Research Article

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The degradable time evaluation of degradable polymer film in agriculture based on polyethylene film experiments

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Abstract: Popularly, the application of biodegradable polymer film can resolve polyethylene (PE) film residual “white pollution” but it is unclear when the degradable film begins to degrade in different regions. To solve these issues, a total of 32 papers on the subject of the relative film coverage durability (RFCD) on positive covering effect from papers published before July 2019 were selected and analyzed by meta-analysis. The results showed that the tobacco relative yield (RY), relative profit (RP), and relative fine and medium (RFM) ratio improved by 11.2%, 12.9%, and 12%, respectively, under fully covered compared with the uncovered tobacco in the whole growth period. The $RY_{0.33 < RFCD < 0.66}$ and $RP_{0.33 < RFCD < 0.66}$ of removed PE treatments significantly improved by 4.3% and 4.0%, respectively, compared with the fully covered treatments. The RFM did not show significance with the fully covered treatments. The $RY_{0.33 < RFCD < 0.66}$ was the highest in the low altitude (less than 1,000 m) region; however, the RY under the fully covered treatments was the greatest in the high altitude (more than 1,000 m) region. Random effect analysis showed that the model between RFCD and RY was $RY = 1 + 0.275 \times (1 - RFCD) - 0.357 \times (1 - RFCD)^2$, and the $RY_{max}(1.053)$ was reached with $RFCD = 0.62$ (removed PE

after covering for 80 days) in the high-altitude region. In the low altitude region, $RFM = 1 + 0.205 \times (1 - RFCD) - 0.246 \times (1 - RFCD)^2$, and the $RFM_{max}(1.043)$ was obtained under the treatments with $RFCD = 0.58$ (removed PE after covering for 75 days). The findings determined the optimum film (PE) covering period of tobacco and provided a crucial theoretical basis for the degradable polymer film material design, synthesis, and manufacturing in different regions.

Keywords: PE film covering, degradable film polymer materials, RFCD, meta-analysis, tobacco yield and quality

1 Introduction

Covering is an effective planting pattern of modification of the microclimatic to enhance crop productivity and water use efficiency (WUE). According to the covering materials applied, covering materials can be broadly classified into three main types: organic materials (plant products, e.g., crop straw, and paper), inorganic materials (synthetic polymers film, e.g., colorful plastic film, biodegradable film, and photodegradable film) and special materials (e.g., sand, concrete). The choice of selection of an appropriate covering material depends on the local crop, climate, planting pattern, and cost-effectiveness (1). The application of plastic film covering in agriculture, called plasti-culture, has increased dramatically throughout the world since 2000 (2). Polyethylene (PE) plastic film covering was found very effective for warming (3,4), reducing soil surface evaporation and preserving soil moisture (5), salt suppression (6), and weed prevention (7) as well as an important technology for increasing more agricultural production, higher quality and higher economic benefits for farmers in China (Figure 1a). In recent 40 years, under the high-intensity continuous PE covering cultivation in China, the pollution of farmland ecosystem caused by the residue PE film that was difficult to recover and degrade was becoming more and more serious (8–10). In the Loess plateau, the northwest and the northeast wind-sand area of

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Figure 1: Plastic film mulched tobacco (a) and film residues (b) in field surface of China.

China, the amount of PE residues in soil has reached over 250 kg/ha. Accumulation of PE residue may cause negative effects on farmland soil structure, nutrient, and moisture movement, crop production, and landscape environment for a series of reasons, affecting the sustainable production of agriculture (10,11) (Figure 1b).

Replacing plastic film with a degradable film was a wise measure to solve the plastic film residue pollution. However, there were many contradictions between degradation time and crop growth and yield mismatch on the practice of degradable plastic film (11). In order to meet the needs of yield and quality formation process to the greatest extent, it was crucial to seek suitable covering and degradation period and design degradable film for the crop. Yan *et al.* (12) proposed the “safe period of crop plastic film covering,” which laid a foundation for exploring the balance between the environmental benefits of plastic film warming, moisture conservation, weed control and high yield and quality of crops, and enhanced the controllability of degradable plastic film materials. Liu *et al.* (13) studied that the dry weight of tobacco roots was 1.72 times that of film covering during the whole growth period after 30 days of exposure to PE (13). Guo *et al.* found that the biodegradable film cracked in the tobacco plant when it entered the cluster stage, which was 5.82% (14) higher than that of the upper-grade tobacco without film covering. The previous removal film experiments (15–18) provided a practical basis for tobacco safe period of film mulching tobacco in China (12).

The meta-analysis used the statistical analysis method to integrate the results of multiple field experimental studies covering the effect on regional scales in China (19,20). Gao *et al.* (2018) quantitatively analyzed the effects of plastic film mulching and residual plastic on yield and WUE of maize, wheat, potato, and cotton in China based on a meta-analysis (21). Yin *et al.* (22) showed that the yield-increasing effect of maize was obvious when 0.008 mm thickness

degradable film was used in flat cropping at high altitude and low temperature by meta-analysis, which provides a reference for the design of degradable film thickness. It makes clear that the safe period of degradable plastic film covering can guide the design and production of plastic film. The degradation of the degradable film was affected by many factors, among which the weathering characteristics of degradable film were closely related to the production cost. Complete biodegradable polymer materials such as polybutylene succinate/adipic acid-butylene glycol ester (PBSA), butylene adipate and butylene terephthalate copolymer (PBAT), and polylactic acid (PLA) mainly increase the film thickness to improve the tensile strength and field weatherability of the film, but the production cost also increases.

Therefore, the experimental data of tobacco PE covering duration in this study are as follows: quantifies the impact on tobacco yield and quality at different altitudes and different covering durations by meta-analysis, optimizes and defines the safety period of tobacco PE covering, and enriches and improves the research methods of continuous safety period of PE covering. It was of great practical significance for the research, production, and application of biodegradable film to design suitable tobacco degradable film products to meet crop demand, reduce the cost of degradable plastic film materials, and avoid blindness in the sale and application of degradable plastic film (Scheme 1).

2 Experimental

2.1 Materials and methods

2.1.1 Literature review and data extraction

We collected peer-reviewed journal articles of publication investigation on the yield-quality effects of PE film-covered

Scheme 1: Synthesis process from meta-analysis on PE experiments (a) to the safe period of crop plastic film covering (b), from manufacturing degradation film (c) to field application (d).

tobacco. Chinese and English databases including China National Knowledge Infrastructure CNKI (<http://www.cnki.net>), WanFang (<http://www.wanfangdata.com.cn>), WeiPu (<http://www.cqvip.com>), Web of Science (<http://access.webofknowledge.com/>) were used to search the field experimental research papers (including academic dissertation) published in China in the past 24 years (1996–2019) on the correlation between different PE exposure times (coverage duration) and tobacco yield and quality. “Tobacco or tobacco leaf or flue-cured tobacco, film uncovering or film removing, yield or quality, film uncovering or film removing or film covering” was conducted, and the retrieved literature was screened. The screening criteria were as follows: (1) the test site was the main of China (longitude, latitude, and altitude); (2) the test treatment consisted of tobacco non-film covering and one of the films covering group during the whole growth period; (3) the film uncovering treatment included different time gradients; (4) the beginning and ending time of the transplanting of the tobacco seedlings

were determined; (5) The test PE film, thickness, and planting pattern was clear; and (6) the literature with the same test site, year, tobacco species and test data were excluded. After the strict screening of the above criteria, 32 available papers were obtained, including 111 paired experiments and 150 experimental observations. The main tobacco varieties were Yunyan 87 and K326, which were distributed in 12 provinces (Yunnan, Guizhou, Sichuan, Hunan, Guangdong, Guangxi, Chongqing, Shaanxi, Shandong, Anhui, Jilin, and Henan). The data of the location of the test site, duration of PE covering, yield, and quality were extracted from criterion-compliant literature studies and are shown in Scheme 1a and Table 1.

2.1.2 Data classification

Based on the six screening criteria, after the searching results were carefully checked, 142 observations from

Table 1: Experiment size of different mulching duration treatments

Effect sizes	Not covering (RFCD = 0) experimental sizes	0 < RFCD < 0.33 experimental sizes	0.33 < RFCD < 0.66 experimental sizes	Whole covering (RFCD = 1) experimental sizes
Tobacco yield	23	37	49	41
Tobacco profit	23	37	48	40
Tobacco fine and medium ratio	16	25	41	28

38 studies fit our selection criteria for the meta-analysis. According to the distribution of altitude data based on test points, 32 papers collected were divided into two categories: low-altitude defined as altitudes less than 1,000 m and high-altitude defined as greater than or equal to 1,000 m. According to the distribution of duration of covering, the PE relative film coverage durability (RFCD) was divided into four intervals: RFCD = 0 (no coverage), partial growth period coverage $0 < \text{RFCD} < 0.33$ and $0.33 < \text{RFCD} < 0.66$ (RFCD = 0.33 does not exist and $\text{RFCD}_{\max} = 0.652$ shown in Figure 2b), and RFCD = 1 (full growth period coverage); all variables were from the literature studies.

or transplanting seedlings to harvesting at the end of the growth period). Therefore, the RFCD value of non-covering treatment was 0, the RFCD value of covering treatment with different covering duration times was between $0 < \text{RFCD} < 1$, and the RFCD value of covering during the whole growth period was 1. RFCD was calculated as follows:

$$\text{RFCD} = \frac{\text{Film coverage duration (days)}}{\text{Film coverage duration in the whole growth period (days)}} \quad (1)$$

2.1.4 Study size

We used average RFCD for each study, and we calculated a measure of accuracy, “study size,” by summing the number of experimental units (replicates) over experiments and treatments:

2.1.3 RFCD

RFCD was the proportion (%) of the actual duration of coverage in the whole growth period (from covering sowing

Figure 2: Cumulative probability distribution of altitude (a), RFCD (b), RY (c), RP (d), and RFM (e) in all experimental sites.

$$\text{Study size} = \sum_{j,k} N_{\text{replicate}_{i,j,k}} \quad (2)$$

where study size i was the study size of publication i , $N_{\text{replicate}_{ijk}}$ was the number of replicates of treatment k from experiment j in publication i (21–23).

2.1.5 Calculation and integration of relative effect quantity

Relative effects of different PE covering duration (no film covering, different time PE removed) treatment (treatment group) and whole growth period covering (control group) on tobacco yield and quality were calculated as follows:

$$\text{RE} = \frac{\text{Agronomic/yield/quality indicators of removal film cover}}{\text{Agronomic/yield/quality indicators of whole film cover}} \quad (3)$$

where RE was the relative yield-quality effect. The yield and quality of no covering and different times PE removed were the treatment groups, and PE covering during the whole growth period was the control group. To more intuitively present yield-quality effects of tobacco under different covering duration, if $\text{RE} = 1$, the response ratio of film-covering and yield-quality indicators during the whole growth period and if $\text{RE} = 1$, showed that yield-quality indicators of the treated group were equal to the control group.

2.2 Statistical analysis

The relationship between RFCD and elevation factor on yield-quality effect was estimated and optimized by mixing effects modeling. The mixed effect of Models 1–5 was used for subgroup analysis of different groups. Models 1 and 3 (Table 2) were non-factor difference effect models and used to find more detailed heterogeneity information and could

also be used as a test of the robustness of meta-regression analysis.

β_1 and β_2 in Models 1–5 were model coefficients. Factor represents logical variables (such as altitude, etc.). The optimal model selection in Models 1–5 was based on Akaike Information Criterion (AIC) (24). The AIC calculation method was as follows:

$$\text{AIC} = 2 \times L + 2 \times k \quad (4)$$

where L was a log-likelihood value and k was the number of model parameters. The smaller the model AIC value, the higher the accuracy of the model, and vice versa. The model with a smaller AIC value was selected for predictive analysis.

All data analysis and mapping were conducted in R (25). The mixed effect models and selection were fitted using the R function lme and AIC (26).

3 Results and discussion

3.1 Cumulative probability distribution of altitude and relative coverage durability at test sites

After searching and screening, the geographic distribution of each test site in China is as shown in Figure 2a and b. Among them, the altitude range of the test site ranged from 52.2 to 1,982 m, with an average value of 991.78 m. The RFCD values of the film-uncovering tests after calculation ranged from 0.127 to 0.652, with an average value of 0.375. As shown in Figure 2c–e, the relative yield (RY) ranged from 0.524 to 1.292, with an average value of 1.005; the relative profit (RP) ranged from 0.553 to 1.311, with an average value of 1.005; and the relative fine and medium (RFM) ratio ranged from 0.470 to 1.230, with a mean value of 0.977. The cumulative probability of RFCD, yield and quality indicators showed a normal distribution. This evidence supported the conclusion that the sample size is sufficient.

3.2 The overall effect on yield and quality

Compared with the whole growth period covered with PE (as shown in Figure 3), $\text{RY}_{\text{RFCD}=0}$ (0.888, $p = 0.0013$) without PE significantly decreased by 11.2%, $\text{RP}_{\text{RFCD}=0}$ (0.871, $p = 0.0007794$) by 12.9%, and $\text{RFM}_{\text{RFCD}=0}$ (0.880, $p = 0.005116$) without PE significantly decreased by 12%.

Table 2: Specification of the models fitted to the data

Model	Equations
1	$\text{RES} - 1 = \beta_1 * (1 - \text{RMD})$
2	$\text{RES} - 1 = \beta_1 * (1 - \text{RMD}) : (\text{factor})$
3	$\text{RES} - 1 = \beta_1 * (1 - \text{RMD}) + \beta_2 * (1 - \text{RMD})^2$
4	$\text{RES} - 1 = \beta_1 * (1 - \text{RMD}) : (\text{factor}) + \beta_2 * (1 - \text{RMD})^2$
5	$\text{RES} - 1 = \beta_1 * (1 - \text{RMD}) : (\text{factor}) + \beta_2 * (1 - \text{RMD})^2 : (\text{factor})$

*Note: RES is the relative effect size (RY/RP/RFM).

Figure 3: The overall effect of RY, RP, and RFM responding to RFCD of tobacco.

When PE was removed within the growth period, $RY_{0 < RFCD < 0.33}$ (1.02, $p = 0.1891$) increased by 2.0% and $RY_{0.33 < RFCD < 0.66}$ (1.043, $p = 0.00019$) increased by 4.3% significantly. $RP_{0 < RFCD < 0.33}$ (1.042, $p = 0.0647$) increased by 4.2%, $RP_{0.33 < RFCD < 0.66}$ (1.040, $p = 0.01691$) significantly increased by 4.0%, and $RFM_{0 < RFCD < 0.33}$ (1, $p = 0.9866$), $RFM_{0.33 < RFCD < 0.66}$ (1.001, $p = 0.9659$) had no significant difference within the whole growth period covering.

3.3 The subgroup effect on yield-quality in different altitudes

In low altitude (elevation < 1,000 m) region, compared with the whole growth period covered with PE (Figure 4), $RY_{0 < RFCD < 0.33}$ (1.053, $p = 0.02$) and $RY_{0.33 < RFCD < 0.66}$ (1.071, $p < 0.01$) significantly increased by 5.3% and 7.1%, $RP_{0 < RFCD < 0.33}$ (1.063, $p = 0.063$, $p = 0.0564$) and $RP_{0.33 < RFCD < 0.66}$ (1.064, $p = 0.00182$) increased by 6.3% and 6.4%, respectively, and $RY_{0 < RFCD < 0.33}$ (1.013, $p = 0.6409$) and $RY_{0.33 < RFCD < 0.66}$ (1.004, $p = 0.846$) increased by 1.4% and 0.4%, respectively. So, $0.33 < RMD < 0.66$ was the highest RY, RP, and RFM in the low altitude region.

Compared with PE covering in the whole growth period (Figure 5), $RY_{0 < RFCD < 0.33}$ (1.026, $p = 0.4251$) and $RY_{0.33 < RFCD < 0.66}$ (1.0095, $P = 0.5425$) increased by 2.6% and 0.9% in the high altitude region (elevation > 1,000 m). $RP_{0 < RFCD < 0.33}$ (1.026, $p = 0.4251$) and $RFM_{0.33 < RFCD < 0.66}$ (1.006573, $p = 0.8172$) increased by 2.6% and 0.7%, and $RFM_{0 < RFCD < 0.33}$ (0.977, $p = 0.4463$) and $RFM_{RFCD=0.66}$ (0.996, $p = 0.8372$) decreased by 2.3% and 0.4%. The RFM of PE removed treatments in the high altitude was as less than 1, and there was no significant difference, which indicated that the yield-quality of PE covering in whole growth period (RFCD = 1) was the highest in the high-altitude region.

3.4 RFCD optimization of yield-quality at different altitudes

Taking the altitude as a model variable factor (low altitude < 1,000 m and high altitude $\geq 1,000$ m), there was no significant difference between RY and RP ($p = 0.2981$, $p = 0.2215$), and the AIC mean value of Model 3 was the smallest. Therefore, Model 3 was adopted with factor

Figure 4: Low-altitude subgroup effect of tobacco RY (a), RP (b), and RFM (c) responding to RFCD of tobacco.

Figure 5: High-altitude subgroup effect of tobacco RY (a), RP (b), and RFM (c) responding to RFCD of tobacco.

effect, its RFM had significant difference ($p = 0.0138$), while Model 4 had the smallest AIC (-130.4), and Model 4 fits RFM effects at high and low altitudes. The random effect analysis and model equation are shown in Figure 6. RFCD has a quadratic linear regression relationship with RY, RP, and RFM. Its $RY_{\max}(1.053)$ was higher than that of PE covering in the whole growth period by 5.3%, and its corresponding $RFCD = 0.615$ (calculated at 130 days of tobacco growth period, about 80 days PE removed after PE covering), and $RP_{\max}(1.056)$ was higher than PE covering in the whole growth period by 5.6%. RFCD can guide better covering and film degradation time.

As shown in Figure 6, there was a quadratic linear correlation between RFCD and $RFM_{<1,000}$ at low altitude ($<1,000$ m). The $RFM_{\max}(1.043)$ was 4.3% higher than PE covering during the whole growth period, and the corresponding RFCD was 0.583 (PE removed after PE covering 75 days). So, removal or degradation film (PE) can increase the photosynthetic assimilation products of tobacco and significantly improve the quality of tobacco leaves at a low altitude region. In high-altitude region where $RFM_{\geq 1,000} = 1 + 0.099 \times (1 - RFCD) - 0.246 \times (1 - RFCD)^2$, $RFM_{\max}$ was 1.01. The film could begin to degrade

after film covering 75–80 days at a low altitude ($<1,000$ m). There was no difference between PE removed and covered in the whole growth period, which indicates that at a high-altitude ($\geq 1,000$ m) region, tobacco should be kept covered during the whole growth period and not degrade during the growth period in order to maintain high yield-quality.

4 Discussion

By meta-analysis around crop yield and quality of PE mulching showed some usefulness in tobacco planting in the southwest of China, but more extensive research, application, and improvement were needed by far. The removal of plastic film at the middle of the tobacco growing season showed increasing yields and quality under undesirable conditions. This RFCD was basically consistent with the results of experiments in Enshi, Hubei Province, and Xunyang, Shanxi Province (27) in China. A higher altitude, lower temperatures, film removal, or degradation were less conducive to ridge insulation, and lower water evaporation in the field was easy to

Figure 6: The relationship and model between RY (a), RP (b), RFM (c), and RFCD.

cause the occurrence and spread of tobacco diseases. The ecological conditions of tobacco growth vary greatly at different altitudes. Altitude was an important factor affecting the ecological environment differences in tobacco-growing areas. The factors such as temperature, light, and rainfall were also different at different altitudes. The influence of altitude on the quality of tobacco leaves still dominates. Shang *et al.* (28) found that tobacco PE covering was more suitable for tobacco cultivation at high altitude >1,000 m, and with the increase of altitude, the time of film covering should be appropriately prolonged; on the contrary, should be appropriately shortened. The RFCD found in this research provides key information for manufacturing degradable film in China. So based on the above results, the cost of the tobacco degradable film material in the different regions could be reduced in the future.

5 Conclusion

In summary, our meta-analysis showed that, compared with PE covering in the whole growth period, the highest yield of film removal was in the low altitude region, while the yield of PE covering was the highest in the whole growth period at a high altitude region. The overall effects of RFCD, RY, and RP were quadratic linear regression models. The predicted RY_{max} and RP_{max} were 1.053 and 1.056, respectively. The corresponding RFCD was 0.615, the highest RFM_{max} was 1.043 at a low altitude, and the corresponding RFCD was 0.583. The yield-quality effect of PE removed after covering 75–80 days was higher than PE covering in the whole growth period, while in the high-altitude PE covering was kept in the whole growth period. The meta-analysis provides a key theoretical basis for evaluating the suitable period of tobacco film safety coverage and optimizing the design and manufacturing of degradable polymer film material products. The results would be useful in helping farmers, water-saving agriculture, and environmental sustainability in the future.

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