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Prevention and Control Strategy for the Pollution of Agricultural Plastic Film

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Abstract: Coverage and use of agricultural plastic films in China have been annually increasing; their area of use has been expanding rapidly from west to east. Therefore, we discuss the current condition of residual plastic film pollution, the resulting deterioration of soil physicochemical properties, and the risks of further ecological deterioration. The four causes of plastic film pollution are summarized. Common polyethylene plastic films are difficult to degrade and have substandard quality; such plastic films are difficult to recycle and have a low reuse efficiency. While degradable plastic is considered to be ideal, the technology for degradable plastic films has not been effectively developed. Moreover, substitute materials and a properly regulated production process are often unavailable. For these reasons, we propose some strategies to control agricultural plastic film pollution in order to provide guidance for the rational utilization of agricultural plastic films in China. For example, the standardized production of plastic films should be promoted, and the national standard of plastic film thickness (≥ 0.01 mm) should be strictly enforced. The scientific and rational use of plastic films in the farmland should be emphasized, and the timely removal of plastic mulching film should be promoted. Moreover, the efficiency of residual film retrieval machines should be improved. We should aim to achieve zero residuals of plastic films. Greater efforts should be devoted in the research and development of degradable plastic films, and the field application of degradable plastic films should be promoted.
Keywords: agricultural plastic films; pollution condition; prevention and control measures

1 Introduction

In recent years, the coverage and use of agricultural plastic films has grown rapidly in China. The area covered by plastic films in China reached 1.84×10^7 hm^2 in 2016, a level of coverage that is the largest of any nation in the world. Although plastic mulching increases crop yield, residual plastic mulch in farmland soils have become the primary form of nonpoint source pollution in the northern regions of China. In this paper, we analyze the trends of plastic film usage in Chinese agriculture, the current state of plastic film pollution, and the causes of this pollution. On this basis, we propose four strategic measures to combat agricultural plastic film pollution: the standardization of plastic film production, rational and scientifically informed plastic film usage, efficient plastic film recycling and the promotion of degradable plastic films. We aim to provide scientific guidelines for efforts to improve the environmental quality of farmland soils.

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2 Use of plastic films in Chinese agriculture and the current state of plastic film pollution

2.1 Current state of plastic film usage

2.1.1 Coverage and use of plastic films are increasing at significant rates

The coverage of plastic films in China increased by a factor of 2.11 from 1992 to 2016 (5.934×10^6 hm^2 in 1992 to 1.84×10^7 hm^2 in 2016), which represents an annual growth rate of 8.76% or 5.195×10^5 hm^2. The use of plastic films has grown by a factor of 2.87 from 1992 to 2016 (3.803×10^5 t in 1992 to 1.47×10^6 t in 2016), which represents an annual growth rate of 11.94% or 4.54×10^4 t. The consumption of plastic films in China now accounts for more than 50% of global plastic film consumption (Fig. 1). These data were obtained from the *China Rural Statistical Yearbook* (1992 – 2016).

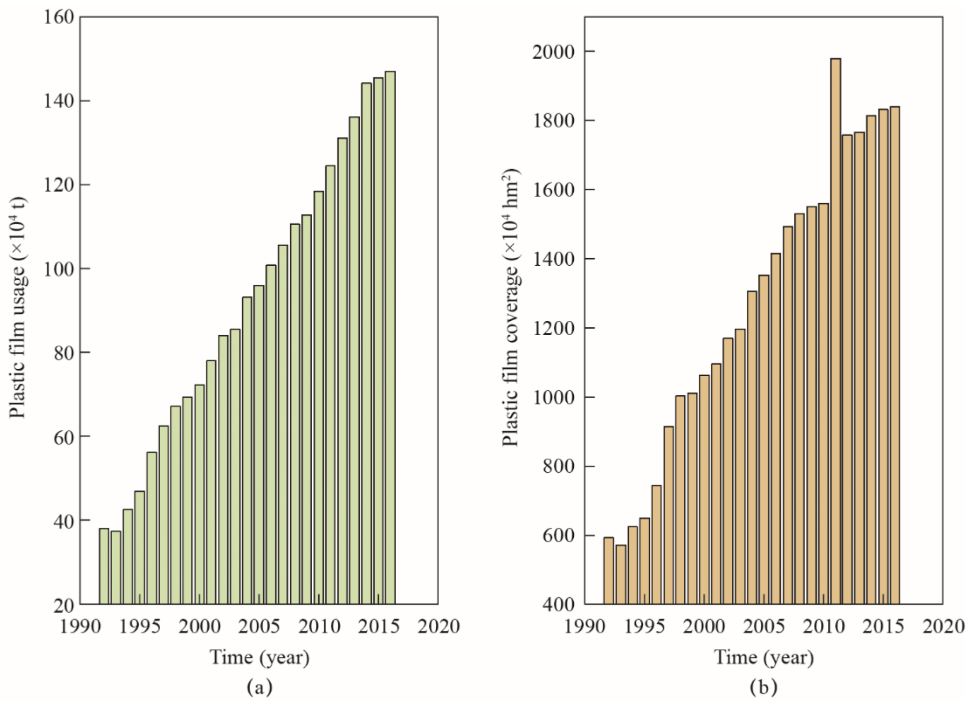

Fig. 1. Nationwide trends in the use and coverage of agricultural plastic films from 1992 to 2016.

2.1.2 The areas that use plastic films are expanding rapidly from the western provinces to the eastern provinces

Based on provincial statistics about plastic film coverage, Shandong, Sichuan, Xinjiang, and Hubei provinces had the largest plastic film coverages in 1992. The plastic film coverages of Shandong and Sichuan were 7.26×10^5 hm^2 and 6.618×10^5 hm^2, respectively, where the films were mostly used for the cultivation of vegetable crops. The area covered by plastic film cultivation was 6.167×10^5 hm^2 in Xinjiang and 5.125×10^5 hm^2 in Hubei, but less than 3.5×10^5 hm^2 in all other provinces. As a whole, the coverage of plastic film cultivation in Sichuan and Shandong greatly exceeds that of Northwestern China (Fig. 2). As of 2016, the number of provinces with plastic film coverages greater than 5×10^5 hm^2 and 1×10^6 hm^2 had increased to 12 and 8, respectively. In fact, the Shandong, Gansu, Inner Mongolia, Hebei, and Henan provinces in the central plains now make up the “great province of plastic film cultivation.” In Southwestern China, Yunnan and Sichuan provinces are the largest areas for plastic film cultivation. The provinces where plastic film coverage has exceeded 1.5×10^6 hm^2 are Xinjiang and Shandong, where plastic films cover areas of 3.405×10^6 hm^2 and 2.092×10^6 hm^2, respectively. The areas where plastic film cultivation is being employed have spread from Central China towards Northwestern China, Northeastern China, and Southern China. Hence, the areas covered by plastic films effectively include all provinces (cities and districts) of China (Fig. 2).

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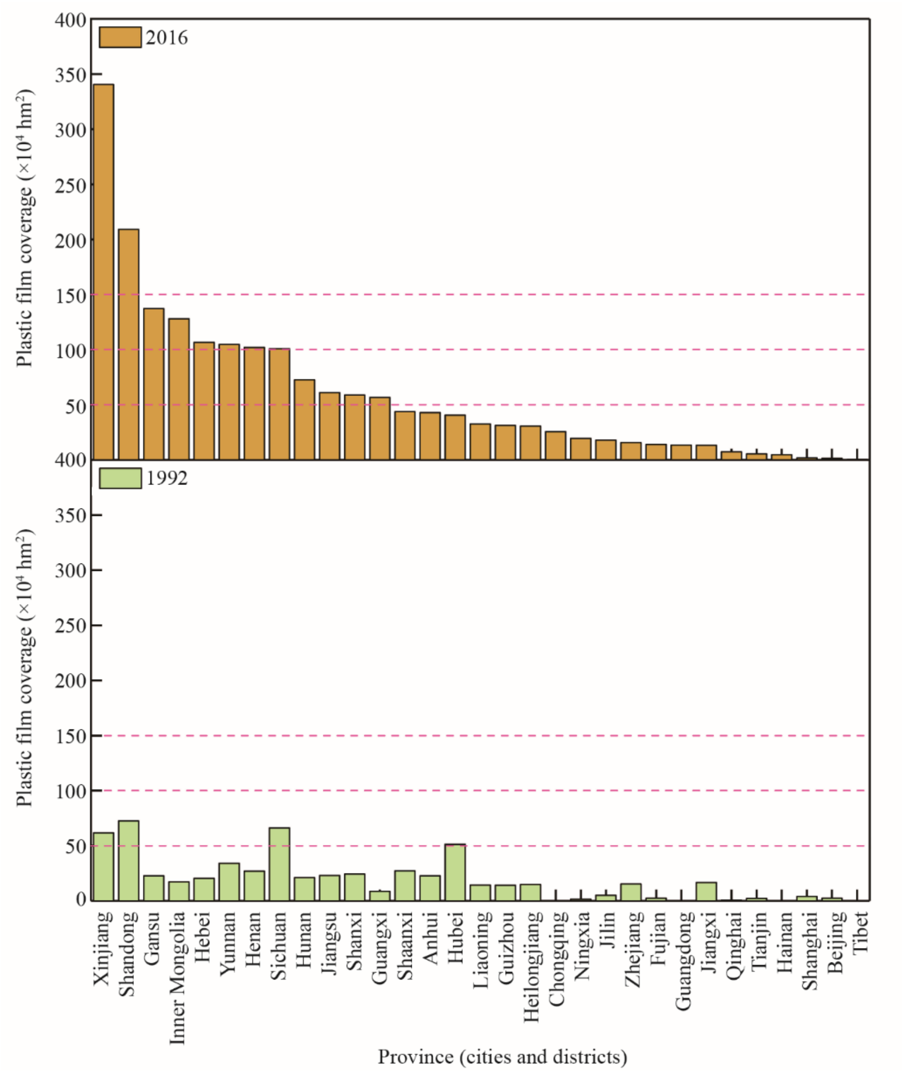

Fig. 2. Area covered by plastic films in each province (cities and districts).

2.2 State of plastic film pollution

At present, the total quantity of residual plastic films in China is almost 2×10^6 t. Moreover, the rate of plastic film retrieval is less than 2/3 of the residual plastic films, and its average quantity in China's farmlands is about 60 kg/hm^2 [1]. Given that plastic film usage is most prominent in the arid oasis areas of Northwestern China, plastic film pollution is also most severe in the farmlands of this region. For example, the plastic film coverage of Xinjiang is close to 3.405×10^6 hm^2, which accounts for more than 50% of the total farmland of this province. Based on the survey data of 20 counties in Xinjiang, the farmlands of Xinjiang have an average residual plastic film content of 255 kg/hm^2, which is five times the national average. Furthermore, farmlands with residual plastic film contents greater than 225 kg/hm^2 account for 80% of Xinjiang's farmlands. Therefore, plastic film pollution in Xinjiang is extremely severe.

Plastic film pollution in farmlands is also quite severe in other regions of China. A survey [2] found that the residual plastic film level was 139 kg/hm^2 in the farmlands of Longdong (Gansu), 110 kg/hm^2 in Shaanxi, 80.5 kg/hm^2 in the plastic film-covered cotton farms of the North China Plain, and 71.9 kg/hm^2 in the tobacco fields of Enshi (Hubei). Levels of 48 kg/hm^2, 58 kg/hm^2, and 40.5 kg/hm^2 were found in the plastic-mulched vegetable farms of Beijing, Hebei, and Shandong, respectively; and 66 kg/hm^2 of residual plastic films was found in the peanut-growing areas of Henan. The severity of plastic film pollution is therefore quite significant across China.

Due to the low rate of plastic film retrieval, the pollution caused by residual plastic films is continuously increasing in severity and coverage. The survey data on Shihezi (Xinjiang) shows that the residual plastic film levels of cotton farms that were covered by plastic films for 20 and 10 consecutive years were 326 kg/hm^2 and 278 kg/hm^2, respectively. Moreover, lands that have been covered for 20 consecutive years for the cultivation of cotton and process tomatoes, contained 358 kg/hm^2 of residual plastic films. Even in the southern region, residual plastic film levels have reached 140 kg/hm^2 in the corn cultivation regions of Hubei, where plastic mulching has been practiced for five consecutive years. The farmland coverage of plastic films has increased in nearly all provinces (cities and districts) of China over the past 20 years, and the increase in plastic film coverage generally ranges between 0.06% and 20.03%. The largest increases in plastic film coverage (greater than 17%) have occurred in Shanghai, Tibet, and Jiangxi. Jilin, Hubei, Sichuan, Qinghai, and Zhejiang saw increases of between 4% and 10%. It is thus clear that the per unit area coverage of plastic films in farmlands is growing over time; the threat posed by plastic film pollution has thus been increasing over time.

2.3 Plastic film pollution has degraded the physicochemical properties of farmland soils and exacerbated pollution levels

2.3.1 Plastic film residues prevent the formation of arable strata and degrades the physiochemical properties of farmland soils, thus reducing crop yield

The plastic films that are used in China are usually less than 0.008 mm thick and extremely easy to tear. The number of 1– 25 cm^2 plastic film fragments contained in each hm^2 of farmland ranges from 1×10^7 to 2×10^7; these fragments mix with the 0 cm – 20 cm layer of arable soil, forming an artificial barrier layer. Experiments have shown that a residual plastic film soil content of 225 kg/hm^2 increases soil bulk density by 18.2% and decreases soil porosity by 13.8%, as compared to uncontaminated soils [3]. This reduces the volumetric water content and the infiltration rate in the 0– 120 cm layer of soil, therefore reducing soil water storage capacity during the crop growing period [4, 5].

The presence of residual plastic films also affects the soil nutrients of cotton cultivation lands to varying degrees. After 10, 15, and 20 years of continuous plastic mulching, soil available phosphorus decreased by 29.14%, 22.09%, and 38.34%, whereas soil available potassium initially increased and then decreased [6]. This is because residual plastic films hinders the mineralization and release of soil nutrients, thus reducing soil fertility. Other studies have also shown that continuous plastic mulching for 3–5 years in farmlands with low plastic film collection rates reduced wheat yield by 2% – 3%, corn yield by approximately 10%, cotton yield by 10% – 23%, and vegetable yields by 14.6% – 59.2% [7,8]. Residual plastic films, therefore, have a significant (negative) impact on crop yields.

2.3.2 Products of plastic film degradation increase the risk of environmental pollution

Residual plastic films may release inorganic and organic pollutants into the soil that will have long-term effects on soil quality and crop yields. The plasticizers, antioxidants, and flame retardants contained in residual plastic films are the primary sources of organic pollutants. In particular, the plasticizers used in plastic films are usually phthalates, which are gradually released into the environment and thus lead to air, water, and soil pollution. Phthalates also pose a danger to human health as they can enter the food chain, which exacerbates their environmental and health risks.

3 Causes of plastic film pollution

3.1 Ordinary polyethylene (PE) films are difficult to degrade

Agricultural plastic films are usually made from polymeric polyethylene and its resins, which usually have high molecular weights, stable properties, high resistance to chemical corrosion, and excellent insulative properties. Therefore, plastic films are difficult to photodegrade or thermally degrade under natural conditions, nor is it easy to degrade by microbial and enzymatic means. Under ordinary conditions, plastic film residues can persist in soil for 200 – 400 years [9]. Residual plastic films are therefore a major nonpoint source pollutant in farmlands.

3.2 Plastic films used in Chinese agriculture are subpar in quality and difficult to collect, which leads to low recycling rates

According to the *Polyethylene blown mulch film for agricultural uses* (GB13735–1992) standard promulgated by the Ministry of Light Industry in 1992, the minimum thickness for PE plastic films is 0.008 mm. In reality however, plastic films are usually 0.004 mm – 0.008 mm thick. Due to market demand and price-related reasons, plastic film producers usually prefer to produce ultrathin plastic films (Table 1).

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Table 1. Overhead cost and quantity of plastic films associated with plastic films of different thicknesses (for cotton cultivation in Xinjiang).

Plastic film thickness /mm	Amount of plastic films /(kg·hm^{-2})	Cost /(CNY·hm^{-2})
0.006	45	585
0.007	57	741
0.008	65	845
0.009	70	910
0.010	78	1014
0.012	92	1196

Note: The average unit price of plastic films is 13 CNY/kg

In addition, plastic films have a very low recycling rate. In Gansu, the market price for regenerated granules was 7500 CNY/t in 2015, but only 4200 – 4800 CNY/t in 2017, which is roughly a 50% decrease in price. Since it costs 4000 CNY/t to produce regenerated granules, the profit margin of plastic film recycling enterprises is less than 2%. Furthermore, it is difficult for plastic processing enterprises to obtain preferential tax rates or electricity charges, which further restricts the rate of plastic film recycling.

3.3 Technology for degradable plastic films has yet to be effectively developed, and there are no suitable replacements for plastic films in the market

The widths, extensibilities, initial breaking times, breaking rates, and degradation products from degradable plastic films differ from one crop to another. Consequently, the compatibility between degradable plastic films and agricultural processes tends to be quite poor. For example, if the degradable plastic film is too ductile for a seed sowing machine, the seed sowing machine may be unable to punch a hole through the plastic film, because the film will simply stretch. This prevents the seed from entering the soil, and the seeding failure rate can be as high as 30% due to this incompatibility. In addition, the initial (mechanical) breakdown time of degradable plastic film can differ in different climates, which leads to regional differences in its usefulness (i.e., its ability to maintain soil warmth and moisture). These operational issues have limited the popularity of degradable plastic films. In the short term, degradable plastic films will not be able to replace ordinary PE films.

3.4 Management system for plastic film production is in disarray and there is a lack of rigorous monitoring mechanisms for the control of plastic film pollution

According to incomplete statistics, there are approximately 800 plastic film-producing companies of varying size in China. Approximately 600 of these companies have an annual production capacity of < 3000 t. Due to industrial policies, pricing systems, and supply and demand-related reasons, the agricultural resins used by these companies come from a wide array of brands, and their product supplies also tend to be unstable. Furthermore, the plastic films produced by these companies are usually subpar in quality, which severely hampers the collection of plastic films. In addition, laws for the monitoring and restriction of plastic film pollution in farmlands are simply non-existent. Most farmers tend to retrieve used plastic films haphazardly, with some simply tilling the plastic films into the soil. There is also a lack of collection points for plastic films throughout China, which prevents the plastic films collected by the farmers from being recycled effectively. Consequently, the plastic films are simply burned or stacked in a pile, which leads to secondary pollution.

4 Strategic measures for combating plastic film pollution in farmlands

4.1 Standardize plastic film production to eliminate the source of subpar plastic films

To facilitate the standardization of plastic film production, each province should formulate standards that are suitable locally. For example, Xinjiang announced the *Polyethylene blown mulch film for agricultural uses* (DB65T/3189–2014) local mandatory standard in 2014, which specifies that agricultural mulch films must have a minimum thinness of 0.01 mm and an endurance time of 180 days. Plastic films that abide by this new standard will not decompose during a production cycle, thus they will be much easier to collect and recycle at the end of the production cycle. In 2016, Xinjiang announced the *Regulations for Agricultural Plastic Film in the Xinjiang Uygur Autonomous Region*, which provides a set of specifications and legislations that will make plastic film usage in farmlands more scientifically informed. This new standard includes three nominal thicknesses for plastic films

(0.012 mm, 0.014 mm, and 0.20 mm) and provides “duration of use” recommendations (180 days for 0.010 mm- and 0.012 mm-thick films, and 360 days for 0.014 mm- and 0.020 mm-thick films), thus controlling plastic film pollution by addressing its sources.

4.2 Optimization of plastic mulching methods and the promotion of techniques like timely plastic film removal

The optimization of plastic mulching methods and the promotion of scientifically informed plastic film usage are important parts of the endeavor to reduce plastic film pollution. Curbing the use of ineffective ultra-wide plastic films is one way to rationalize plastic film usage with respect to different crop types and cropping patterns, as it effectively reduces plastic film coverage and usage. For example, in a study comparing the use of plastic films of varying widths (50 cm, 100 cm, and 150 cm) during off-season (winter/spring) cucurbit planting in Southern China (Guangdong and Guangxi), it was shown that 100 cm-wide plastic films achieved higher levels of watermelon growth and yield than 50 cm- and 150 cm-wide plastic films. This is because plastic mulching has a different function in each season; it helps maintain soil warmth and moisture during the cold and dry months of winter, whereas its role in the rainy spring and summer months is to protect the soil from nutrient leaching. During the early stages of crop growth, the 100 cm-wide plastic film is superior to the 50 cm-wide plastic film in terms of its ability to maintain soil warmth and moisture and therefore promotes root system growth. During the later stages of crop growth, the 100 cm-wide plastic film facilitates steady and healthy crop growth, as it is superior to the 150 cm-wide plastic film in terms of soil nutrient/moisture regulation, soil nutrient retention, and soil aeration. Therefore, a plastic film width of 100 cm is optimal for reducing plastic film residues and maximizing crop productivity. The use of plastic films with an appropriate width effectively reduces the amount of plastic films used per unit area (of farmland) and the accumulation of residual plastic films. Another approach that could reduce the accumulation of residual plastic films is the promotion of timely plastic film removal practices. This refers to the removal of plastic films from farms in a timely manner, before they begin to break apart due to age and exposure. In Hebei and Xinjiang, some farms have begun to remove plastic films before the watering of their cotton crops. At this point, the plastic film has not deteriorated due to age; thus, it is ductile and difficult to tear, which makes it relatively easy to collect. Collection rates greater than 90% have been achieved in this way. In the corn farms of Shanxi, the appropriate timing for plastic film removal is the jointing stage, which is about 45 days after the corn plants begin to emerge. This approach greatly increases the rate of plastic film collection. In corn growing regions at altitudes higher than 1 000 m above sea level, the appropriate timing for plastic film removal is the large bell mouth stage, which is somewhat later; this timing ensures a plastic film collection rate of 85% without compromising crop yield.

4.3 Strengthen research on plastic film retrievers and promote their use to improve the effectiveness of mechanical plastic film retrieval

Machines for the retrieval of plastic films should be designed to ensure compatibility with cropping patterns. Multi-purpose plastic film retrievers that are also capable of pulverizing/pulling stalks are the current focus of research and development (R&D) efforts in this area. Two representative results of this research are the 4SJ-1.6 and 4SJ-2.0 machines developed by the Xinjiang Academy of Agricultural Sciences. Currently, these machines have complex mechanical structures, making it difficult to achieve high plastic film retrieval rates when they operate at high speeds – which is now the primary focus of R&D efforts. In Gansu and Inner Mongolia, much of the R&D efforts are focused on the development of small machines for crops like corn and potatoes. One example is the 1MC-70 developed by Shengeng Machinery Co., Ltd. (Hebei). This machine uses a front-mounted shoveling structure to dig up stubble and plastic films, which are then separated by a vibrating mesh and a drum screen. The plastic films are then stored in a rear-mounted frame. These machines are widely used in the corn farms of Gansu, Inner Mongolia, and Shanxi. However, as these machines are relatively small (in width), they have low operating efficiencies and are only suitable for small strip fields [10]. In summary, it is necessary to devote more resources to the development of plastic film retrievers.

4.4 Strengthen efforts to develop degradable plastic films

The aim of R&D efforts in this area is to develop a plastic film that is fully degradable, and whose degradation products will not cause secondary pollution. For example, CO_2 and water are the optimal ultimate degradation products for oxo-biodegradable plastic films. Degradable plastic films should be pilot-tested in a variety of regions

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to determine how they break down mechanically and decompose under different climatic/ecological conditions, as well as under different growth stages of various crops, to provide reference data for the development of degradable plastic film products. Our group has previously conducted an experimental study on the mechanical breakdown of degradable plastic films during the cultivation of cotton, corn, and process tomatoes in Xinjiang. In this study, we found that degradable plastic films become ineffective in maintaining soil warmth and moisture when their level of mechanical breakdown reaches 20% per unit area. Based on the monitoring of plastic film breakage and field burial tests, we found that different plastic films differ significantly in their breakdown rates; 20% plastic film breakage per unit area occurred after 1 061 days for ordinary PE, 136 days for 0.01 mm-thick degradable plastic films, and 111 days for 0.012 mm-thick degradable plastic films (Table 2). Since thicker degradable plastic films broke down more quickly than thinner degradable plastic films, degradable plastic films should be produced with a thickness of 0.01 mm.

Table 2 Breakdown rates of different types of plastic films.

Type of plastic film	Time required to reach each level of breakdown in days					
	20%	35%	50%	65%	80%	100%
Ordinary PE film	1 061	1 384	1 642	1 863	2 062	2 296
0.01 mm-thick degradable plastic film	136	167	192	214	233	256
0.012 mm-thick degradable plastic film	111	137	158	176	191	210

In addition to mechanical breakdown, chemical decomposition properties are also an important performance measure for degradable plastic films. Our group has also conducted a three month-long burial test on the aforementioned plastic films, to ascertain the time needed for degradable plastic films to decompose into non-polluting substances (Fig. 3). After three months, the decomposition level of the degradable plastic films was only 2.89%–16.43%. Black degradable plastic films exhibited a higher level of decomposition than white degradable plastic films, and the decomposition rate of these films decreased over time. This indicates that there is a delay in the decomposition of degradable plastic films, and it is not possible for these films to fully decompose within a year.

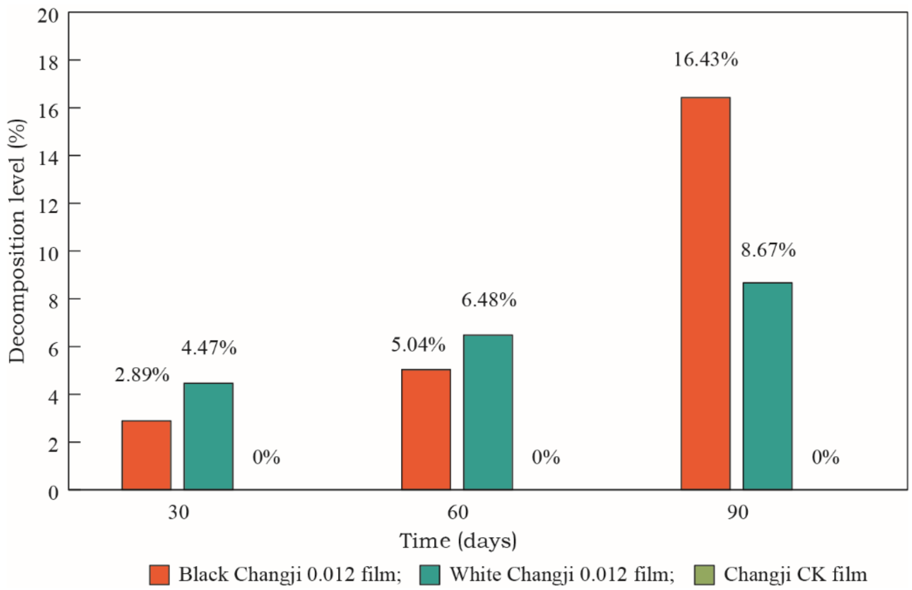

Fig. 3. Decomposition levels of different types of plastic film.

In view of the mechanical and chemical degradation behaviors of plastic films, research efforts should be devoted to the development of plastic films that are slow to break down mechanically but decompose quickly once they are tilled into the soil. This will ensure that the degradable plastic films will be able to maintain soil warmth and moisture for an extended period of time and produce a minimal quantity of residual plastic films.

4.5 Introduce legislative and regulatory systems to control residual plastic films

We suggest that legislative and regulatory systems for the control of plastic film pollution should be formulated and improved, so as to provide a legal basis for the mitigation of plastic film pollution. For example, remediation measures should be formulated for situations wherein residual plastic films reach excessive levels. Moreover, plastic film production and residual plastic film standards should be unified and improved to standardize the quality of plastic film products. In this way, the control of plastic film pollution will be integrated into China's legal system.

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