Effects of biodegradable mulching films on soil hydrothermal conditions and yield of drip-irrigated cotton (*Gossypium hirsutum* L.)

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Abstract: The pollution of cotton fields by residual films is serious on ground that has been subjected to long-term drip irrigation in Xinjiang, China, and biodegradable mulches are therefore advocated as an alternative to plastic ones. In this study the mulching with biodegradable films under drip irrigation conditions in the extremely arid region of Xinjiang was investigated to determine the effects on soil hydrothermal conditions and cotton (*Gossypium hirsutum* L.) yield over two consecutive years (2019–2020) using plastic mulch made from polyethylene (PE) film and four types of biodegradable films, including black opaque oxidation-biodegradable film (M1), colorless transparent oxidation-biodegradable film (M2), black opaque fully biodegradable film (M3) and white translucent fully biodegradable film (M4), which had different levels of biodegradability (i.e. different degradation times and rates). The biodegradability, soil water contents, soil temperatures and cotton yields were compared between the degradable (M1 to M4) and PE films. The results indicated that M2 was degraded the quickest and showed the highest degree of degradation compared with the other degradable films and PE films. The degradation rates of the various mulching films were ranked in a descending order as M2, M4, M1, M3 and PE, but the PE mulch exhibited the best performance in terms of soil water and heat conservation throughout the growth period. The soil heat preservation and moisture conservation performance under biodegradable films mulching at the cotton seedling stage and budding stage was similar to that of PE film. The average soil temperature at a depth of 5 cm under mulching with the degradable films was 2.66℃-5.06℃ ($p<0.05$) lower than that under traditional PE films at the flowering stage. At the late stage of cotton growth, the water content of shallow soil mulched with PE film was better for plant grown than that under the biodegradable films. The effect of film degradation on the shallow soil water content was much greater than that in deep soil, especially at a depth of 0-40 cm. However, in all treatments, the seedling rate and growth index of cotton under M2 were equivalent to that found under the PE film. Moreover, the cotton yield using M2 was slightly higher than that for the PE film. Compared with the PE film, the yield of cotton mulched with M1, M3 and M4 was decreased by 7.50%, 6.45% and 2.83% in 2019, and 9.82%, 6.48%, and 2.13%, in 2020, respectively. Therefore, based on the performance in improving cotton yield and maintaining soil moisture, the biodegradable transparent film (M2) with an 80 d induction period is recommended as a competitive alternative to plastic mulch to enhance crop yield and control soil pollution.

Keywords: arid environment, biodegradable films, cotton yield, oasis agroecosystem, soil temperature, soil moisture
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1 Introduction

Xinjiang, in northwest China, is the largest cotton (*Gossypium hirsutum* L.) growing region in China[1]. This area is part of a typical temperate continental climate zone. The annual rainfall in this region (50-250 mm/a) cannot meet the potential demand caused by evaporation (>1000 mm/a)[2,3]. Therefore, the shortage of water has become an important factor in limiting agricultural development in Xinjiang. Moreover, nearly one-third of the existing cultivated land is facing the hazards of salinization and secondary salinization[4]. To ensure the sustainable development of agriculture in this region by improving irrigation efficiency and controlling secondary salinization, surface drip irrigation under mulch films (i.e., mulched drip irrigation) has been in place since

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the 1990s[5,6]. Drip irrigation under mulch film is the integration of drip irrigation technology and plastic film mulching-based cotton planting technology. Plastic film mulching reduces soil water evaporation, has a good water conservation effect and has far-reaching significance in agricultural water saving[7-9]. However, the application of drip irrigation under plastic film has led to a sharp increase in the amount of plastic film used in China[10-13]. The global usage of agricultural films, including plastic films, rose from 4.4 million t in 2012 to 7.4 million t in 2019 and is predicted to continue to increase, with China and the Middle East being the major markets[14-16].

Moreover, with the large-scale application of drip irrigation technology under film, varying degrees of residual film pollution have occurred on farmland that has been covered in plastic over a long period in China[17]. According to previous studies, the average accumulation of residual film was 265.3 kg/hm^2 in the cotton fields of Xinjiang, and this was 4.5 times higher than the national average[18]. The amount of residual film in drip-irrigated cotton fields is increasing year on year, accounting for 60.7% of the total residual film in Xinjiang[19,20]. He et al.[14] studied six cotton fields that had been subjected to drip irrigation under film over different lengths of time (5, 9, 11, 13, 15 and 19 years) in the Shihezi area and found that the residual film densities were 127.11, 215.85, 250.63, 294.17, 327.83, and 348.83 kg/hm^2, respectively. The amount of residual film increases at a rate of 16.37 kg/hm^2 per year, and it is predicted that the residual film density on fields that undergo drip irrigation under film for 30 years will reach 419.19 kg/hm^2[21]. Despite the positive effects on crop yields, plastic mulches do not readily biodegrade and may even be non-degradable[22]. Years of continuous mulching have promoted the accumulation of plastic film fragments in soil, causing serious residual film pollution, which has greatly affected the sustainable development of ecological agriculture[23]. Furthermore, the release of plastic fragments from croplands has been recognized as a primary source of plastic accumulation in the sea[24]. Residual film in the soil changes the soil's physical properties, affects soil permeability, hinders water and fertilizer migration and microbial activity, affects seed germination, seedling emergence and crop root growth, and finally leads to reduced crop yields[25]. Crop yields have been shown to decrease with the increased accumulation of residual film[26]. For example, it was found that when the amount of residual film reaches 240 kg/hm^2, crop yields decrease significantly[27]. Hence, the 'white revolution' which should have brought the gospel to modern agriculture has become 'white pollution'[28].

Biodegradable films are composed of polysaccharides with low permeabilities and harmless decomposition products (mainly water and carbon dioxide)[29,30]. This means they can be incorporated directly into the soil after harvest and are biodegraded by soil microorganisms[31]. The application of degradable films can prevent the residual film from entering the soil at the source, so degradable films would be a better alternative to traditional plastic mulching film[1]. Additionally, the period over which biodegradable films degrade can be controlled to meet the growth needs of crops[23]. Research into the effect of biodegradable plastic mulching film has been carried out on a variety of crops in many places. For example, following mulching with drip irrigation for 2 a, cotton yield showed no significant difference between plots covered with polyethylene (PE) film (5722 kg/hm^2) and those under thicker polybutyrate adipate terephthalate film (5699 kg/hm^2)[1]. Furthermore, yields from corn mulched with plastic and biodegradable films increased by 19.96% and 19.67%, respectively, while water use efficiency increased by 32.08% and 31.81%, respectively[32]. Biodegradable and plastic films both have significant effects on soil water conservation and corn yields, with no large difference between them[32]. In Brazil, biodegradable film (made from polybutylene adipate-co-terephthalate) provided efficient mulching for strawberry production, because it produced fruits that had a similar weight and quality to those grown using PE film[33]. In the North China Plain, a field experiment using biodegradable film instead of PE film demonstrated that the accumulation, transport and transfer efficiency of dry matter and the grain yield obtained under treatment with a biodegradable black film increased significantly by 21.0%, 33.3%, 21.4%, and 12.6%, respectively[34]. Moreover, the application of biodegradable films has been found to improve farmland microclimates and promote crop growth. However, there are also some negative effects associated with the use of biodegradable film mulching. Compared with PE film, the biodegradable film shows poor performance in improving soil temperature, water retention and yield[35]. Furthermore, in terms of overall economic benefits, it is not clear whether biodegradable film can replace PE film in agricultural production.

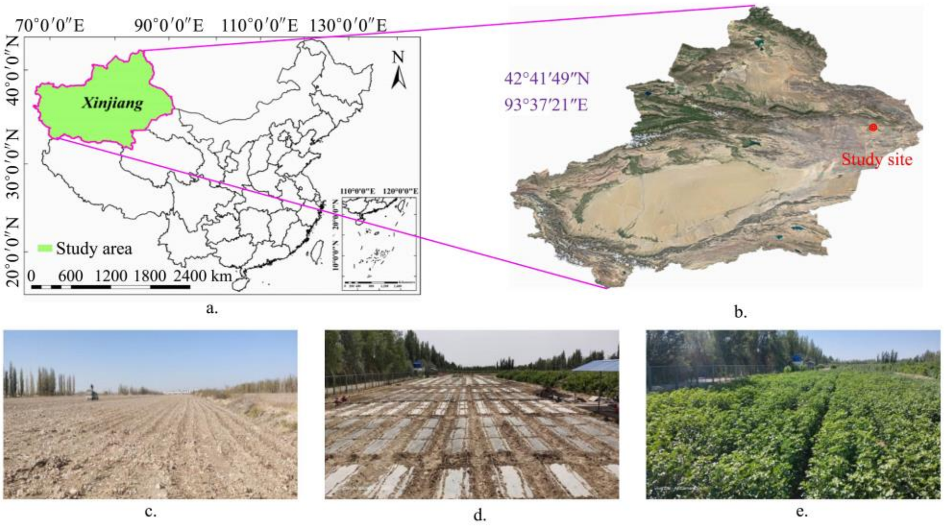
Different climatic conditions, crop varieties, irrigation methods, and materials used to produce the biodegradable films significantly impact their biodegradability and therefore have different effects on the soil environment and crop growth[36], suggesting that the effect of applying biodegradable film mulching is not clear in all cases[37]. Previous studies have focused mainly on comparing the effects of biodegradable film mulching and PE film mulching on soil hydrothermal conditions and crop growth[38]. However, studies on the effect of applying biodegradable film and the degradation performance (including degradation time and degradation rate) of the biodegradable film are very limited. Therefore, it is essential to test the potential of biodegradable mulch as an environmentally sustainable alternative to conventional plastic mulch in mulched drip irrigation. It was hypothesized that biodegradable mulching films have similar effects in maintaining soil moisture and improving cotton yield. Therefore, this study was carried out to explore the differences between the effects of PE and biodegradable films with varying levels of biodegradability (i.e. different degradation times and rates) on the soil environment and cotton yield, and to determine which biodegradable film has the optimal degradation rate for use in cotton fields grown using drip irrigation under mulch film in the Hami Basin, Xinjiang. Based on the performance in improving cotton yield and maintaining soil moisture, the biodegradable transparent film (M2), with an induction period of 80 d, is recommended as an alternative to the conventional plastic film adopted in Xinjiang to increase water efficiency and mitigate the harmful effects of residual plastic film pollution.

2 Materials and methods

2.1 Experimental site

A field experiment was conducted during 2019 and 2020 at the Irrigation Experimental Station of Xinjiang Production and Construction Corps (42°41′49″N, 93°21′37″E; 412 m a.s.l.) in Hami City, Xinjiang, in northwest China (Figure 1). This region has an arid continental climate. The average annual rainfall and potential evaporation are 33.8 mm and 3300 mm, respectively. The average annual duration of sunshine at the study site is 3358 h, and the accumulated air temperature above 10 ℃ is 4058.3 ℃, with an average frost-free period of 182 d. Air temperature, precipitation, wind speed and other meteorological data were recorded by an automatic weather station located 50 m away from the study site. The total precipitation and average air temperature during the cropping season (April to November) were 38.4 mm and 21.6 ℃ in 2019 and 15.6 mm and 23.4 ℃ in 2020, respectively (Figure 2).

The soil at the site was a sandy loam with a pH of 7.68. The average soil bulk density was 1.51 g/kg^3, the average field capacity was 18.6%, and the concentration of organic matter was 14.5 g/kg. In the 0-100 cm soil layer, the total N, available P, and available K were 0.54 mg/kg, 15.39 mg/kg and 197 mg/kg, respectively. The regional groundwater level was deeper than 10 m, and the salinity of the groundwater was 1.05-2.46 g/L (The detailed soil physical-chemical properties of the experiment site are listed in Table 1).



a. Xinjiang is located in northwest China b. Xinjiang is characterized by an extremely arid desert climate c. The residual film pollution of cotton fields under long-term drip irrigation under film is serious d. and e. Comparison of four different biodegradable mulches as well as conventional plastic mulch in drip irrigated cotton fields in an oasis agroecosystem in northwest China

Figure 1 Description of the study site

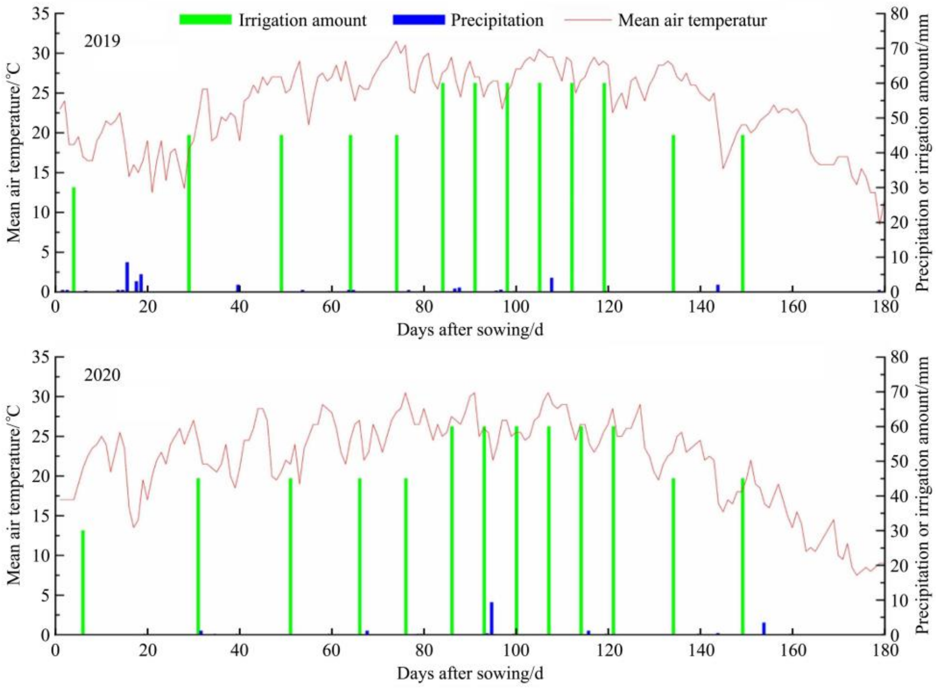


Figure 2 Daily precipitation (blue bars), mean air temperatures (red lines) and amount of irrigation (green bars) during the cotton growing season at the experimental site during 2019 and 2020

Table 1 Physical and chemical properties of the soil at a depth of 0-100 cm before the experiment

Soil depth/cm	Soil texture	Soil bulk density/g cm^{-3}	Field capacity/%	Organic matter/mg·kg^{-1}	Total soil nitrogen/mg·kg^{-1}	Available soil phosphorus/mg·kg^{-1}	Available potassium/mg·kg^{-1}
0-20	Sandy loam	1.46	20.24	15.26	0.57	18.85	213.55
20-40	Sandy loam	1.49	19.15	15.18	0.53	19.58	238.46
40-60	Sandy loam	1.52	18.86	14.55	0.61	14.64	191.15
60-80	Sandy loam	1.54	17.41	14.08	0.51	12.36	168.36
80-100	Sandy loam	1.54	17.34	13.43	0.48	11.52	173.48

2.2 Experimental design

The experiment was prepared following a randomized block design with five treatments, i.e., mulching with four different types of biodegradable films and PE films. The biodegradable films tested in the experiment included black opaque oxidation-biodegradable film (M1), colorless transparent oxidation-biodegradable film (M2), black opaque fully biodegradable film (M3) and white translucent fully biodegradable film (M4), all with different appearances and induction periods. The detailed properties of the biodegradable films and PE films are listed in Table 2. The biodegradable films were selected according to local agriculture management practices and the preliminary comparison of several more types of biodegradable film.

A typical setup of the mulched drip irrigation system comprised four rows of plants sown under one strip of mulch (120 cm wide) with two drip tapes (Figure 3). Each drip tape was laid in the middle of a narrow row, and the distance between the wide and the narrow rows was 50 cm and 20 cm, respectively. The interval between the mulches was 30 cm and was left as bare land. A common local cotton variety, the early-maturing cultivar “Xinlong T6”, was planted in each of the two years. Cotton (*Gossypium hirsutum* L.) was sown at a rate of 180 000 plants/hm^2 on 22 April 2019 and 24 April 2020. Dibble sowing was carried out, which allowed drip tape laying, mulching and seed sowing to be completed in one run. All of the cotton plants were sown in rows along the drip lines with 10 cm between plants. Each treatment was replicated in three plots, and each plot measured 20 m×5 m. A schematic representation of the experimental setup is shown in Figure 3.

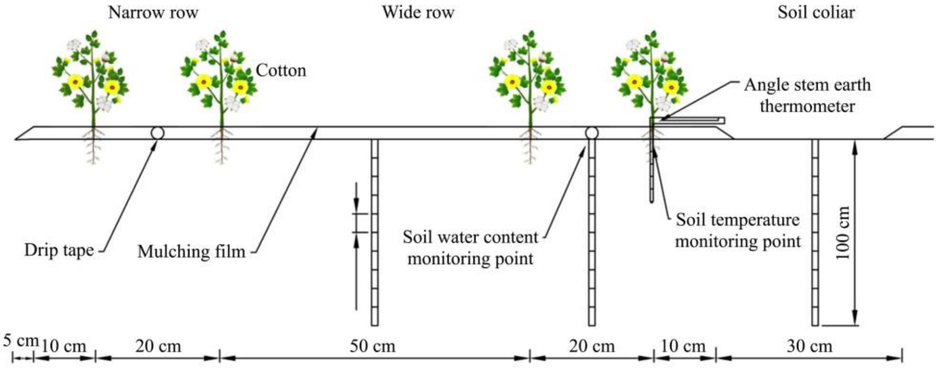


Figure 3 Layout of the mulched drip irrigation design and locations of soil core samples used to measure soil water content and soil salinity

Table 2 Properties of the biodegradable and plastic films used in this study

Film	Material	Thickness/mm	Induction period[c]	Appearance	Manufacture
M1[a]	PBAT	0.010	100 d	Black opaque	Shandong Tianzhuang Co., Ltd
M2[a]	PBAT	0.010	80 d	Colorless transparent	Shandong Tianzhuang Co., Ltd
M3[b]	PBSA	0.010	100 d	Black opaque	Guangzhou Kingfa Co., Ltd
M4[b]	PBSA	0.010	80 d	White translucent	Guangzhou Kingfa Co., Ltd
PE	Polyethylene	0.008	Many years	Transparent	Xinjiang Tianye Co., Ltd

Note: PBAT: polybutyrate adipate terephthalate; PBSA: polybutylene succinate-co-butylene adipate. [a] Biodegradable films are made from polybutyrate adipate terephthalate (PBAT). [b] Biodegradable films are made from polybutylene succinate-co-butylene adipate (PBSA). [c] Induction period indicates the time taken for the films to degrade to the point at which almost no film (less than 10%) is left on the soil surface.

The cotton was sown using the method of “dry sowing and wet out”. During the growing period, the method of drip irrigation under the film was used to provide the necessary water and nutrients for cotton growth. Single wing labyrinth-type drip irrigation laterals (manufactured by Xinjiang Tianye Co., Ltd., China) were used. The external diameter and wall thickness were 16 mm and 0.3 mm, respectively, and the emitter flow rate was 2.6 L/h. Interval spacing between two emitters was 30 cm. The water supply system in the study area was mainly pressurized by a water pump, and the pressure gauge and regulating valve were installed at the head of the system. The amount of irrigation, irrigation dates, and frequencies, and fertigation frequencies for each plot were the same throughout the experiment. The cotton was irrigated 13 times during the entire growth period. The irrigation quota was 682.5 mm; the fertilization ratio of N: P_2O_5: K_2O was 2:1:2 and the total amount of fertilization was 750 kg/hm^2. The irrigation interval was 7-10 d. The fertilizer was dissolved in the water for fertilization while irrigating. Detailed information on the irrigation schedule at different stages of cotton growth is listed in Table 3. Apart from the mulching films, all of the other agriculture management techniques were the same as for local cotton fields.

Table 3 Irrigation schedule during the cotton growing season in 2019 and 2020

Growth stage*	2019		2020	
	Irrigation date	Irrigation amount/mm	Irrigation date	Irrigation amount/mm
Seedling	April 22	30	April 24	30
	June 16	45	June 9	45
Budding	June 24	37.5	June 16	37.5
	June 30	37.5	June 23	37.5
	July 7	37.5	July 1	37.5
Flowering	July 14	67.5	July 9	67.5
	July 21	67.5	July 16	67.5
	July 28	67.5	July 23	67.5
Bolling	August 4	67.5	July 30	67.5
	August 11	67.5	August 6	67.5
	August 18	67.5	August 13	67.5
Maturity	August 25	45	August 20	45
	September 1	45	August 27	45
Total irrigation amount/mm		682.5		682.5

Note: * Seedling stage indicates the period from emergence to budding of the cotton; budding indicates the beginning of differentiation of the first flower bud of cotton; flowering indicates the beginning of flowering; bolling indicates boll development; and maturity indicates that over 90% of the bolls are open.

2.3 Sampling and field measurements

2.3.1 Biodegradability

The degradation of the exposed mulching films in the field was evaluated every 10 d after sowing (DAS) throughout the cotton growing seasons using a qualitative scale[39]. The degradation process was divided into six stages[40]: the induction, cracking, rupture, disintegration, residual, and disappearing stages. The induction stage indicates that the film is practically intact; the cracking stage occurs after the induction period, when the film begins to crack; the rupture stage indicates that the film contains cracks 2.0-2.5 cm in length; the disintegration stage indicates that large cracks 20-25 cm in length have begun to appear, and the number of cracks is increasing; the residual stage represents the film breaking down into fragments smaller than 4 cm×4 cm; and the disappearing stage indicates that almost no residual film exists on the soil surface. After the cotton harvest, three sampling quadrats (1 m×1 m) were randomly placed in each of the experimental plots to calculate the rate of loss for each type of mulch. The number of membrane ruptures, crack lengths, and crack widths within 1 m^2 was counted, and then the area loss rate of the films (D) was calculated as:

$$D=\sum\nolimits_{i=1}^{n} L_i W_i \tag{1}$$

where, L is the length of the film rupture, m; W is the width of the rupture, m; n is the number of cracks.

2.3.2 Soil temperature

Soil temperature was measured at depths of 5, 10, 15, 20, and 25 cm in each plot using geothermometers (YuHuan ZhiTuo Technology Co., Ltd, Zhejiang, China). Each set of geothermometers was inserted near the cotton roots in each plot. In both years, the soil temperature was measured every two hours from 08:00 to 20:00 (local standard time) on one day of the seedling, budding, flowering, bolling and maturity stages. The average soil temperature of different soil layers monitored for 5 d during each growth period was used as the representative soil temperature for the growth period. The automatic weather station in the experimental station was used to monitor the real-time atmospheric temperature.

2.3.3 Soil water content

In both years, gravimetric soil moisture was measured to a depth of 100 cm at 10 cm intervals at 30, 60, 80, 110, and 150 d after film mulching. Three soil cores were auger drilled in each plot to collect samples from narrow rows, wide rows and bare land between the mulching film at different stages of cotton growth. Soil samples were collected using a cutting ring (100 cm^3) and dried to measure the soil moisture and bulk density. Soil samples were taken from each depth described above, and this was repeated three times. Soil sampling and soil moisture measurements were carried out as described by Wang et al.[4]

2.3.4 Plant height, stem diameter, leaf area index, and dry matter accumulation

The dry matter accumulation was measured 45 DAS and continued at the 30 d intervals after the seedling stage in 2019 and 2020. On each measurement day, five cotton plants were dug out at the root. The roots, stem, leaves, and buds of the plant were separated and placed in the oven. After 30 minutes of green-killing treatment at 105 ℃, the plant samples were dried to a constant weight at 75 ℃. The dry matter was weighed using an electronic balance. Five cotton plants were selected randomly in each plot to determine the crop height, stem diameter, and leaf area index (LAI) at 10-15 d intervals after the seedling stage. Crop height, leaf length, and leaf width were determined using a steel tape. The LAI was calculated using the following equation[41]:

$$\mathrm{LAI}=0.84\frac{\rho\sum\nolimits_{i=1}^{j} L_i\times B_i}{10000} \tag{2}$$

where, LAI is the leaf area index; ρ is the cotton planting density, plants/m^2; L is the leaf length, cm; B is the leaf width, cm; j is the number of leaves per plant; and 0.84 is the conversion coefficient.

2.3.5 Seedling rate and cotton yield

The emergence rate of the cotton in each experimental plot was measured. Before harvest, three observation areas (1 m×1.5 m) were randomly selected in each experimental plot to count the number of cotton bolls in the observation area, and then 50 cotton bolls were randomly picked to calculate the average single boll weight. The cotton yield was determined by harvesting the center rows (1.2 m×10 m) in each plot by hand and converting this to the yield per unit area (kg/h).

2.4 Statistics and analysis

The test data were graphed and processed using SPSS 20.0 (IBM SPSS Statistics, USA) and Origin 9.0. Measurement data were analyzed using one-way analysis of variance tests. Significant differences among various treatments were calculated using the least significant difference at the p<0.05 level.

3 Results

3.1 Biodegradability

The degradation performances of the four biodegradable films were similar in 2019 and 2020 (Table 4). No biodegradation of the traditional PE film was noticed throughout the whole cotton growing period. The M2 film showed the first signs of degradation at 80 DAS and experienced further deterioration (the maximum surface area of the residual film was <16 cm^2) at 180 DAS each year. The degradation of M2 was the greatest, as it entered the cracking stage 10-20 d earlier than the other degradation films. The degradation rate of M4 was relatively slow in the early stage, with cracks appearing >90 DAS. The degradation rate of M4 was the same as that of M2 on >150 DAS. M1 and M3 degraded relatively slowly. The degradation of M1 started at 90 DAS in 2019 and 100 DAS in 2020, respectively; M1 entered the cracking stage 10 d earlier than M3. The degradation of M1 and M3 was the same on >130 DAS, and these films experienced further deterioration (natural cracks >2 cm in length) at 160 DAS in both years. M1 and M3 were relatively intact at the end of the growth period and had not fragmented.

The area loss rate (Formula 1) of M2 at 180 DAS was 66.48% and 68.36% in 2019 and 2020, respectively, indicating that the biodegradability of this film was significantly higher than that of the PE film and the other biodegradable films (Figure 4). The area loss rate of M4 was the second highest at 46.85% and 45.88% in 2019 and 2020, respectively. The area loss rate of M1 and M2 was about 30%, while the area loss of the PE film was not obvious. In general, the degradation rates of the various mulching films were ranked in a descending order as M2, M4, M1, M3 and PE.

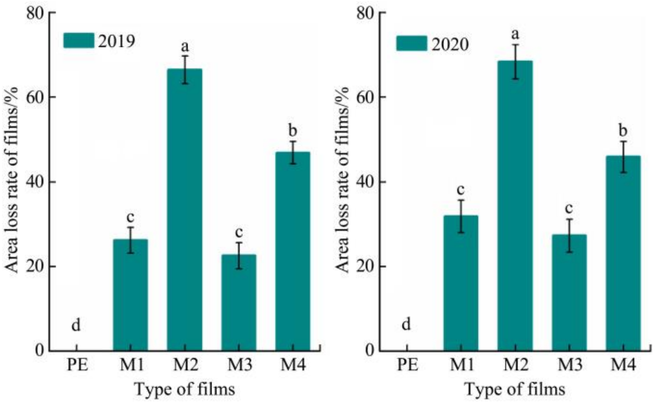
3.2 Soil temperature

The difference in the average temperature of the topsoil (5, 15, and 25 cm) between the plots with biodegradable films and PE film is listed in Table 5. The effect of soil warming and heat preservation following mulching with traditional PE film was better than that following mulching with biodegradable plastic film during the whole growth period of cotton. However, the warming effect of M2 and M4 was more evident than that of M1 and M3 at the early growth stage (particularly from the seedling to budding stages). The temperature of soil mulched by M2 and M4 films were lower than that mulched by M1 and M3 films from the flowering stage to maturity stage. In general, the warming effect first increased and then decreased with the growth of cotton and then gradually decreased with the increase in soil depth (Table 5). During the period of 0-70 DAS, the various mulching films remained intact, and the heat lost by cotton transpiration was limited. Therefore, mulching was effective in warming the soil, although at late stages of cotton growth (i.e., 70-180 DAS), the warming effect of mulching was gradually reduced as the cotton leaves prevented sunlight from reaching the ground. In addition, the degradation of the biodegradable mulches also reduced the ability of the soil to conserve heat.

Table 4 The degradation stage of films under five different mulching patterns for two cotton growing seasons in 2019 and 2020

Year	Treatment	Days after film mulching/d											
		70	80	90	100	110	120	130	140	150	160	170	180
2019	M1	0	0	1	1	1	1	2	2	2	3	3	3
	M2	0	1	1	1	2	2	2	2	3	3	3	4
	M3	0	0	0	1	1	1	2	2	2	3	3	3
	M4	0	0	1	1	1	2	2	2	3	3	3	4
	PE	0	0	0	0	0	0	0	0	0	0	0	0
2020	M1	0	0	0	1	1	1	2	2	2	3	3	3
	M2	0	1	1	1	2	2	2	2	3	3	3	4
	M3	0	0	0	0	1	1	2	2	2	3	3	3
	M4	0	0	0	1	1	2	2	2	3	3	3	4
	PE	0	0	0	0	0	0	0	0	0	0	0	0

Note: M1, M2, M3, and M4 indicate different types of biodegradable films. No film degradation was observed before 70 d after film mulching in both years. Degree 0 represents the induction stage; Degree 1 represents the cracking stage; Degree 2 represents the rupture stage; Degree 3 represents the disintegration stage; and Degree 4 represents the residual stage. See the definition of each film degradation stage in the text.



Note: PE indicates conventional plastic film. M1, M2, M3, and M4 indicate different types of biodegradable films. M1, M2, M3, and M4 represent black opaque oxidation-biodegradable film with 100 d induction period mulching, colorless transparent oxidation-biodegradable film with 80 d induction period mulching, black opaque fully biodegradable film with 100 d induction period mulching, and white translucent fully biodegradable film with 80 d induction period mulching, respectively. The vertical bars represent the standard errors.

Figure 4 The area loss rates under various mulching treatments in 2019 and 2020

There was no significant difference in soil temperature at the seedling and budding stages under different film mulching treatments. At the flowering stage, the degradable films began to break down, and the soil thermal insulation performance began to decrease, while the traditional PE film did not degrade, and the thermal insulation performance was better. After flowering, the effects of different film mulching treatments on soil warming and heat preservation began to show significant differences. At a depth of 5-25 cm, the daily average soil temperature of the cotton fields covered with the degrading films was lower than that of fields covered with the PE film, and the difference in the soil temperature at a depth of 5 cm was the most significant. Compared with the PE film, the average temperature at a depth of 5 cm in soil mulched by degradable films M1, M2, M3, and M4 at the flowering stage were decreased by 14.20%, 11.51%, 9.08%, and 13.96% in 2019, and 13.85%, 7.28%, 10.29%, and 8.18% in 2020, respectively. The average temperature at a depth 5-25 cm in soil mulched by degradable films M1, M2, M3, and M4 at the flowering stage were decreased by 12.13%, 10.01%, 7.67%, and 10.48% in 2019, and 10.52%, 6.33%, 6.87%, and 5.72% in 2020, respectively.

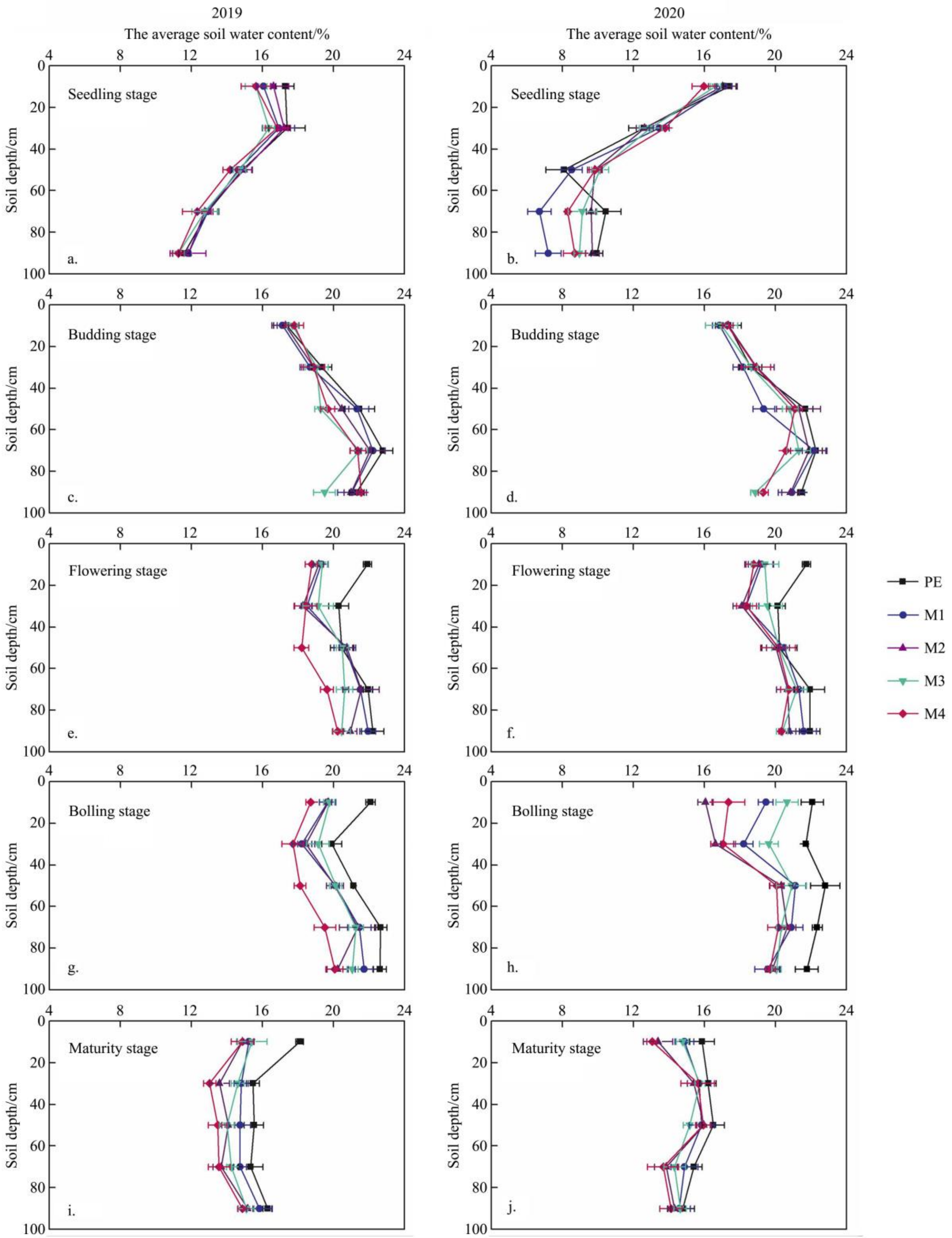
Table 5 Daily average (08:00-18:00) soil temperatures (℃) at 5 cm, 15 cm, and 25 cm under different film mulching treatments with various types of films at different growth stages in 2019 and 2020

Growing season	Soil depth /cm	Treatment	Growth stages				
			Seedling	Budding	Flowering	Bolling	Maturity
2019	5	PE	32.77a	35.98a	33.37a	30.13a	25.50a
		M1	32.19a	34.96b	28.63c	29.99a	23.69b
		M2	32.51a	35.94a	29.53b	28.24b	22.76b
		M3	31.71a	35.10a	30.34b	29.80a	22.86b
		M4	32.31a	35.41a	28.71c	27.14c	22.46bc
	15	PE	30.76a	33.24a	29.63a	28.81a	23.43a
		M1	29.14a	31.27b	27.31b	26.23b	22.26a
		M2	29.19a	31.59b	26.46b	26.23b	22.11b
		M3	28.76a	31.23b	27.37b	26.71b	22.47a
		M4	29.91a	31.97b	27.07b	25.21c	21.51b
	25	PE	28.96a	30.33a	27.73a	26.47a	23.57a
		M1	28.00a	28.99ab	25.74b	25.74a	22.34a
		M2	28.14a	29.66a	25.71b	25.73a	22.03a
		M3	27.97a	28.63b	26.04ab	25.87a	22.98a
		M4	28.23a	30.11a	25.91b	25.59a	22.14a
2020	5	PE	33.26a	35.26a	36.54a	30.81a	20.89a
		M1	31.06b	33.14b	31.06d	30.09a	19.71a
		M2	33.46a	34.47a	33.46b	29.21a	17.73b
		M3	32.36a	33.39b	32.36c	30.44a	19.73a
		M4	33.11a	33.40b	33.11b	28.51b	17.83b
	15	PE	29.86a	32.50a	30.71a	29.24a	19.69a
		M1	27.43b	30.09b	27.43c	27.80b	18.13b
		M2	29.03a	31.51a	28.89b	27.71b	17.57b
		M3	28.39a	29.44b	28.39b	28.11a	17.71b
		M4	28.91a	30.01b	28.91b	27.16b	17.53b
	25	PE	26.17a	28.71a	27.66a	28.54a	18.64a
		M1	25.76a	26.94a	25.76b	26.73b	18.09a
		M2	26.11a	27.26a	26.04a	26.47b	17.01b
		M3	26.23a	26.33a	26.23a	27.70a	18.19a
		M4	26.24a	27.29a	26.20a	26.13b	17.83ab

Note: Different letters within a column indicate significant differences among treatments within each depth and season at $p<0.05$.

3.3 Soil water content

The difference in the soil water content at a depth of 0-100 cm between the plots covered with biodegradable films or PE film is revealed in Figure 5. The soil water content during the seedling stage was mainly distributed at a depth of 0-40 cm, and the effect of precipitation on the initial soil water content was higher in 2019 than in 2020. The soil wetting front gradually migrated to the deeper layers with the increase in irrigation at the budding stage, and the soil water content increased with soil depth in the 0-80 cm range; whereas, the soil water content in each soil layer decreased due to less irrigation during the boll opening stage. There was no significant difference in the soil water content between the seedling and budding stages. Due to the degradation of the biodegradable films from the flowering stage to the boll-opening stage, the water content of the shallow soil mulched with PE film was significantly higher than that mulched with the biodegradable film. The effect of film degradation on the shallow soil water content was much greater than that in deep soil, especially at a depth of 0-40 cm.



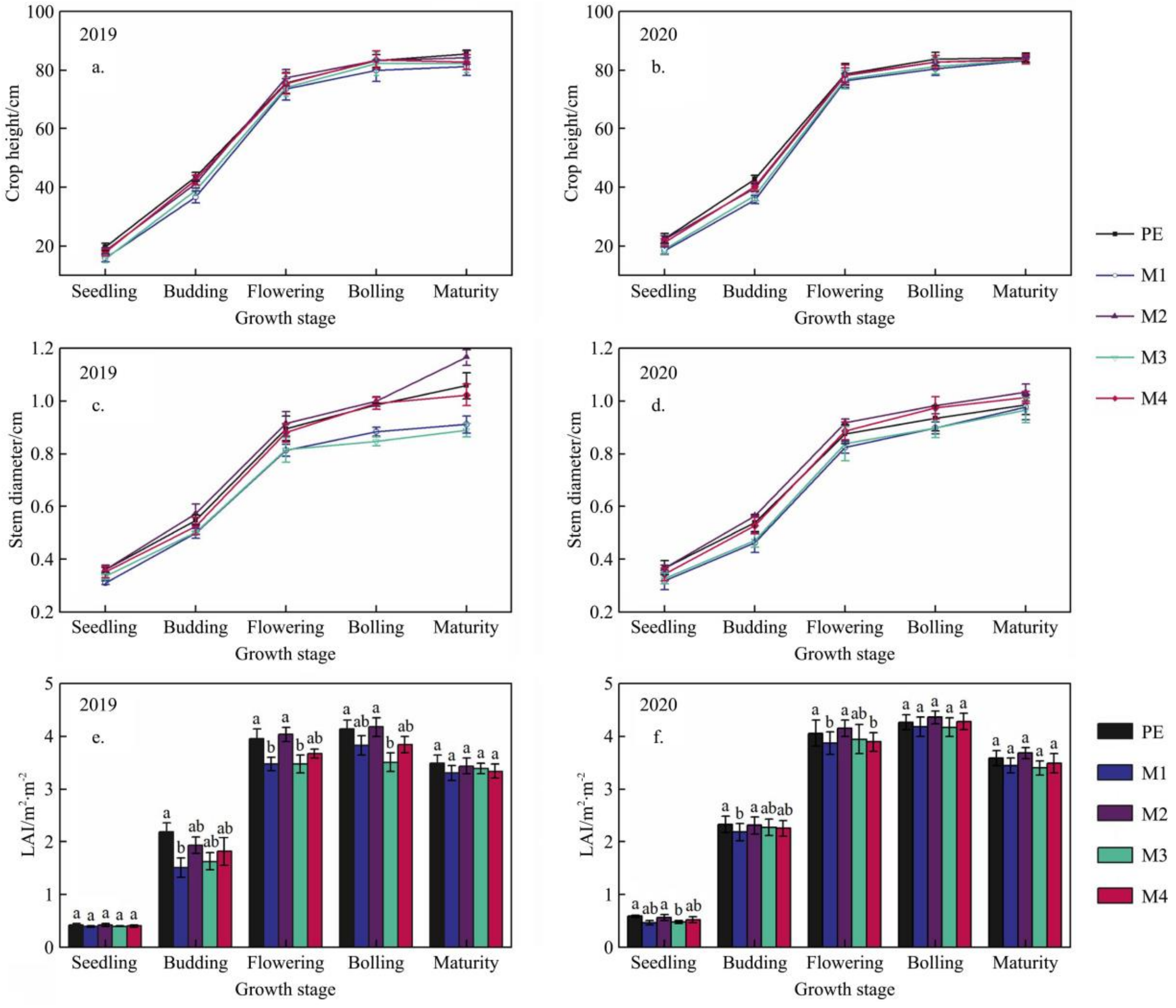
Note: PE indicates conventional plastic film. M1, M2, M3, and M4 indicate different types of biodegradable films. M1, M2, M3, and M4 represent black opaque oxidation-biodegradable film with 100 d induction period mulching, colorless transparent oxidation-biodegradable film with 80 d induction period mulching, black opaque fully biodegradable film with 100 d induction period mulching, and white translucent fully biodegradable film with 80 d induction period mulching, respectively. The symbols are the mean of three repetitions; the horizontal bars represent the standard errors.

Figure 5 The soil gravimetric water content with various types of mulch at different growth stages in 2019 and 2020

When averaged over the entire cropping season, the PE mulch achieved the best outcome in maintaining soil water in both years (Figure 5). Compared with that measured under the PE film, the soil water content of the 0-20 cm soil layer covered by the degradable films M1, M2, M3, and M4 at the flowering stage in 2019 and 2020 decreased by 11.93%, 12.40%, 11.63%, and 14.29%, and 11.72%, 12.28%, 10.71%, and 13.68%, respectively ($p<0.05$). The water content of the 0-20 cm layer of soil mulched with the degradable films M1, M2, M3, and M4 at the bolling stage was 10.94%, 10.74%, 10.53%, and 15.35% lower than that of soil covered with the PE film in 2019 and 11.86%, 27.25%, 6.42%, and 21.37% lower than that of soil covered with the PE film in 2020 ($p<0.05$). Therefore, for the purpose of soil water preservation, the biodegradable films with a longer induction period (e.g., M1 and M3) are more suitable.

3.4 Plant height, stem diameter, and leaf area index (LAI)

Figure 6 indicates the effects of various mulching technologies on crop height, stem diameter and LAI (Equation (2)) over the 2-year period. The effects of the different degradable films on plant height, stem diameter and LAI in cotton were similar to those of the PE film. The changes in cotton plant height and stem diameter showed an “S-shaped” trend. Crop height increased rapidly from the budding stage to the flowering stage, with an average growth rate of 7.64 mm/d in 2019 and 6.15 mm/d in 2020, respectively. The growth rate slowed after flowering due to top-cutting and chemical control. The LAI increased over time until the blooming stage and then gradually decreased (Figure 6).



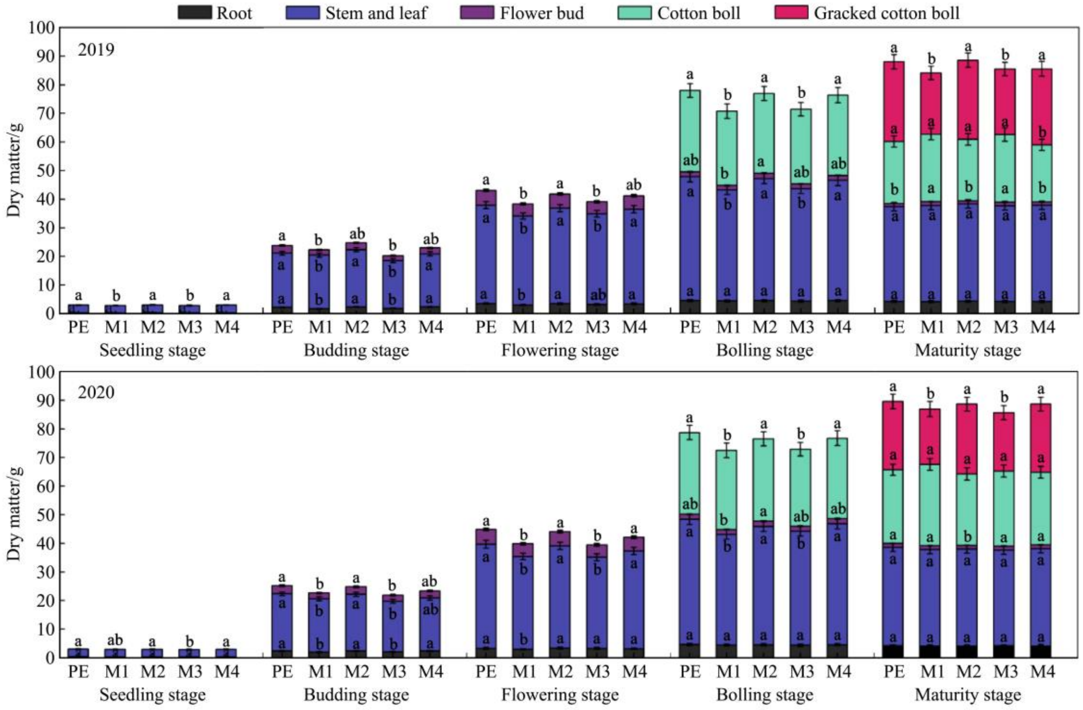
Note: M1, M2, M3, and M4 indicate different types of biodegradable films. M1, M2, M3, and M4 represent black opaque oxidation-biodegradable film with 100 d induction period mulching, colorless transparent oxidation-biodegradable film with 80 d induction period mulching, black opaque fully biodegradable film with 100 d induction period mulching, and white translucent fully biodegradable film with 80 d induction period mulching, respectively. The symbols are the mean of three repetitions. The vertical bars represent the standard errors.

Figure 6 Plant height, stem diameter and leaf area index of drip irrigated cotton under various mulching treatments at different growth periods in 2019 and 2020

At the seedling stage, the crop height and stem diameter using the M2, M4 and PE film treatments was significantly higher than that for the M1 and M3 treatments, but the difference in LAI was not significant. At the budding stage, the mulching materials affected the crop height and LAI significantly. Compared with those grown using the PE film, the heights of cotton plants grown under M1 and M3 decreased by 15.63% and 10.55%, and 16.36% and 13.08% in 2019 and 2020, respectively. The diameters of the stems of plants covered by degradable films M1 and M3 decreased by 9.12% and 8.57%, and 13.76% and 12.33%, compared with those grown under PE film in 2019 and 2020, respectively. The LAI of the cotton plants covered with degradable films M1 and M3 was 31.31% and 25.67% lower than that of plants grown under PE film in 2019, respectively. There was no significant difference in plant height, stem diameter, and LAI between plants grown using the M2, M4, and PE films. From the flowering stage to the boll opening stage, there was no significant differences in the heights of cotton plants grown under the different treatments due to top-cutting and chemical control. However, there were significant differences in the stem diameter and LAI of plants between the flowering and bolling stages, and the stem diameter and LAI of plants grown under M2 film were the largest of all the treatments. At the flowering and bolling stages, the average stem diameters and LAI of plants mulched with M2 were 1.57%-13.10% and 1.47%-14.99% higher than for those grown using the other degradable films and PE film, respectively. The stem diameters and LAI of plants grown under the M1 and M3 film (induction period of 100 d) treatments were significantly lower than those of plants grown under the M2, M4 (induction period of 80 d), and PE film treatments (p<0.05).

3.5 Dry matter accumulation

The amount of dry matter per cotton plant under the degradable films M1 and M3 decreased by 10.12% and 13.13%, and 3.23% and 12.38%, compared with that of plants grown under PE film in 2019 and 2020, respectively. However, the dry matter accumulation of cotton grown under degradable films M2 and M4 was not significantly different from that grown under the PE film (Figure 7). As for the composition of the dry matter, there were significant differences in the dry matter content of roots covered with the different plastic films at the budding and flowering stages, but there was no significant difference at other growth stages. The degradable films had the most significant effect on the dry matter of cotton stems and leaves. From the flowering to bolling stages, the dry matter of plants under the M1 and M3 films were 7.68%-12.55% lower than that of plants under the PE film (p<0.05). At the flowering stage, the dry matter of buds covered with the M1 and M3 film was 18.93%-20.27% and 13.90%-15.64% lower than that of those covered with PE film, respectively (p<0.05). The dry matter of cotton bolls covered with the degradable films M1 and M3 at the bolling and maturity stages was 8.22%-11.96% and 14.59%-23.12% lower than that of those under PE film. However, the dry matter of cotton bolls covered with degradable films M2 and M4 was not significantly different from that of those under PE film.



Note: M1, M2, M3, and M4 indicate different types of biodegradable films. M1, M2, M3, and M4 represent black opaque oxidation-biodegradable film with 100 d induction period mulching, colorless transparent oxidation-biodegradable film with 80 d induction period mulching, black opaque fully biodegradable film with 100 d induction period mulching, and white translucent fully biodegradable film with 80 d induction period mulching, respectively. The vertical bars represent the standard errors.

Figure 7 Dry matter accumulation under various mulching treatments in 2019 and 2020

3.6 Seedling emergence rate and cotton yield

The seedling emergence rate of cotton grown under PE film was the highest (Table 5). Compared with the PE film, the seedling emergence rates of cotton grown under the M1, M2, M3 and M4 treatments were decreased by 16.09%, 1.41%, 15.39% and 10.49% in 2019, and 15.86%, 1.38%, 15.86% and 10.35% in 2020, respectively. The seedling emergence rate of cotton mulched with M1, M3 and M4 was significantly lower than that for the PE film, whereas the seedling emergence rate for cotton under M2 was slightly lower than that under PE film, but there was no significant difference. The yield of cotton in the M1, M3 and M4 treatments was significantly lower than that from plants under the PE film, while the yield of cotton in M2 treatment was slightly higher than that of plants covered with PE film. Compared with those mulched with PE film, the yield of cotton mulched with M1, M3 and M4 decreased by 7.50%, 6.45% and 2.83%, and 9.82%, 6.48% and 2.13%, in 2019 and 2020, respectively.

Table 5 Seed cotton yield of cotton under different plastic film mulching in 2019 and 2020.

Year	Treatments	Seedling emergence rate/%	Cotton yield /kg·hm^{-2}	Increased production rate/%
2019	PE	91.67±1.70a	7740.63±229.17a	/
	M1	76.92±4.44b	7160.09±259.97b	-7.50
	M2	90.38±2.22a	7764.50±257.82a	+0.31
	M3	77.56±3.39b	7271.59±170.96b	-6.45
	M4	82.05±3.39ab	7521.59±242.16ab	-2.83
2020	PE	92.95±1.70a	7793.53±311.58 a	/
	M1	78.20±4.49b	7028.58±282.78 c	-9.82
	M2	91.67±1.70a	7900.48±273.06 a	+1.37
	M3	78.21±2.80b	7288.31±272.88 bc	-6.48
	M4	83.33±3.57ab	7626.79±297.81 ab	-2.13

Note: Different lowercase letters indicate significant differences between the five different types of mulch treatments in each year ($p \leq 0.05$).

4 Discussion

The biodegradability of degradable films is related to their material composition and the production process as well as the geographical location and environment of the study site[23]. Gu et al.[42] identified that the most significant environmental factors associated with PE film could be replicated using degradable film in cotton cultivation using a meta-analysis, i.e., altitudes, precipitation, evaporation, ambient temperature, thickness, effective accumulated temperature was 1000-1500 m, smaller than 500 mm, larger than 2000 mm, 10 ℃-15 ℃, 10 μm, 3000 ℃-4000 ℃, respectively. Xinjiang meets such requirements, except for the altitudes. The process of biodegradable film degradation is complex and variable. In a previous experiment on cotton, Yi et al.[43] found that three biodegradable films (starch-based) with different material compositions deteriorated faster in Hebei Province than in the Xinjiang autonomous region. Some scholars have studied the biodegradability of degradable mulching films in regions other than extremely arid areas and reached the following conclusions; compared with traditional PE films, biodegradable films began to degrade significantly 40 d after mulching, reaching the residual stage at 90 d after mulching[44]. A second study showed that the biodegradable films began to degrade significantly 50-60 d after mulching, reaching the disintegration stage at 140 d after mulching[45]. In this study, the degradation of traditional PE film was not obvious during the whole growth period of cotton. The M2 film showed the first signs of degradation at 80 DAS and experienced further deterioration at 180 DAS each year over the 2-year study. These results are different from those found in previous studies[46]. There are two possible reasons for this. Firstly, our study site was located in an area with an extremely arid climate, which is different from previous studies. Secondly, the appearance characteristics and degradation performance (including degradation time and degradation rate) of the degradation film used in the study were different. This suggested that the control of biodegradable film degradation needs to be further improved, especially for specific climatic conditions and crop species.

Film mulching improves farmland ecological microclimates and the plant growth environment by coordinating soil water, fertilizer, gas, and heat[47]. The application of biodegradable film improves soil heat preservation and moisture retention, and soil temperature and soil water content have a significant impact on the early emergence and yield of cotton[48]. Compared to air temperature, crop growth is more sensitive to soil temperature and is visibly affected by variations in soil temperature[49]. In some cold temperate zones and high-altitude areas, plastic film mulching has long been considered as an effective agricultural measure to improve soil temperature, especially during the early growth period of crops[50]. Accordingly, in this study, the PE film showed the strongest heat preserving ability at each growth stage. The soil heat preservation and moisture conservation performance under biodegradable film mulching at the cotton seedling stage and budding stage was similar to that of PE film. The main reason for this may be that the small plant canopy at the early growth stages allowed most of the mulched soil surface to receive solar energy. In addition, the degradable film was not degraded during this period, and there was no difference in warming performance[51]. The warming effect first increased and then decreased with the growth of cotton, and gradually decreased with increased soil depth (Table 5). Similar results were observed by Bu et al.[10] At the flowering stage of cotton, the soil temperature when mulched with various degradation films was significantly lower than that under the PE film. This was consistent with the results provided by Moreno et al.[52] The main reason for this may be that the biodegradable film begins to degrade, and then the effect of soil thermal insulation is weakened.

Many studies have indicated that mulching with both biodegradable and PE films mulching can greatly increase the soil water content, especially during the early crop stages and in the topsoil layer[53-55]. In our study, the soil heat preservation and moisture conservation performance under biodegradable film mulching at the cotton seedling stage and budding stage was similar to that of PE film. At the late stage of cotton growth, the water content of shallow soil mulched with PE film was more effective than biodegradable films. The effect of film degradation on the shallow soil water content was much greater than that in deep soil, especially at a depth of 0-40 cm. This finding was in agreement with observations reported by Braunack et al.[56] The differences in the soil water content between the different treatments increased first and then decreased over time. The reason behind this is that the water retention effect of the plastic films was higher before degradation and gradually decreased after degradation. However, it needs to point out that one of the shortcomings of the study is the discrete nature of the data for soil temperature and water content. Soil temperature and water content were manually measured on selected days, which did not reflect the dynamic nature of the soil thermal and hydraulic environment well. In follow-up experiments, we will rectify this deficiency and strengthen the continuous dynamic monitoring of soil temperature and water content throughout the growth period, so as to better explain the impact of degradable film mulching on soil hydrothermal dynamics and crop growth.

The degradable films were previously shown to be similar to traditional PE films in providing a suitable soil hydrothermal environment for improving crop emergence, growth, and yield[57]. A similar result was found in the current study; in all treatments, the seedling rate and growth index of cotton under M2 were similar to those found under the PE film. Mulching could change the way water is consumed on cropland, from soil evaporation to crop transpiration and from unproductive consumption to valid consumption, thereby increasing crop yield and water use efficiency[58,59]. Biodegradable films with appropriate degradation rates can better optimize soil hydrothermal conditions, promote crop growth, increase yield, and reduce soil residual film pollution[60] as was also found by our investigation. In this study, compared with the PE film, the yield of cotton mulched with M1, M3, and M4 was decreased by 7.50%, 6.45% and 2.83%, and 9.82%, 6.48% and 2.13%, in 2019 and 2020, respectively. However, the cotton yield using M2 was slightly higher than that observed using the PE film. There are two possible reasons for these differences. Firstly, the material composition of degradation film M2 is different from that of M3 and M4. Secondly, the appearance and degradation characteristics (degradation time and degradation rate) of M2 are different from those of M1 and M3. These differences affect the soil microenvironment, therefore, affecting the growth and yield of cotton. Based on the biodegradability, soil hydrothermal conditions, and cotton yield, the M2 film should be a potential alternative to PE film for improving cotton yield and controlling soil pollution.

5 Conclusions

A 2-year experiment in a cotton field was conducted to test the potential of biodegradable films to replace PE film in mulched drip irrigation. The results revealed that the degradable film was similar to the traditional PE film in increasing soil surface temperature, maintaining soil moisture, and improving crop growth. M2 degraded the quickest and showed the highest degree of degradation compared with the other degradable films and PE films. The warming effect first increased and then decreased with the growth of cotton, while gradually decreasing with increased soil depth. The effect of film degradation on the shallow soil water content was much greater than that in deep soil, especially at a depth of 0-40 cm. Furthermore, in all treatments, the seedling emergence rate and growth index of cotton under M2 were similar to those found under the PE film. Moreover, the yield of cotton under M1, M3, and M4 was significantly lower than that grown under PE film, while the cotton yield using M2 was slightly higher than that grown under the PE film. Considering the cotton yield and the low accumulation of residual film in the soil, the colorless transparent oxidation-biodegradable film (M2) was recommended as a potential alternative to PE films for the large-scale application of mulched drip irrigation. This study will be beneficial to improving the sustainable development of agricultural ecology and controlling soil residual film pollution in similar arid regions.

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[References]

[1] Wang Z H, Wu Q, Fan B H, Zhang J Z, Li W H, Zheng X R, et al. Testing biodegradable films as alternatives to plastic films in enhancing cotton (*Gossypium hirsutum* L.) yield under mulched drip irrigation. Soil & Tillage Research, 2019; 192: 196−205.

[2] Wang Z H, Fan B H, Guo L. Soil salinization after long-term mulched drip irrigation poses a potential risk to agricultural sustainability. European Journal of Soil Science, 2019; 70: 20−24.

[3] Su H C, Shen Y P, Han P, Li J, Lan Y C. Precipitation and its impact on water resources and ecological environment in Xinjiang region. Journal of Glaciology and Geocryology, 2007; 25: 343−350. (in Chinese)

[4] Wang D W, Wang Z H, Lv T B, Zong R, Zhu Y, Zhang J Z, et al. Effects of drip tape modes on soil hydrothermal conditions and cotton yield (*Gossypium hirsutum* L.) under machine-harvest patterns. PeerJ, 2021; 9: e12004.

[5] Liu M X, Yang J S, Li X M, Yu M, Wang J. Effects of irrigation water quality and drip tape arrangement on soil salinity, soil moisture distribution, and cotton yield (*Gossypium hirsutum* L.) under mulched drip irrigation in Xinjiang, China. Journal of Integrative Agriculture, 2012; 11: 502−511.

[6] Zhong R S, Tian F Q, Yang P N, Yi Q X. Planting and irrigation methods for cotton in southern Xinjiang, China. Irrigation and Drainage, 2016; 4: 461−468.

[7] Naveen G, Humphreys E, Eberbach P L, Balwinder S, Sudhir Y, Kukal S S. Effects of tillage and mulch on soil evaporation in a dry seeded rice-wheat cropping system. Soil & Tillage Research, 2021; 209: 104976. doi: 10.1016/j.still.2021.104976.

[8] Ginovart M, Mas M T, Verdu A, Josa R. The effect of a prototype hydromulch on soil water evaporation under controlled laboratory conditions. Journal of Hydrology and Hydromechanics, 2020; 68: 404−410.

[9] Zhong R S, Tian F Q, Yang P L, Yi Q X. Planting and irrigation methods for cotton in southern Xinjiang, China. Irrigation and Drainage, 2016; 65: 461−468.

[10] Bu L, Liu J L, Zhu L, Luo S S, Chen X P, Li S Q, et al. The effects of mulching on maize growth, yield and water use in a semi-arid region. Agricultural Water Management, 2013; 123: 71−78.

[11] Zhao Y, Chen X G, Wen H J, Zheng X, Niu Q, Kang J M. Research status and prospect of control technology for residual plastic film pollution in farmland. Transactions of the CSAM, 2017; 48: 1-14. (in Chinese)

[12] Sintim H Y, Flury M. Is biodegradable plastic mulch the solution to agriculture's plastic problem? Environmental Science Technology, 2017; 51: 1068−1069.

[13] Wang Y J, Huang Q Q, Liu C, Ding Y Y, Liu L, Tian Y L, et al. Mulching practices alter soil microbial functional diversity and benefit to soil quality in orchards on the Loess Plateau. Journal of Environmental Management, 2020; 271: 110985. doi: 10.1016/j.jenvman.2020.110985.

[14] He H J, Wang Z H, Guo L, Zheng X R, Zhang J Z, Li W H, et al. Distribution characteristics of residual film over a cotton field under long-term film mulching and drip irrigation in an oasis agroecosystem. Soil & Tillage Research, 2018; 180: 194−203.

[15] Fu W, Fan J, Hao M D, Hu J S, Wang H. Evaluating the effects of plastic film mulching patterns on cultivation of winter wheat in a dryland cropping system on the Loess Plateau, China. Agricultural Water Management, 2021; 244(C). doi: 10.1016/j.agwat.2020.106550.

[16] Liu E K, He W Q, Yan C R. 'White revolution' to 'white pollution'-agricultural plastic film mulch in China. Environmental Research Letters, 2014; 9(9): 091001. doi: 10.1088/1748-9326/9/9/091001.

[17] Zeng L S, Zhou Z F, Shi Y X. Environmental problems and control ways of plastic film in agricultural production. Applied Mechanics and Materials, 2013; 295: 2187−2190.

[18] Yan C R, Liu E K, Shu F, Liu Q, Liu S, He W Q. Review of agricultural plastic mulching and its residual pollution and prevention measures in China. Journal of Agricultural Resources and Environment, 2014; 31: 95−102. (in Chinese)

[19] Zhang D, Ng E, Hu W, Wang H, Galaviz P, Yang H, et al. Plastic pollution in croplands threatens long-term food security. Global Change Biology, 2020; 26: 3356−3367.

[20] He W, Yan C, Zhao C, Chang R, Liu S. Study on the pollution by plastic mulch film and its countermeasures in China. Journal of Agro-Environment Science, 2009; 28: 533−538. (in Chinese)

[21] Zhang J Z, He H J, Wang Z H, Fan B, Zheng X R, Li W H, et al. Returning cotton stalks to the field increases residual plastic film in oasis agroecosystems under long-term mulched drip irrigation. Soil Science Society of America Journal, 2019; 83: 1502−1511.

[22] Wang P. Measures to reduce the pollution of residual of mulching plastic film in farmland. Transactions of the CSAE, 1998; 14(3): 185−188. (in Chinese)

[23] Kasirajan S, Ngouajio M. Polyethylene and biodegradable mulches for agricultural applications: A review. Agronomy for Sustainable Development, 2012; 32: 501−529.

[24] Dong H G, Liu T, Li Y G, Liu H F, Wang D. Effects of plastic film residue on cotton yield and soil physical and chemical properties in Xinjiang. Transactions of the CSAE, 2013; 29(8): 91−99. (in Chinese)

[25] Hu Q, Li X Y, Goncalves J M, Shi H B, Tian T, Chen N. Effects of residual plastic-film mulch on field corn growth and productivity. Sci Total Environ, 2020; 729: 138901. doi: 10.1016/j.scitotenv.2020.138901.

[26] Zou X Y, Niu W Q, Liu J J, Li Y, Liang B H, Guo L L, et al.. Effects of residual mulch film on the growth and fruit quality of tomato (*Lycopersicon esculentum* Mill.). Water, Air & Soil Pollution, 2017; 228(2): 71.1−71.18.

[27] Gao H H, Yan C R, Liu Q, Ding W L, Chen B Q, Li Z. Effects of plastic mulching and plastic residue on agricultural production: A meta-analysis. Science of the Total Environment, 2019; 651: 484−492.

[28] Kyrikou L, Briassoulis D. Biodegradation of agricultural plastic films: A critical review. Journal of Polymers and the Environment, 2007; 15(2): 125−150.

[29] Scarascia-Mugnozza G, Schettini E, Vox G, Malinconico M, Immirzi B, Pagliara S. Mechanical properties decay and morphological behaviour of biodegradable films for agricultural mulching in real scale experiment. Polymer Degradation and Stability, 2006; 11: 2801−2808.

[30] Vox G, Schettini E. Evaluation of the radiometric properties of starch-based biodegradable films for crop protection. Polymer Testing, 2007; 5: 639−651.

[31] Scarascia-Mugnozza G, Schettini E, Vox G. Effects of solar radiation on the radiometric properties of biodegradable films for agricultural applications. Biosystems Engineering, 2004; 4: 479−487.

[32] Zhang J, Ren X L, Luo S F, Hai J B, Jia Z K. Influences of different covering materials mulching on soil moisture and corn yield. Trans. Transactions of the CSAE, 2017; 26:14−19. (in Chinese)

[33] Bilck A P, Grossmann M V E, Yamashita F. Biodegradable mulch films

for strawberry production. Polym Test, 2010; 29:471–476.

[34] Tan D C, Guo L L, Liu J M, Fan Y L, Li Q Q. Response of dry matter translocation and grain yield of summer maize to biodegradable film in the North China Plain. International Agrophysics, 2020; 34:87−94.

[35] Kader M A, Senge M, Mojid M A, Ito K. Recent advances in mulching materials and methods for modifying soil environment. Soil & Tillage Research, 2017; 168: 155−166.

[36] Costa R, Saraiva A, Carvalho L, Duarte E. The use of biodegradable mulch films on strawberry crop in Portugal. Scientia Horticulturae, 2014; 173: 65−70.

[37] Li Z H, Zhang L F, Kang X, Zhao P Y, He W Q, Wei F S. Research of soil environment and fertility of potato grow in dry land mulching degradable plastic film. Chinese Agricultural Science Bulletin, 2011; 27: 249−253.

[38] Siegenthaler K O, Kunkel A, Skupin G, Yamamoto M. Ecoflex (R) and Ecovio (R): biodegradable, performance-enabling plastics. Synthetic Biodegradable Polymers, 2012; 245:91−136.

[39] Hu W, Sun J S, Shan N N, Yan J, Wang X Y. Effect of COPO degradable membrane on soil temperature and crop yield and analysis of its degradable characteristics. Xinjiang Agricultural Sciences, 2015; 52: 317−320. (in Chinese)

[40] Wang Y Z, Yang K K, Wang X L, Zhou Q, Zheng C Y, Chen Z F. Agricultural application and environmental degradation of photo-biodegradable polyethylene mulching films. Journal of Polymers and the Environment, 2004; 12(1): 7−10.

[41] Zong R, Wang Z H, Zhang J Z, Li W H. The response of photosynthetic capacity and yield of cotton to various mulching practices under drip irrigation in Northwest China. Agriculture Water Management, 2021; 249: 106814. doi: 10.1016/j.agwat.2021.106814.

[42] Gu X B, Cai H J, Fang H, Li Y P, Chen P P, Li Y N. Effects of degradable film mulching on crop yield and water use efficiency in China: a meta-analysis. Soil & Tillage Research, 2020; 202: 104676. doi: 10.1016/j.still.2020.104676.

[43] Yi M H, Li Y N, Fang H, Chen P P. Biodegradable mulching film with an optimum degradation rate improves soil environment and enhances maize growth. Agriculture Water Management, 2019; 216: 127−137.

[44] Gu X B, Cai H J, Fang H, Chen P P, Li Y P, Li Y N. Soil hydro-thermal characteristics, maize yield and water use efficiency as affected by different biodegradable film mulching patterns in a rain-fed semi-arid area of China. Agricultural Water Management, 2021; 245: 106560. doi: 10.1016/j.agwat.2020.106560.

[45] Deng L, Yu Y, Zhang H Y, Wang Q, Yu R D. The effects of biodegradable mulch film on the growth, yield, and water use efficiency of cotton and maize in an arid region. Sustainability, 2019; 11(24): 7039. doi: 10.3390/su11247039.

[46] Feng H, He W Q, Zhang F H, Liu Q, Lv J, Liu X W. Study on the Performance of Biodegradable Film and Its Influence on Cotton Yield. Ecology and Environmental Sciences, 2019; 28: 580−586

[47] Li Q, Li H B, Zhang L, Zhang S Q, Chen Y L. Mulching improves yield and water-use efficiency of potato cropping in China: A meta-analysis. Field Crops Research, 2018; 221: 50−60.

[48] Sun T, Li G, Ning T Y, Zhang Z M, Mi Q H, Lal R. Suitability of mulching with biodegradable film to moderate soil temperature and moisture and to increase photosynthesis and yield in peanut. Agricultural Water Management, 2018; 208: 214−223.

[49] Zhou L M, Jin S L, Liu C A, Xiong Y C, Si J T, Li X G, et al. Ridge-furrow and plastic-mulching tillage enhances maize-soil interactions: Opportunities and challenges in a semiarid agroecosystem. Field Crops Research, 2012; 126: 181−188.

[50] Bu L D, Liu J L, Zhu L, Luo S S, Chen X P, Li S Q, et al. The effects of mulching on maize growth, yield and water use in a semi-arid region. Agriculture Water Management, 2013; 123: 71−78.

[51] Gu X B, Li Y N, Du Y D. Biodegradable film mulching improves soil temperature, moisture and seed yield of winter oilseed rape (Brassica napus L.). Soil & Tillage Research, 2017; 171: 42−50.

[52] Moreno M M, Moreno A. Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. Scientia Horticulturae, 2008; 116: 256−263.

[53] Li Y, Shao M G, Wang W Y, Wang Q J, Horton R. Open-hole effects of perforated plastic mulches on soil water evaporation. Soil Science, 2003; 168: 751−758.

[54] Li X Y, Gong J D, Gao Q Z, Li F R. Incorporation of ridge and furrow method of rainfall harvesting with mulching for crop production under semiarid conditions. Agricultural Water Management, 2001; 50: 173−183.

[55] Li R, Hou X Q, Jia Z K, Han Q F, Ren X L, Yang B P. Effects on soil temperature, moisture, and maize yield of cultivation with ridge and furrow mulching in the rainfed area of the Loess Plateau, China. Agricultural Water Management, 2013; 116: 101−109.

[56] Braunack M V, Johnston D B, Price J, Gauthier E. Soil temperature and soil water potential under thin oxodegradable plastic film impact on cotton crop establishment and yield. Field Crops Research, 2015; 184: 91−103.

[57] Saglam M, Sintim H Y, Bary A I, Miles C A, Ghimire S, Inglis D A, Flury M. Modeling the effect of biodegradable paper and plastic mulch on soil moisture dynamics. Agricultural Water Management, 2017; 193: 240−250.

[58] Jia H, Wang Z H, Zhang J Z, Li W H, Reng Z L, Jia Z C, et al. Effects of biodegradable mulch on soil water and heat conditions, yield and quality of processing tomatoes by drip irrigation. Journal of Arid Land, 2020; 12: 105−122.

[59] Wu Q, Wang Z H, Zheng X R, Zhang J Z, Li W H. Effects of biodegradation film mulching on soil temperature, moisture and yield of cotton under drip irrigation in typical oasis area. Transactions of the CSAE, 2017; 33: 135−143. (in Chinese)

[60] Abduwaiti A, Liu X W, Yan C R, Xue Y H, Jin T, Wu H Q, et al. Testing biodegradable films as alternatives to plastic-film mulching for enhancing the yield and economic benefits of processed tomato in Xinjiang Region. Sustainability, 2021; 13(6): 3093. doi: 10.3390/su13063093.