM2: biodegradable film with a moderate degradation rate; DM3: biodegradable film with a slow degradation rate; PE: Common plastic film.

Figure 3 Temperature increase value of different films in 2017 and 2018



a. 2017 5 cm a. 2017 15 cm c. 2017 25 cm

d. 2018 5 cm e. 2018 15 cm f. 2018 25 cm

Note: DM1: biodegradable film with a fast degradation rate; DM2: biodegradable film with a moderate degradation rate; DM3: biodegradable film with a slow degradation rate; PE: Common plastic film; CK: No mulching.

Figure 4 Temperature changes in the 5 cm, 15 cm, and 25 cm soil layers during the entire growth period of maize under different film mulching treatments in 2017 and 2018

3.5 Soil temperature

The soil temperature fluctuated greatly in different layers, and the difference among each treatments was significantly greater at the seedling stage of maize than at other periods. The soil temperature in the 5 cm, 15 cm, and 25 cm layers in PE was significantly lower than that in DM1, DM2, and DM3 and significantly higher than that in CK, and the differences observed among the treatments gradually decreased as the soil depth increased. For example, in DM1, the average soil temperatures in the 5 cm, 15 cm, and 25 cm layers were 4.6°C, 4.3°C, and 4.0°C higher than CK respectively in 2017, and 2.1°C, 1.7°C, and 1.5°C higher than CK respectively in 2018 during the seedling stage.

As time went on, the film became crisp, its tensile strength decreased and, coupled with some cracks due to degradation, its temperature-increasing effect decreased. However, the fluctuation in soil temperature in each layer under the different mulching treatments was more stable than that at the seedling stage, and there was no significant difference between the biodegradable film and the common plastic film. There was no significant difference in the temperature increase value among DM1, DM2, and DM3 due to their low degradation rate in 2017. However, in 2018, the difference was obvious because the degradation rate in 2018 was higher, and the temperature increase value was the highest in DM3 and the lowest in DM1.

At the heading stage (approximately 65 DAS), the fluctuation range of soil temperature in each layer and the difference in soil temperature among the treatments were further reduced because of canopy coverage. The average soil temperature in the 5 cm, 15 cm, and 25 cm layers was 3.2°C, 3.1°C, and 3.2°C respectively in 2017, and 1.2°C, 1.7°C, and 2.1°C respectively in 2018 during the entire growth period.

3.6 Maize yield and quality

The maize yields in DM1, DM2, DM3, and PE were increased by 14.3%, 14.3%, 10.4%, and 13.2% respectively, in 2017 and by

11.6%, 24.7%, 22.4%, and 19.1% respectively in 2018 compared with CK (Table 2). There was no significant difference among the three kinds of biodegradable film and the common plastic film. The maize yield was the highest in DM2 in 2017 and 2018 and the lowest in DM1 in 2018, which did not differ significantly from CK.

There were no significant differences in seed protein, starch, and oil among the different treatments. Among them, the protein content in the three biodegradable film treatments decreased as the degradation rate increased, but the difference was not significant.

Table 2 The maize yield and quality under the different treatments in 2017 and 2018

Years	Treatment	Protein/%	Starch/%	Oil/%	Yield/kg·hm^{-2}
2017	DM1	8.2±0.15b	71.6±0.46a	3.9±0.12a	11762.19±60.62a
	DM2	8.4±0.15ab	72.0±0.29a	3.5±0.12b	11762.77±382.57a
	DM3	8.7±0.25a	71.4±0.30a	4.0±0.15a	11362.75±37.27a
	PE	8.3±0.17ab	71.7±0.31a	3.9±0.17a	11648.22±247.12a
	CK	8.4±0.40ab	71.4±0.50a	3.9±0.10a	10293.92±283.15b
2018	DM1	8.1±0.06c	72.1±0.20a	3.8±0.12a	10129.27±307.51ab
	DM2	8.3±0.12bc	72.3±0.25a	3.8±0.10a	11314.53±677.63a
	DM3	8.5±0.10a	71.9±0.40a	3.9±0.06a	11107.04±786.10a
	PE	8.3±0.06bc	71.7±0.87a	3.8±0.06a	10803.39±1119.10a
	CK	8.4±0.20ab	71.6±0.35a	3.7±0.06a	9074.49±336.00b

4 Discussion

4.1 The degradability of biodegradable film

Biodegradable plastic film degrades gradually under environmental effects, including precipitation, sunlight, and soil micro-organisms after mulching. Studies had shown that degradable film degrades rapidly after the induction period, and the macromolecular polymer in the film was gradually decomposed by soil micro-organisms into a small molecular polymer[28]. The content of additives for degradation is an important factor in a degradable film's properties. Yuan et al.[29] found that biodegradable film with a high content of additives for degradation had a faster degradation rate than biodegradable film with a lower content of additives for degradation, which was consistent with the results of this study. The degradation rate of the biodegradable film accelerated after 30 DAS but slowed down after 60 DAS after mulching. This was due to the fact that the full crop canopy weakened the damaging effects of precipitation, ultraviolet rays, and wind on the degradable film, which ultimately resulted in the degradation of film being insufficient after maize harvesting.

A SEM is an electronic optical instrument that allows for the observation of changes in the surface microstructure of materials. The degradation degree of the degradable plastic film was qualitatively judged by changes in surface microstructure on behalf of the compatibility of the film's components. Qiao et al.[30] indicated, through SEM observations, that the surface microstructure of the biodegradable film was uniform before mulching, which meant that the compatibility of the film's composition materials was good. After 170 DAS of mulching, there were holes with different sizes on the surface of the film that were caused by the effects of ultraviolet rays, wind, and precipitation. The SEM results showed that the surface heterogeneity increased as the degradation rate of the plastic film increased, and the heterogeneity in the ridge-side film was more evident than that in the ridge-top film because of its faster degradation rate.

A degradable plastic film needs to have enough tensile strength and elongation at break to ensure the integrity of its structure during the early stage of crop growth and maintain a good covering effect. Faradilla et al.[31] reported that a biodegradable plastic film made from nano-cellulose separated from the outer layer of a banana (Musa nana) pseudostem had remarkable tensile strength, but its elongation at break was only 1.7%, which meant that it was vulnerable to wind and precipitation that ultimately led to a reduction in the covering effect. In this study, the tensile strength of the biodegradable film was found to be slightly lower than that of the common plastic film. However, its elongation at break was significantly higher than that of the common plastic film, which ensured a sufficient covering effect. Liu et al.[32] studied the degradation process of biodegradable film in a maize field. The results showed that the mechanical properties of the biodegradable film decreased rapidly after it came into contact with soil. The tensile strength of the biodegradable film decreased by 61.9% after 100 DAS of cover and 72.5% after 140 DAS of cover. In other words, the tensile strength increased as the degradation process developed. This study obtained the consistent results, and also found that the rate of loss of mechanical properties in the biodegradable film with a fast degradation rate was higher than in the biodegradable films with a lower degradation rate. In addition, consistent with the SEM results, the rate of loss of mechanical properties in the ridge-top film was significantly higher than that in the ridge-side film. There are two possible reasons for this: the ridge-top film was in good contact with the soil surface, which accelerated the erosion by soil micro-organisms of the film; or the ridge-top film was under better illumination conditions than the ridge-side film, which caused a violent photocatalysis reaction.

4.2 Soil temperature

The safety period of plastic film mulching determines the optimum amount of time that plastic film can be mulched[33]. The study of Qin et al.[34] in Shandong Province, China showed that the difference in daily average soil temperature in the 10 cm soil layer between a treatment with mulching and a treatment without mulching was obvious in the early stage of potato growth, and became smaller as time elapsed, ultimately reached 0 around 70 DAS. This indicated that the crop safety period of film mulching was approximately 70 DAS in this area. In this study, the temperature increase value of film mulching reached its minimum at approximately 80 DAS, which was the crop safety period of biodegradable mulching film in the local area.

The biodegradable film had the same warming effect as the polyethylene film before it cracked. A film that had degraded and cracked into fragments that were in close contact with the soil's surface was found to still have a temperature-increasing effect[35]. Some studies had also reported that the temperature-increasing effect of degradable film mainly acted on the 0-15 cm soil layer. In other words, the temperature increase value and the range of variation in soil temperature decreased as the soil depth increased, and the temperature-increasing effect weakened after cracks appeared[36,37]. This study obtained similar results: the temperature increase value of the degradable plastic film decreased as the soil depth and film degradation rate increased.

The duration of degradation film's warming effect is also related to crop species. Sun et al.[38] showed that the soil temperature in a field with peanut crop that had been treated with biodegradable film was significantly higher than that with non-mulching treatment during the entire growth period, mainly because the peanut canopy was small and the film could absorb solar radiation directly. However, different conclusions have been drawn in tall-stem crops, such as maize. Yin et al.[26] found that biodegradable plastic film had the same warming effect as PE during maize's early growth period. However, different from peanut, maize's canopy intercepts sunlight after the jointing stage. Therefore, the temperature increase value of biodegradable plastic film was found to be significantly lower than that of common plastic film.

In this study, the soil temperature in biodegradable plastic film mulching was found to be significantly higher than that in a non-mulching treatment in the early growth stage (0-40 DAS). In the middle and late growth stages, the covering effects of the film were weakened because of degradation and maize canopy coverage. For the crop's entire growth period, the warming effect of three kinds of biodegradable plastic film was significant in the maize's early growth stage, but not significant in the middle and late stages of maize growth compared with PE and CK. These results are consistent with those of Li et al.[39] and Hu et al.[40].

4.3 Seed yield and quality

The studies of Zhang et al.[41] and Siwek et al.[42] showed that there was no significant difference in yield increase between degradable plastic film and common plastic film, which was consistent with the conclusions of this study. Although the degradation of degradable plastic film would lead to a decrease in the mulching effect, its temperature-increasing effect was still better than that of the common plastic film, and the broken part of the degradable plastic film was favorable to rainfall infiltration and an increase in soil water storage capacity. Therefore, the yield obtained with the biodegradable plastic film treatment was not significantly different from that obtained with the common plastic film treatment. Yin et al.[26] studied the effects of three kinds of degradable plastic film with different degradation rates on maize growth, and the results showed that the degradable plastic film with the medium degradation rate had the most obvious covering effect on maize growth, and produced the largest increase in yield and the highest economic benefit. This is consistent with conclusion from this study that the DM2 treatment produced the largest yield increase. In 2018, due to the fast degradation rate of DM1, cracks appeared in the film during the early stage of maize growth, which affected the covering effect and eventually led to a lower yield increase than that of DM2, DM3, and PE. If the degradation rate of the plastic film is too high, its covering effect will be reduced. This phenomenon suggested that it is important to select the biodegradable film with an appropriate degradation rate to guarantee the effect on increasing yield of degradable plastic film.

Li et al.[43] found non-significant differences in the effect of plastic film mulching on maize quality among years. This study obtained a similar result, only protein content was insignificantly decreased with the increased degradation rate of the film.

Compared with the non-mulching treatment, biodegradable film significantly increased the soil temperature at the early stage of maize growth in the 2-year experiment. Except DM1 treatment in 2018, the yields of maize under various film treatments were significantly higher than that in the non-mulching treatment. In terms of yield increase and degradation performance, DM2 treatment in 2018 was better than DM1 and DM3 treatment. If the degradation rate of DM2 is further accelerated, it might be degraded too early like DM1 and reduce the effect on increasing yield.

5 Conclusions

After the biodegradable plastic film was degraded, the surface microstructure of the film was obviously rougher, and its tensile strength and elongation at break had decreased. The degradation performance of the ridge-side biodegradable film was better than that of the ridge-top biodegradable film because it was susceptible to external environmental effects. The crop safety period of the film in the local area was approximately 80 DAS. In other words, the biodegradable film needed to maintain its structural integrity for 80 DAS to ensure a sufficient covering effect on the maize, and then to complete its degradation quickly. The biodegradable plastic film significantly increased the soil temperature in the 5-25 cm soil layer in the maize's early growth stage, promoted the maize's growth, and had a similar yield-increasing effect with the common plastic film. Therefore, they could be used to replace common plastic film in agricultural production, and DM2 (2018) is considered as the optimal treatment and more suitable to local conditions than others in this experiment.

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