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Analysis of Carbon Reduction Benefits of Ecological Plastic Film Promotion and Use in Qingcheng Town, Shanxi Province

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Abstract: This study applied a life cycle assessment (LCA) and SimaPro software to calculate the carbon footprint of ecological plastic film in Qingcheng Town. The results indicate that the carbon reduction efficiency of ecological plastic film compared to 0.01 mm PE film ranged from 30.8% to 40.0%, without accounting for the substitution of humus for chemical fertilizers. When humus substitution was considered, the range increased to 70.2% to 74.2%. Ecological plastic film achieved the greatest emission reduction in the final treatment stage, accounting for 54.1% of total CO_2 reduction, followed by the production stage at 44.8%, while the transportation phase contributed only 1.1%. Projecting to 2030, if half of the cultivated land in Shanxi Province uses ecological plastic film instead of 0.01 mm PE film, a 19.7% reduction in carbon emissions is expected. Full coverage with ecological plastic film could raise this to 39.4%. To encourage its adoption, the study suggests that the government offers financial subsidies to enterprises or farmers, promotes agricultural carbon taxes, or supports carbon trading. With a carbon price or tax exceeding 67.1 CNY/t, ecological plastic film achieves cost parity with 0.01 mm PE plastic film.

Keywords: ecological plastic film; life cycle assessment; SimaPro software

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1. Introduction

Although China's plastic film covering technology started relatively late, it has developed rapidly through technology adoption, innovation, and national policy support [1,2]. Substantial progress has been achieved in material research, production technology enhancement, and the scale of application, positioning China as the largest market for agricultural plastic film globally [3–5].

As a key agricultural material, plastic film significantly aids in soil warming [6,7], moisture retention, and crop growth [8,9]. However, with its increasing usage, plastic film recycling challenges have emerged [10–14].

Wei Haidong et al. [15] reported that residual plastic film negatively affects soil humus, nitrogen, phosphorus, potassium, and microbial content, reducing crop yields. Jin Ping et al. [16] and Wang Jun et al. [17] also noted that plastic film residues harm soil structure and reduce crop yields. Yang Xiaotao [18] found that yield losses from residual plastic film vary across crops, with reductions of 11–13% for corn, 9–10% for wheat, 8–14% for rice,

5.5–9% for soybeans, and 14.5–59.2% for vegetables. Uncollected plastic film can cause "white pollution", harming water environments and human health [19]. Zhao Zhiguo's research showed that plastic film residues degrade soil properties and adversely affect crop growth, yields, and living conditions for both people and livestock [20].

Given the effects of plastic film on soil structure and crop production, national measures focus on recycling plastic film and developing biodegradable alternatives [21–25].

Zhao Hui et al. [26,27] reported that low recycling rates, weak incentives, and limited funding hinder effective recycling efforts, worsening residue problems. Hu Yu et al. [28,29] highlighted insufficient regulatory measures for recycling in China, noting that fragmented policies across regions cause oversight gaps and redundant efforts. According to Zhang Xin et al. [30], various technologies for recycling plastic film help reduce environmental pollution, support green, low-carbon, circular economy goals, and contribute to the national "dual carbon" targets.

Ecological plastic film, an environmentally friendly, biodegradable alternative, reduces pollution, improves crop yield and quality, enhances soil structure, and decomposes naturally without harming the environment [31–34]. Its adoption supports sustainable agricultural production, food security, and environmental protection, addressing pollution from traditional plastic film and fostering sustainable agricultural growth [35–38].

As agriculture is a major source of carbon dioxide emissions, carbon footprint assessment has become crucial in promoting low-carbon agricultural practices [39,40]. Although studies on the carbon footprint of plastic film are limited, some researchers [41–43] have examined the carbon footprint of petrochemical products, such as polypropylene, xylene, and caprolactam. Findings suggest that polypropylene's emission coefficient is relatively low compared to other products, though improvements are still achievable.

Qingcheng Town is under the jurisdiction of Shanxi Province. Agricultural carbon emissions of Shanxi Province were estimated using the emission factor method by Wang Shufen [44], regarding carbon emissions from 2000 to 2020, showing an initial increase followed by a fluctuating decrease, and agricultural carbon emissions during 2021–2030 were predicted. This study assesses the carbon footprint of ecological plastic film in both the research and application phases, evaluating its carbon reduction contributions in Shanxi Province based on the results by Wang Shufen [44], thus supporting the promotion of ecological plastic film as a sustainable alternative.

2. Materials and Methods

2.1. Research Boundary

Figure 1 illustrates the research boundary, which is based on the quantitative evaluation of two types of plastic films using life cycle assessment (LCA) methods. The carbon footprint for each experimental field of 200 hm^2, which includes 0.01 mm PE film and ecological plastic film, includes the production, transportation, and final treatment of the plastic film.

As shown in Figure 1, the first three scenarios are hypothetical based on the actual situation of agricultural film recycling in Qingcheng Town. Due to varying levels of environmental awareness among farmers and differences in management and supervision policies for film recycling, there still exists the practice of manually collecting film and burning it in the fields. In China, for 0.01 mm PE film, due to its relative thinness, the highest recycling rate is only 30%, which can be achieved by mechanical collection in one time; whereas, manual collection is required three times to reach this rate. For 0.015 mm PE film, the recycling rate can reach up to 90%. These scenarios are consistent with the current status of film recycling in China, as described in the research by Tan [45].

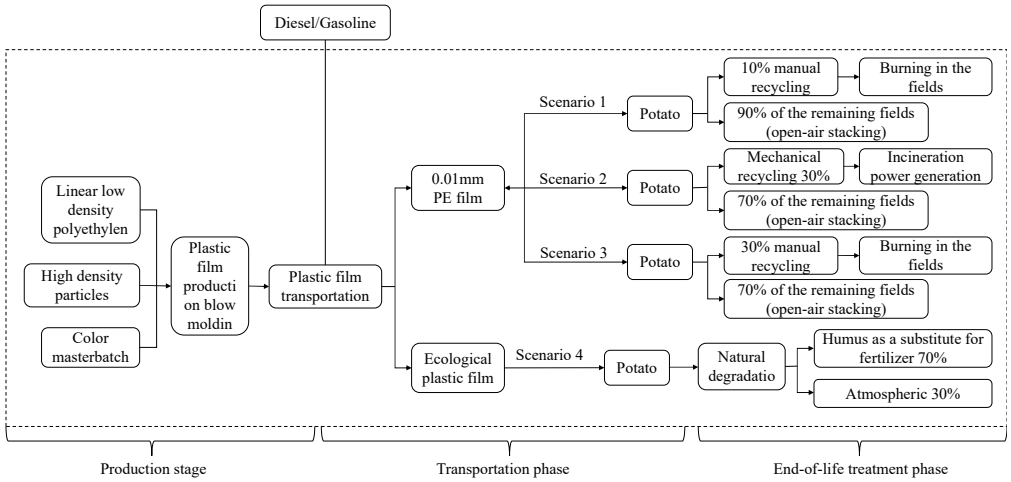

Figure 1. Research boundary.

2.2. Basic Data for Two Types of Plastic Film

To analyze the environmental effect of two different plastic films made in China, we focus on 0.01 mm PE film from Anhui Fengyuan Group Co., Ltd., Bengbu, China and ecological plastic film from Suzhou Zhongke Derun Environmental Governance Co., Ltd., Suzhou, China. Their basic properties are summarized in Table 1.

Table 1. Basic properties of two types of plastic films.

Name	Thickness mm	Density kg/m^3	Laying 200 hm^2 of Membrane Quantity t
PE film	0.010	920	18.400
Ecological plastic film	0.004–0.008	920–950	11.220

The 0.01 mm PE film made of high-density polyethylene has a thickness of 0.01 mm and a density of 920 kg/m^3, with white color. Approximately, 18.4 t of this film is used to cover 200 hm^2 of farmland. Recycling methods for PE film include 10% manual recycling, 30% manual recycling, and 30% mechanical recycling. The mechanically recycled film is used for energy recovery through incineration, while the remaining portion remains on the cultivated land or is piled outdoors.

For the ecological plastic film, its composition is complex, including high-density PE particles, low-density linear PE particles, color masterbatch, and core masterbatch. The mass ratio of these four components is 3970: 90: 40: 10. The carbon content of the ecological mulch film is 82.5%. The core masterbatch accounts for 2.4‰ of the total weight of the ecological mulch film, and this part is a commercial secret. In this study, CO_2 emissions corresponding to the core masterbatch are ignored. The thickness is considered to be the average of 0.006 mm, and the density has an average of 935 kg/m^3, with white color. Approximately, 11.22 t of this film is used for 200 hm^2 of farmland. This ecological plastic film is designed for natural degradation in farmland, requiring no additional human or material resources. Its recycling method allows for 30% to be released into the atmosphere, with 70% decomposing into the soil, thus avoiding long-term environmental pollution.

2.3. Carbon Footprint Accounting Method

This study utilizes LCA theory to establish a carbon footprint calculation method [45]. This approach ensures the precise measurement of lifecycle carbon dioxide emissions from

ecological film used in Qingcheng Town. The findings provide a scientific basis for decision makers and businesses, supporting sustainable development and environmental protection.

Various methods exist for carbon emission accounting, including emission coefficients, field measurements, and model simulation methods. Among these, the emission coefficient method is the most prevalent [45]. Therefore, we adopted this method for carbon emission estimation, primarily using the following formula: production x average emission factor. To address the environmental impact of global warming, our system boundary covers production, transportation, and the final treatment of agricultural film, thereby enabling a cradle-to-grave quantitative analysis. The production process for agricultural film involves raw material acquisition and plastic preparation. Specifically, 0.01 mm PE film uses blow molding technology, while biodegradable plastics require extrusion and rolling processes. The calculation formula is similar to the research by Tan [45] as follows:

$$E = G \times (a + b) + G \times L \times c + G \times d$$

In the formula:

E = total carbon emissions from agricultural film, t;

G = amount of agricultural film used, t;

L = transportation distance, 1 km;

The carbon emission coefficients for this study are categorized as a, b, c, and d.

a is the carbon emission coefficient obtained from raw materials;

b is the carbon emission coefficient for the plastic film production process;

c is the carbon emission coefficient of the trucks;

d is the carbon emission coefficient for the final treatment of agricultural film, as shown in Figure 1.

(1) Emission factors of two types of plastic films during production.

All coefficients, except for the coefficient of naturally degradable biodegradable agricultural film cited in the literature [45], are sourced from the Ecoinvent 3.0 database via SimaPro 9.4 software. The definitions of each coefficient are as follows; specific values can be found in Tables 2–5.

Table 2. Carbon dioxide emission factors of 0.01 mm PE film production process.

Technological Process	Emission Factors/kg CO_2eq·kg^{-1}
High-density polyethylene	2.390
Blow molding	1.350

Table 3. Carbon dioxide emission factors of ecological plastic film raw material components.

Technological Process	Emission Factors/kg CO_2eq·kg^{-1}
Low-density linear polyethylene	2.330
High-density polyethylene	2.390
Color masterbatch	7.180
Blow molding	1.060

Table 4. List of main parameters during transportation stage.

Types of Plastic Film	Distance/km	Truck Type	Emission Factors/kgCO_2eq·(t·km)$^{-1}$
0.01 mm PE film	797.300	16–32 t Euro 6	0.170
Ecological plastic film	735.600	7.5–16 t Euro 6	0.220

Table 5. List of main parameters in the end processing stage.

Process	Emission Factors
Manual recycling	0.860 kg CO_2eq·kg^{-1}
Open burning	3.170 kg CO_2eq·kg^{-1}
Air storage	0.170 kg CO_2eq·kg^{-1}
Mechanical recycling	5.610 kg CO_2eq·kg^{-1}
Incineration	2.990 kg CO_2eq·kg^{-1}
Electricity generation	−1.900 kg CO_2eq·kg^{-1}
Natural degradation of ecological plastic film	0.027 kg CO_2eq·kg^{-1}
Ecological plastic film carbon sequestration	4.910 kg CO_2eq·kg^{-1}
3.5–7.5 t Euro 6 trucks	0.540 kg CO_2eq·(t·km)$^{-1}$

Emission factors of two types of plastic films during the production stage.

The production processes and carbon dioxide emission factors of the 0.01 mm PE film and ecological film raw materials are detailed in Tables 2 and 3.

(2) Emission factors of two types of plastic films during transportation.

For this phase, we selected the most common land transportation method. Given the varying quality of the two plastic films, we chose different trucks based on their usage amounts, with the principle of minimizing the number of trucks. The main parameters during transportation are listed in Table 4.

(3) Emission factors of two types of plastic films in the final treatment stage.

In the final processing stage, the recycling methods for the two plastic films differ. Each method requires different stages, leading to varying emission factors.

For 0.01 mm PE film, the recycling process typically includes manual recycling, outdoor incineration, outdoor stacking, mechanical recycling, incineration, and power generation. Transport to the treatment plant is carried out using 3.5–7.5 t Euro 6 trucks. In contrast, ecological plastic film undergoes only natural degradation, without requiring human or material resources. Thus, it has two components: carbon sequestration and natural degradation. The carbon dioxide emission factors for this final treatment stage are detailed in Table 5.

(4) Data collection: we collected relevant data through field research, factory records, government statistical data, and other means.

Carbon footprint calculation: using the collected data, we calculated the carbon dioxide emissions for the two types of plastic films throughout their entire lifecycle.

2.4. Scenario Assumptions

Two types of plastic films were used in this experiment: traditional 0.01 mm PE film and ecological film. Four scenarios were established, each covering an experimental field area of 200 hm^2. The 0.01 mm PE film was used in scenarios 1, 2, and 3.

The 0.01 mm PE film includes components with manual recycling rates of 10% and 30%, as well as mechanical recycling at 30%. The remaining plastic film remains in the farmland as open-air stacking. The manually recycled plastic is piled in fields for incineration, while the mechanically recycled plastic is transported by 3.5–7.5 t Euro 6 trucks to domestic waste treatment plants for incineration and power generation.

In contrast, ecological plastic film naturally degrades in farmland. Scenario 4 involves the natural degradation of ecological mulch film, where 70% of the carbon in the film remains in the soil, forming humus as a substitute for chemical fertilizers, thereby achieving carbon sequestration. The calculation for this part, according to the research by Tan [45] and Hermann [46], is based on the premise that each kilogram of carbon in compost can save 4.9 kg of CO_2. The remaining 30% of carbon is released into the air as carbon dioxide.

Research was conducted to determine the actual distances between plastic film production factories in Qingcheng Town and the farmland, as well as the distances between farmland and domestic waste incineration plants. These data are critical for understanding transportation efforts. Additionally, the size, load capacity, and carbon dioxide emissions of the trucks used in transportation were assessed.

Table 6 compares the end processing stages of the four scenarios mentioned above.

Table 6. Comparison of end processing stages for four scenarios.

Scenario Setting	Type of Plastic Film Used	End of Pipe Processing Stage
Scenario 1	0.01 mm PE film	10% manual recycling (90% open-air stacking)
Scenario 2	0.01 mm PE film	Mechanical recycling 30% (70% open-air stacking)
Scenario 3	0.01 mm PE film	30% manual recycling (70% open-air stacking)
Scenario 4	Ecological plastic film	Natural degradation (70% humus replacing fertilizer, 30% entering the atmosphere)

3. Results

3.1. Experimental Field

Figure 2 shows the CO_2 emissions during the production, transportation, and final treatment of two types of plastic films.

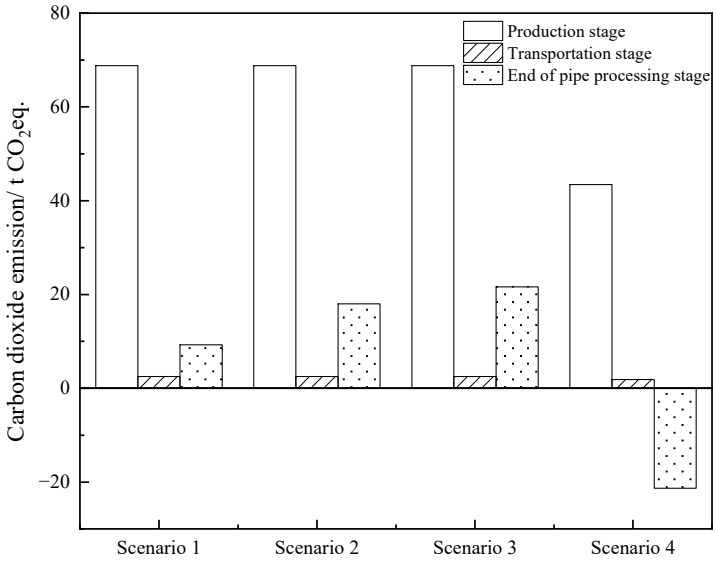

Figure 2. Carbon dioxide emissions generated at different stages of the life cycle of four scenarios.

Scenario 1: Production emitted 68.8 t of CO_2, transportation 2.49 t, and end-of-life treatment 9.27 t, totaling 80.56 t.

Scenario 2: Production emitted 68.8 t of CO_2, transportation 2.49 t, and end-of-life treatment 17.99 t, totaling 89.29 t.

Scenario 3: Production emitted 68.8 t of CO_2, transportation 2.49 t, and end-of-life treatment 21.60 t, totaling 92.89 t.

Scenario 4: Production emitted 43.44 t of CO_2, transportation 1.85 t. For the end-of-life stage, 10.48 t of CO_2 was released from ecological mulch biodegradation, and 31.8 t

of CO_2 from biochar residue remained in the soil. When the carbon reduction effect of humus as a fertilizer substitute is included, the total CO_2 emissions from production to final biodegradation are 23.97 t. Excluding the humus effect and considering only CO_2 emissions to the atmosphere from mulch biodegradation, the total emissions amount to 55.77 t.

Throughout the lifecycle of plastic film, ecological plastic film demonstrated a significant reduction in carbon emissions compared to PE plastic film in the production, transportation, and final treatment stages. During production, ecological plastic film achieved a carbon reduction of 36.9% relative to PE plastic film. In the transportation phase, the reduction was 25.7%. This difference is primarily due to ecological plastic film requiring fewer raw materials and being of lower quality, which results in lower CO_2 emissions, while covering the same soil area. In the final treatment stage, if we consider only the CO_2 emissions released into the atmosphere through degradation for ecological plastic film, the carbon reduction effects compared to the three scenarios are −13.1%, 41.7%, and 51.5%, respectively. If we assess both gas and solid phase emissions simultaneously, the reduction effects increase to 330%, 218.5%, and 198.7%. Notably, the final treatment stage yielded the most significant carbon reduction. This is because the ecological plastic film examined in this study released 30% of carbon into the atmosphere during soil biodegradation, while 70% was fixed in the soil as humus. By converting the carbon fixed in the soil into 4.9 kg of CO_2 per kg of carbon in compost, as noted in reference [46], we can illustrate the carbon fixation effect of humus solid carbon. Although this calculation lacks direct measurement data, it provides a meaningful evaluation of the carbon reduction effect of ecological plastic film. Future research is recommended to conduct a green evaluation of ecological mulching films to gather experimental data and enhance our understanding of solid carbon fixation.

3.2. Qingcheng Town

According to the research, the cultivated land area in Qingcheng Town is 1821 hm^2. Each piece of cultivated land in the experimental field measures 200 hm^2. Thus, the experimental field accounts for approximately 10.98% of Qingcheng Town's total cultivated land area, representing an increase of 9.105 times. Using the basic data from Scenario 1 and Scenario 4-2 in Figure 3, we reference Scenario 1 at 100% application. The CO_2 emissions are calculated for production, transportation, and end-of-pipe treatment, based on a 50% application of simulated ecological plastic film in both scenarios and a 100% application in Scenario 4-2.

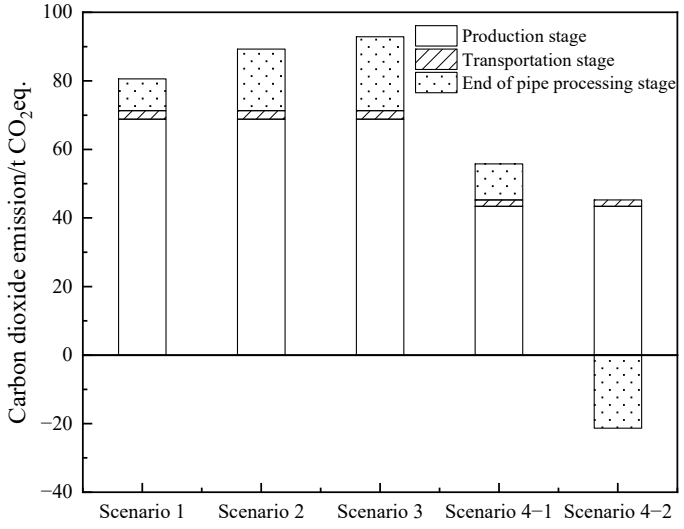

Figure 3. Total CO_2 emissions over the entire life cycle of five scenarios.

Figure 4 illustrates the total CO_2 emissions resulting from the promotion of ecological plastic film on 50% and 100% of farmland in Qingcheng Town. The 0.01 mm PE film serves as a reference, with total life cycle CO_2 emissions at 733.49 t. Using ecological plastic film on 50% of arable land leads to total emissions of 475.9 t, achieving a carbon reduction effect of 35.1%. Conversely, when covering 100% of arable land, total emissions drop to 218.2 t, yielding a 70.2% reduction compared to the reference. This demonstrates that promoting green and low-carbon agriculture through ecological plastic film is a viable strategy.

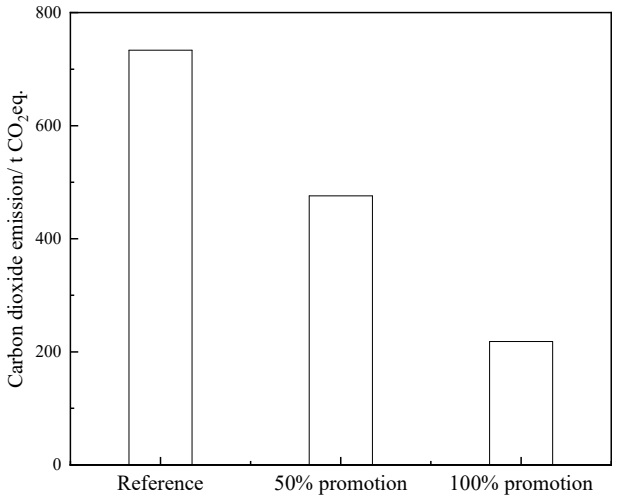

Figure 4. Total CO_2 emissions during the life cycle of promoting ecological plastic film on farmland in Qingcheng Town.

For the 50% application of ecological plastic film, carbon reduction contributions were analyzed across three stages. The final treatment stage contributed the most, followed by the production stage and transportation stage, with reductions of 139.26 t, 115.45 t, and 2.91 t, respectively. The percentage contributions were as follows: final treatment stage (54.1%), production stage (44.8%), and transportation stage (1.1%), as shown in Figure 5.

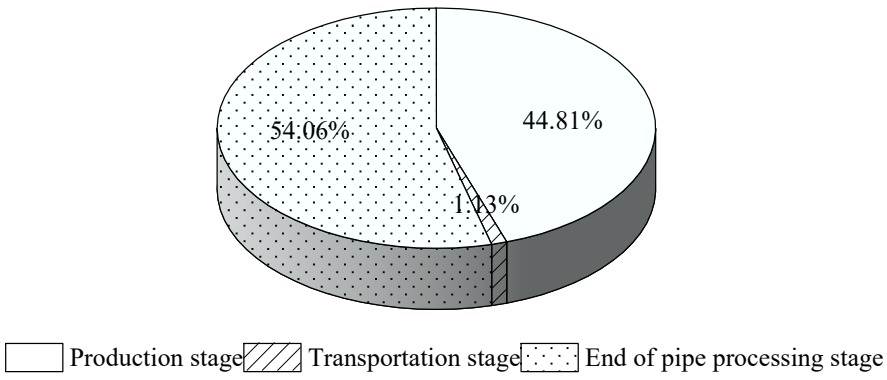

Figure 5. Percentage of carbon reduction in each stage of 50% promotion of ecological plastic film.

For the 100% application of ecological plastic film, the carbon reduction contributions mirrored those from the 50% application. The order remained the same, with final treatment contributing 278.52 t, production contributing 230.9 t, and transportation contributing 5.83 t, maintaining the same proportional distribution as the 50% application.

3.3. Shanxi Province

Figure 6 illustrates the total CO_2 emissions resulting from the promotion of ecological plastic film usage on 50% and 100% of cultivated land in Shanxi Province. Using a reference

of 0.01 mm PE film, the total life cycle CO_2 emissions for the film amounted to 1,555,520.2 t. With 50% of cultivated land using ecological plastic film, CO_2 emissions totaled 1,009,182.7 t. In the case of 100% land coverage, emissions decreased to 462,823.9 t.

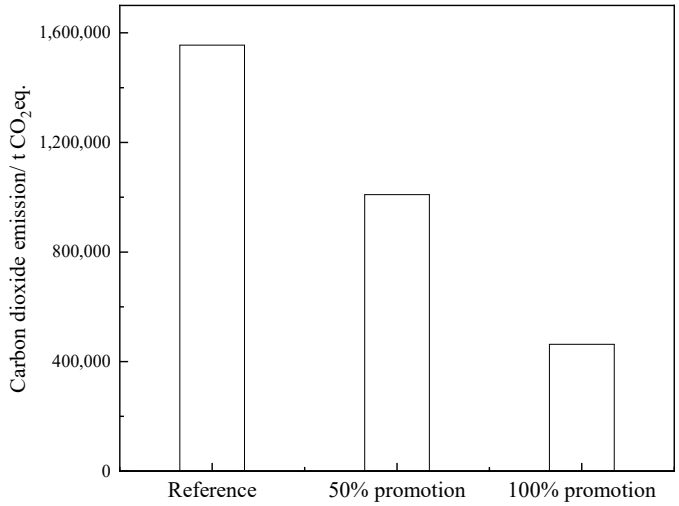

Figure 6. Total CO_2 emissions at different stages of the life cycle of 50% and 100% promoted use of ecological plastic film on cultivated land in Shanxi Province.

Wang Shufen et al. [44] projected that agricultural carbon dioxide emissions in Shanxi Province will reach 2,772,000 t by 2030. Comparing the calculated CO_2 emissions after implementing ecological plastic film for carbon reduction to this estimated value reveals that promoting the use of ecological plastic film on 50% and 100% of the land will contribute to a carbon reduction of 19.7% and 39.4%, respectively.

During the production stage, if all cultivated land in Shanxi Province employs 0.01 mm PE plastic film, CO_2 emissions will amount to 1,328,455.7 t. If 50% of arable land uses ecological plastic film, emissions will be 1,083,619.63 t, resulting in a reduction of 244,836.07 t. This reduction represents 8.8% of the total agricultural CO_2 emissions for Shanxi Province in 2030. If 100% of arable land promotes ecological plastic film, emissions will be reduced to 838,783.56 t, a total reduction of 489,672.14 t, accounting for 17.7% of the total agricultural CO_2 emissions for the same year.

In the transportation phase, if all cultivated land in Shanxi Province utilizes 0.01 mm PE plastic film, CO_2 emissions will be 48,076.52 t. A 50% adoption of ecological plastic film will lead to emissions of 41,905.25 t, reducing emissions by 6171.27 t. If 100% is covered with ecological plastic film, emissions will decrease to 35,712.77 t, yielding a reduction of 12,363.75 t. The carbon reduction contributions when promoting ecological plastic film at 50% and 100% coverage will account for 0.2% and 0.4%, respectively, of the total agricultural CO_2 emissions in Shanxi Province by 2030.

In the final treatment stage, using 0.01 mm PE plastic film across all cultivated land in Shanxi Province will result in CO_2 emissions of 178,988 t. If 50% of the cultivated land adopts ecological plastic film, it will yield a negative emission value of −116,342.2 t. This indicates that the mixed covering method has a carbon sequestration effect, reducing emissions by 295,330.21 t. If 100% of arable land utilizes ecological plastic film, the emissions would be −411,672.39 t, leading to a reduction of 590,660.39 t. When promoting ecological plastic film for 50% and 100% of cultivated land, the carbon reduction contributions compared to total agricultural CO_2 emissions in Shanxi Province for 2030 are 10.7% and 21.3%, respectively.

The promotion of ecological plastic film requires guidance from national policies. Research indicates that the density of 0.01 mm PE film is 920 kg/m^3, while ecological

film has a density of 935 kg/m^3. The thickness of ecological film is 0.006 mm, primarily supported by financial subsidies from national and local governments. To cover 100 hm^2 of land, 9.2 t of 0.01 mm PE film or 5.61 t of ecological film is typically required. The costs for these films are 955 RMB and 16,000 RMB per t, respectively. Therefore, the government needs to subsidize 190,000 RMB/hm^2. Green agriculture is the future development trend. Considering agricultural carbon tax, the data for a 200 hm^2 experimental field suggest that using ecological plastic film reduces CO_2 emissions by 28.3 t compared to 0.01 mm PE film when laying 100 hm^2 of plastic film. If the agricultural carbon tax is at least 67.1 CNY/t CO_2, government subsidies for ecological plastic film may not be necessary. Additionally, carbon trading can be initiated at the township level to encourage the use of ecological plastic film. According to data from 2024, Chinese carbon trading prices exceeded 100 CNY per t for the first time in April and remained stable at this rate in October and November. With improved accounting and certification methods, farmers could benefit from carbon trading without the need for national subsidies. Each 100 hm^2 of ecological plastic film laid could yield a profit of 930 CNY. Deciding whether to distribute this profit to farmers or ecological film producers is crucial. If allocated to the manufacturer, the price of ecological plastic film could decrease from 16,000 CNY/t to 15,495 CNY/t, or the manufacturer could invest in research and development. Conversely, providing the profit to farmers could enhance their motivation to choose ecological plastic film. Ultimately, investing in technological innovation may yield greater economic and environmental benefits.

4. Conclusions

This study utilized LCA methods and SimaPro software to evaluate the carbon footprint of ecological plastic film in Qingcheng Town. The findings revealed that the carbon reduction efficiency of ecological plastic film ranges from 30.8% to 40.0% compared to 0.01 mm PE film, excluding the benefits of residual humus in the soil from the film's degradation, which can substitute for chemical fertilizers. When accounting for this humus, the carbon reduction efficiency increases to 70.2% to 74.2%, highlighting the substantial advantages of ecological plastic film in lowering carbon dioxide emissions.

Research indicated that when ecological plastic film was adopted in Qingcheng Town and Shanxi Province, the final treatment stage resulted in the most significant emission reductions, contributing 54.1% to the total CO_2 emissions reduced. This was followed by the production stage, which accounted for 44.8%, while the transportation phase contributed only 1.1%.

Looking ahead to 2030, if half of the cultivated land in Shanxi Province is covered with 0.01 mm PE plastic film and the other half with ecological plastic film, the overall carbon reduction contribution could reach 19.7%. Should all farmland be converted to ecological plastic film, this contribution could further increase to 39.4%. These findings will support the advancement of low-carbon agriculture in China, fostering a balance between agricultural production and environmental protection.

Suggestion

To facilitate the adoption of ecological plastic film, the local government can implement the following measures: (1) Offer financial subsidies to businesses to lower the cost of ecological film or provide incentives to farmers to enhance its price competitiveness. (2) Promote the enactment of an agricultural carbon tax or encourage the use of carbon trading for ecological films at the township level. Currently, both the carbon price and carbon tax hold a competitive price advantage over 0.01 PE plastic film when valued above 67.1 CNY per t.

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