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Straw Return with Biodegradable Film Mulch: A Synergistic Cultivation Measure with Environmental and Economic Benefits Based on Life Cycle Assessment

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Abstract: Straw return and plastic film mulching are two critical management measures that not only maintain high and stable crop yields, but also have a significant impact on the ecological environment. However, there is still a lack of research on the comprehensive effects of straw return and different film mulching treatments on the ecological environment. Thus, a 2-year field experiment was conducted and six treatments, which included two main treatments, namely straw return (SR) and non-straw return (NR), and three sub-treatments, namely no film mulching (CK), plastic film mulching (PM) and fully biodegradable film mulching (BM), were applied in a garlic cropping system. Based on the life cycle assessment method, six endpoint damage categories, resource consumption, global warming potential, environmental acidification, eutrophication, human health, and ecotoxicity, were assessed. Furthermore, we also evaluated the costs and economic benefits of the six treatments and optimized the treatment of used mulch and straw off-farm. The results indicated that the environmental impacts of the six endpoint damages in the garlic cropping system were ranked as ecotoxicity, eutrophication, environmental acidification, global warming potential, human health, and resource consumption. The SR-BM treatment had the lowest life cycle environmental impact composite index at 27.68 per unit area, followed by SR-PM at 27.75. All six endpoint damage categories for the PM and BM treatments were lower than the CK treatment per t of yield, with the SR-BM treatment being the most economically efficient, yielding at 3691.03 CNY·t^{-1} and exceeding that of the SR-CK treatment by 7.26%. Fertilizer inputs were the primary contributor to resource consumption, global warming potential, environmental acidification, eutrophication, and ecotoxicity, accounting for about 72.80% of these five environmental impacts. Crop protection significantly affected human health, and garlic mulching helped minimize pesticide use, thereby reducing potential health impacts. Compared to straw incineration and waste mulch power generation, straw power generation and waste mulch recycling granulation offered positive environmental benefits and were more effective offset strategies. In conclusion, straw return with biodegradable mulch is a synergistic cultivation measure that offers both environmental and economic benefits. For straw return with plastic film mulch, environmental impacts can be reduced by waste mulch recycling granulation.

Keywords: straw return; fully biodegradable plastic film mulching; life cycle assessment; environmental effect; economic benefit

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1. Introduction

Amid the severe challenges facing the global ecological environment, the importance of the sustainable development of agriculture has become increasingly evident, as agriculture is a fundamental industry for human survival [1]. Traditional agricultural practices often depend heavily on the extensive use of chemical fertilizers and pesticides or methods like "flood irrigation", etc. While these practices have somewhat boosted crop yields, they have also led to problems such as excessive energy consumption, soil degradation, and environmental pollution [2]. How to minimize the negative impact on the environment while ensuring crop yields and increasing farmers' income has become a critical issue in the agricultural sector that needs to be addressed urgently [3].

Straw return and film mulching are key management practices in modern agricultural production [4]. Straw return to the field, as an effective soil improvement method, can significantly boost the soil organic matter content, improve soil structure and function, increase soil fertility and enhance crop yield [5]. It is estimated that over 40 billion tons of straw are returned to the fields in China each year [6]. Research has shown that straw return to the field can increase the total and effective nitrogen content in soil by 10.3% and 9.6%, respectively, enrich soil organic matter, reduce evaporation loss from the soil surface, protect the soil surface from the impact of rainfall, and promote the formation of soil agglomeration structure. These effects, in turn, enhance the decomposition and transformation of organic matter in the soil, ultimately improving both the yields and quality of agricultural crops [7]. Furthermore, as a key technology for conservation and climate-smart agriculture, straw return can enhance carbon sequestration and emission reduction capacity of farmland systems [8]. However, studies have also indicated that returning straw to the field can increase pathogenic microorganisms and weeds, hindering the sowing of the next crop and reducing yields by "dead seed", among other negative effects [9]. Under high temperature conditions, straw decay will produce ammonia, hydrogen sulfide, and other harmful gases, which are toxic to crops. Additionally, the crushing and returning of straw to the field releases significant amounts of dust, contributing to environmental pollution [10]. Mulching, as the fourth largest agricultural production method in China, enhances water-use efficiency by 58.0% and increases average crop yields by 45.5%, making a significant contribution to ensuring food security [11]. According to statistics, the global use of mulch has increased significantly, reaching 2 million tons annually, with 29 million ha^{-1} of mulch coverage [12]. Although the use of mulch enhances crop yields, its environmental impact throughout its lifecycle cannot be overlooked. Film mulching helps increase the carbon input from both crop roots and plays a vital role in soil carbon sequestration [13]. Currently, there is no consensus on the effect of mulching on carbon emission from farmland. Some studies indicate that mulching has increased the SOC content, while others claim that mulching accelerates the decomposition of SOC and stimulates the process of nitrification and denitrification of the soil, which may lead to higher CO_2 emission from farmland soils [14]. Currently, the number of studies on the environmental impacts of individual straw return or mulching treatments is gradually increasing. However, there is still a lack of research on the environmental impacts of the interactions between straw return and plastic film mulching.

Studies have shown that the use of plastic films for mulching may cause problems with residual contamination [15]. Mulch residues can cause soil compaction, impede crop root development, destroy soil aggregates, and affect soil water and nutrient transport, thereby affecting crop growth and reducing crop yields [16]. Residual films in the soil can release phthalates (PAEs) under the effect of mechanical abrasion and light aging, etc., which affects soil health [17]. The management of mulch has become a growing global concern due to the negative impacts of mulch residues [2]. Despite the Chinese government's emphasis on increasing efforts to recycle plastic films, it faces significant practical challenges. On one hand, recycling and processing waste plastic films requires substantial labor input, which increases costs and work intensity [18]. On the other hand, due to the inadequacies in the current system, the end-of-life treatment for used mulch primarily involves incineration for electricity generation or secondary generation. However, the environmental impacts of different treatment methods may vary considerably under different circumstances and remain uncontrolled [19]. The scientific treatment of waste plastic films has become a crucial focus for advancing the sustainable development of modern agriculture.

The key to sustainable mulch management lies in the integration of national policies, regulations, and recycling technologies [20]. To address waste film pollution, the Chinese government has implemented the Measures for the Management of Agricultural Films, which actively promote the use of thick films (the policy requires a thickness of more than 0.01 mm) and fully biodegradable films [21,22]. This initiative seeks to establish a recycling system for discarded mulch films and significantly reduce the amount of mulch films remaining in the soil, thereby reducing its pollution on the environment. Fully biodegradable plastic mulch is composed of low-permeability polysaccharides, which can be converted to water and CO_2 through soil microbial mineralization, offering an innovative solution for the treatment of waste plastic films [23]. Biodegradable mulch can increase soil temperature, enhance water content, improve soil nutrient availability, and increase crop yield, with no significant difference compared to plastic films [24,25]. Compared to plastic mulch, fully biodegradable mulch enhances soil aeration, decreases the abundance of soil methanogenic bacteria, and increases the abundance of methane oxidizing bacteria, thereby reducing CH_4 emissions from rice fields [26]. Additionally, using fully biodegradable mulch can increase the abundance and diversity of ammonia-oxidizing bacteria (AOB) as well as the concentration of N_2O, and significantly reduce N_2O emissions [27]. However, current research on the environmental impacts of fully biodegradable mulch primarily focuses on greenhouse gas emissions [28]. The full life-cycle environmental impacts of biodegradable plastic film mulching, such as resource consumption, environmental acidification, eutrophication, and human health, are still unclear [21]. Existing studies on the environmental impacts of plastic films during the production or use stage are more abundant, and few studies address the treatment stage after the use of waste film mulch. Additionally, the differences in the full life-cycle environmental impacts of fully biodegradable plastic films and plastic films remain unclear.

Life Cycle Assessment (LCA) is a systematic approach used to evaluate and compare the environmental impacts of various products, technologies, and solutions. It has been extensively applied across various fields, including printing plastic films, waste recycling, and rural environmental management [29–31]. Several studies have utilized the LCA method to assess the environmental impact of agricultural straw and mulch. Zhao et al. [32] found that compared to incineration and removal, the amount of energy consumption of straw returned to the field is at an intermediate level, with the least amount of greenhouse gas emissions, making it an efficient method to dispose straw. However, straw returned to the field can cause an increase in the number of pests and diseases and an increase in pesticide inputs, and the methods of returning the straw to the field should be continuously improved to reduce the occurrence of pests and diseases. Choi et al. [33] found that the environmental impact of fully biodegradable mulch films is lower than that of conventional plastic films throughout their life cycle. Additionally, incinerating used plastic films generates higher greenhouse gas emissions compared to recycling or landfill methods. Current research offers valuable insights into the environmental impact of plastic film mulch methods but lacks local Chinese data regarding the impacts of agricultural straw, different mulches, and their interactions across multiple environmental categories using the LCA approach.

In summary, considering the reliance of the current agricultural system on straw return and film mulching, the study conducted a two-year field trial in garlic season to determine the environmental impacts across the six endpoint categories: resource consumption, global warming potential, environmental acidification, eutrophication, human health, and ecotoxicity under straw return and different film mulch treatments based on an innovative life cycle assessment (LCA) methodology. Furthermore, the study evaluated the costs and economic benefits under straw return and different film mulch treatments, which aimed to explore which cultivation measure could maximize the economic and environmental benefits of garlic cropping system. The study analyzed the environmental impacts of used mulch and straw off-farm, so as to explore the best modes of offsetting and mitigating the environmental impacts of straw and waste mulch. This study provided both scientific methodology and empirical data to support policy formulation regarding resource utilization of farmland waste in China.

2. Materials and Methods

2.1. Experimental Area and Cropping Systems

The experiment was conducted in 2022 and 2023 at the Experimental Demonstration Site of the Xuzhou Institute of Agricultural Science, Xuzhou City, Jiangsu Province, China (117°24′ E, 34°17′ N) (Figure 1a). The test site experienced a temperate monsoon climate with an annual temperature of 14 °C, annual sunshine hours of 2284 to 2495 h, a sunshine rate of 52% to 57%, an average annual frost-free period of 200 to 220 days, and an average annual precipitation of 800 to 930 mm. The crop rotation pattern before the experiment was rice–garlic rotation, the previous crop was rice, the soil texture was sandy loam, and the organic matter content of the top soil (0–20 cm) was 16.96 g kg^{-1} by potassium dichromate oxidation. Total nitrogen was 0.92 g kg^{-1} by sulfuric acid + catalyst ablation Kjeldahl nitrogen determination, alkaline dissolved nitrogen was 107.33 mg kg^{-1} by alkaline dissolution diffusion, available phosphorus was 5.22 mg kg^{-1} by molybdenum–antimony antimicrobial colorimetry, available potassium was 219.00 mg kg^{-1} by a flame photometer, and the pH was 8.60 by the electrode method (Mettler Toledo, SG2). Weather data for the garlic season in both years were obtained from the Agricultural Experimental Meteorological Station of Xuzhou City. The total annual rainfall during the crop growing season in 2022 and 2023 was 478.20 mm and 725.8 mm, respectively.

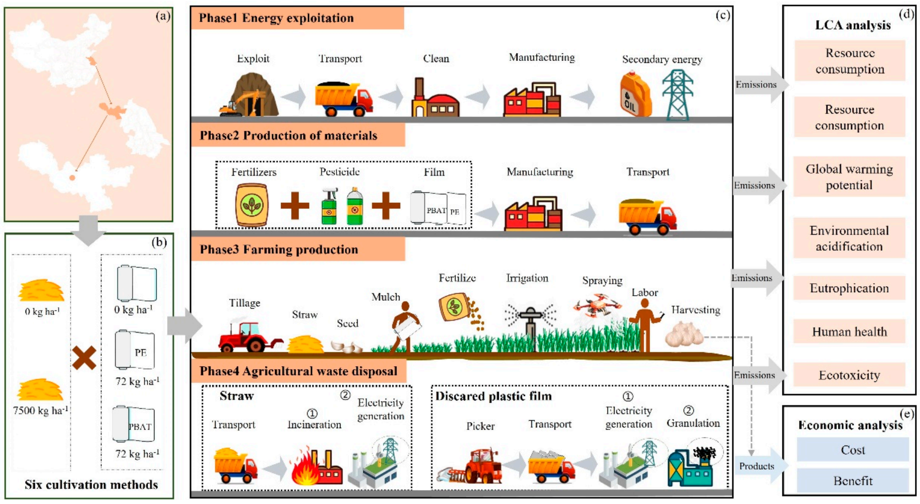


Figure 1. Experimental area (**a**), system boundary (**b**), four life cycle phases (**c**), LCA analysis (**d**), and economic analysis (**e**). The environment quantitative models and four phases damage evaluated in the present study (**c**). Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching.

The two-year experiment was conducted using split-zone experimental treatments, with straw returned to the field as the main treatments, namely straw return (SR) and non-straw return (NR), and different mulching as the sub-treatments, namely no film mulching (CK), plastic film mulching (PM), and fully biodegradable film mulching (BM) that were set in a garlic cropping system (Figure 1b), each replicated three times. The plot area was 630 m^2, and the plastic film used in the experiment was transparent polyethylene plastic film (PE), with a thickness of 0.01 mm and a width of 200 cm. The fully biodegradable mulch film was provided by Nanjing Bochuang Youjie New Material Technology Co. and produced according to GB/T 35795-2017 standard [34]. The fully biodegradable film, composed primarily of polybutylene terephthalate (PBAT), was white and translucent, with the same thickness of 0.01 mm and a width of 200 cm. The degradation products of the biodegradable film included water, CO_2, and the mineralized inorganic salts of the elements contained in the film [35,36]. The garlic variety used was Xu Garlic 917, provided by the Agricultural Science Research Institute of Xuzhou, Jiangsu Xuhuai region. The garlic was sown in mid-to-early October. Prior to sowing, the soil was deeply tilled to a depth of 30 cm, followed by rotary tillage to prevent the rice straw from the previous crop from returning to the field and interfering with garlic germination. Garlic base organic fertilizer was applied at 6000 kg·ha^{-1}, compound fertilizer (15–5–25) was applied at 600 kg·ha^{-1}, and compound fertilizer (12–18–22) was applied at 750 kg·ha^{-1}. During the garlic bud differentiation and shoot elongation stages, compound fertilizer (15–5–25) was applied at 285 kg·ha^{-1} and 300 kg·ha^{-1}, respectively. During the bulb expansion phase, 3 kg·ha^{-1} of foliar fertilizer (Potassium dihydrogen phosphate, KH_2PO_4) was sprayed. The garlic was harvested in early May. The field management strategies, such as irrigation and drug application during the garlic season, were in line with local conventional management practices.

2.2. Life Cycle Assessment (LCA)

An LCA approach was used to quantify the environmental impacts of garlic cultivation with different straw return and film mulch. In accordance with the ISO 14040/14044 standard series [37,38], this study followed a four-step LCA procedure including objective and scope definition, life cycle inventory analysis, impact evaluation, and interpretation [39].

2.2.1. Goal and Scope Definition

The objective of this study was to quantify the environmental impacts of six cultivation practices within the garlic ecosystem across six endpoint damages: resource consumption, global warming potential, environmental acidification, eutrophication, human health, and ecotoxicity. Additionally, the study aimed to identify the key factors for each endpoint damage category. This study defines two functional units of environmental impacts based on 1 ha area and based on 1 t of garlic production. The scope of LCA in the garlic production chain encompasses all material and energy inputs and outputs from 'cradle to farm gate', including potential environmental impacts associated with the disposal of non-returned straw and waste plastic films at the end of their useful life (end of growing season). In this study, the entire life cycle of garlic production was categorized into four stages, as shown in Figure 1:

(1) Energy exploitation: resource consumption and pollutant emissions resulting from the extraction and production of various energy resources.
(2) Production of materials: resource consumption and pollutant emissions from the manufacturing of agricultural materials such as fertilizers, pesticides, and agricultural films.
(3) Farming production: resource consumption and pollutant emissions generated by various types of agricultural production material inputs throughout the process of growing garlic from sowing to harvesting.
(4) Agricultural waste disposal: resource consumption and pollutant emissions from the collection and treatment of straw and waste film mulch after garlic harvest.

2.2.2. Life Cycle Inventory (LCI) Analysis

Life Cycle Inventory (LCI) analysis mainly refers to the process of identifying all inputs and outputs, as well as the process of performing operations throughout the entire life cycle of a product system. This process typically consists of three steps: classification and characterization, standardization, and weighted assessment. In LCI analysis, life cycle inventory data were listed in the order of field operations (Table 1).

During the energy exploitation phase, data on pollution emissions from the extraction and production of various energy resources were obtained from actual research and the Ecoinvent 3.5 (International Life Cycle Inventory Database 3.5) database [40]. In the material production phase, data on agricultural machinery, biodegradable films, ordinary plastic films, and fertilizers were obtained from actual field inputs, with their pollutant emission coefficients derived from CLCD 0.7 (China Life Cycle Database 0.7) and Ecoivent 3.5. Since each use of agricultural machinery reduces its lifespan, this study quantified the lifetime of agricultural machinery based on its usage as shown in the Table S1. The fuel consumption of agricultural machinery was calculated based on engine power and operating hours. The mileage and fuel consumption of agricultural transportation to farmland were obtained from measured data. Pollution from diesel combustion, electricity use, fertilizer and pesticide application, agricultural labor, straw return to the field, and mulching were considered during the farming production phase. N_2O emissions, NH_3-N volatilization, NO_3^--N leaching and runoff, and P (phosphorus) runoff loss due to fertilizer application were based on the IPCC guidelines [41] and previous works of literature [42–44]. Additionally, fertilizer application can lead to the accumulation of heavy metals in agricultural soils, thereby harming the environment [45]. In the previous studies, Cu, As, Cd, Pb, Zn, Cr, and Hg metals were selected and their emission factors were specified in this study. The pesticide residue pollutants entering the atmosphere, water, and soil were calculated as 10%, 1%, and 43% of the input amount of the active ingredient of the pesticide, respectively [46]. For each site operation in Table S2, the method of operation (mechanical or manual) and facilities were listed to accurately estimate the corresponding emissions. In the agricultural waste disposal stage, for straw not returned to the field and waste plastic mulch, this study considered the most common previous treatments of straw incineration and incineration of waste mulch for electricity generation, respectively [47,48]. After harvesting the previous rice crop, rice straw from plots where straw was not returned to the field was collected and transported to a waste incineration plant for burning. After the garlic harvest, waste plastic film was collected by a film picker in the plots covered with plastic film treatments, which was then transported to the nearest waste-to-energy plant. Relevant data were primarily obtained from actual transportation records and the Ecoinvent 3.5 database. In this study, in addition to the methods of straw incineration and waste mulch power generation in the fourth stage, the methods of straw power generation and waste mulch recycling granulation were evaluated separately for comparison. The data on straw power generation were mainly derived from previous studies [49–52]. The waste mulch recycling granulation was 90% and the conversion efficiency of recycled plastic pellets to virgin material substitutes was about 66% [53,54]. The environmental impacts caused by recycled pellets were primarily based on previous studies [55] and the Ecoinvent 3.5 database as shown in Table S2.

Table 1. Inventory items for garlic production under the six cultivation methods in a two-year field trial.

Items	Unit	SR-CK	SR-PM	SR-BM	NR-CK	NR-PM	NR-BM
Tillage							
Deep plowing	kg·ha^{-1}·year^{-1}	3	3	3	3	3	3
Rotary-harrow	kg·ha^{-1}·year^{-1}	3.19	3.19	3.19	3.19	3.19	3.19
Diesel oil	L·ha^{-1}·year^{-1}	158.796	158.796	158.796	63.54	63.54	63.54
Straw	kg·ha^{-1}·year^{-1}	7500	7500	7500	0	0	0
Seeding							
Garlic seeds	kg·ha^{-1}·year^{-1}	2100	2100	2100	2100	2100	2100
Garlic seed dressing	kg·ha^{-1}·year^{-1}	3.39	3.39	3.39	3.39	3.39	3.39
Labor	person·ha^{-1}·year^{-1}	60	60	60	60	60	60
Plastic film mulching							
Biodegradable film	kg·ha^{-1}·year^{-1}	0	0	72	0	0	72
PE film	kg·ha^{-1}·year^{-1}	0	72	0	0	72	0
Labor	person·ha^{-1}·year^{-1}	0	78	78	0	78	78
Fertilization							
Organic fertilizer	kg·ha^{-1}·year^{-1}	6000	6000	6000	6000	6000	6000
Nitrogen	kg·ha^{-1}·year^{-1}	267.75	267.75	267.75	267.75	267.75	267.75
Phosphorus (P_2O_5)	kg·ha^{-1}·year^{-1}	194.25	194.25	194.25	194.25	194.25	194.25
Potassium (K_2O)	kg·ha^{-1}·year^{-1}	461.25	461.25	461.25	461.25	461.25	461.25
Labor	person·ha^{-1}·year^{-1}	15	15	15	15	15	15
Crop Protection							
Insecticide	kg/ha·year^{-1}	4.5	4.5	4.5	4.5	4.5	4.5
Fungicide	kg/ha·year^{-1}	4.5	4.5	4.5	4.5	4.5	4.5
Herbicide	kg/ha·year^{-1}	3	1.8	1.8	3	1.8	1.8
Drone spraying	kWh·ha^{-1}·year^{-1}	16.875	13.5	13.5	16.875	13.5	13.5
Irrigation							
Irrigation water	m^3·ha^{-1}·year^{-1}	96.75	90	90	96.75	90	90
Electricity	kWh ·ha^{-1}·year^{-1}	30.88	28.8	28.8	30.88	28.8	28.8

Table 1. *Cont.*

Items	Unit	SR-CK	SR-PM	SR-BM	NR-CK	NR-PM	NR-BM
Crop Harvesting							
Labor	person·ha^{-1}·year^{-1}	247.5	247.5	247.5	247.5	247.5	247.5
Discarded plastic film collection							
Picker machine	kg/ha·year^{-1}	0	8.95	0	0	8.95	0
Diesel oil	L·ha^{-1}·year^{-1}	0	18.4	0	0	18.4	0

Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching.

2.2.3. Impact Assessment

The LCA impact assessment consists of three parts: characterization, normalization, and weighting. This study utilized six environmental potential impact categories from CML2001 [56], which included resource consumption, global warming potential, environmental acidification, eutrophication, human health, and ecosystem. Normalization parameters and weights were derived from previous studies, which are shown in the Table S3 [57].

2.2.4. Interpretation

In the interpretation phase, the environmental impacts of straw return and mulch treatments will be examined. Conclusions and recommendations will be formulated based on the respective environmental impact potentials.

2.3. Cost–Benefit Analysis

Economic profit is a determinant of farmers' production behavior and agricultural practices [58]. In this study, a cost–benefit analysis was selected to assess the economic attributes of the six treatments. Table 2 presents the raw data of the input–output details and economic parameters of the six cultivation methods.

Table 2. Cost and benefit for garlic production under six cultivation methods in a two-year field trial.

	Unit	SR-CK	SR-PM	SR-BM	NR-CK	NR-PM	NR-BM
Cost							
Machine	CNY ha^{-1}·year^{-1}	2025	2025	2025	1125	1125	1125
seed	CNY ha^{-1}·year^{-1}	7800	7800	7800	7800	7800	7800
Fertilizer	CNY ha^{-1}·year^{-1}	11,625	11,625	11,625	11,625	11,625	11,625
Film	CNY ha^{-1}·year^{-1}	0	1200	2400	0	1200	2400
Irrigation	CNY ha^{-1}·year^{-1}	525	525	525	525	525	525
Pesticide	CNY ha^{-1}·year^{-1}	2400	2400	2400	2400	2400	2400
Labor	CNY ha^{-1}·year^{-1}	7500	11,910	9300	9750	14,160	11,550
Allowance	CNY ha^{-1}·year^{-1}	2175	2175	3075	2175	2175	3075
Output							
Yield in 2022	kg ha^{-1}	25,699.65 ± 707.88 b	25,911.46 ± 319.94 ab	24,913.19 ± 1387.53 ab	23,263.89 ± 2933.46 ab	26,822.92 ± 646.69 a	24,392.36 ± 429.67 ab
Yield in 2023	kg ha^{-1}	15,407.99 ± 4078.83 b	27,199.07 ± 6921.76 a	25,101.27 ± 6386.71 a	17,939.81 ± 4605.66 b	27,777.78 ± 7059.81 a	26,909.72 ± 6844.66 a

Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching. Different lowercase letters indicate that there are significant differences among the treatments by LSD's new multiple range test ($p < 0.05$). Values are expressed as mean ± standard error (SE; n = 3).

3. Results

3.1. Six Endpoint Damage Categories per Hectare

Figure 2 presents the damage categories (based on unit area scale) for six endpoints per hectare under straw return and film mulching. When considering the contribution of the four phases to the six endpoint damage categories per hectare, Phase 2 (production of materials) emerged as the key contributor to energy consumption and ecosystem endpoint damage, representing 67.16% and 71.73% of the total endpoint results, respectively. This was due to the fact that agricultural production of fertilizers, organic fertilizers, pesticides, and mulch films (plastic films and biodegradable plastic films) consumes large amounts of energy in the form of raw coal, crude oil, and natural gas. As a result, the energy consumption endpoint damage category reflected high values. Additionally, heavy metal elements (e.g., cadmium, lead, mercury) and chemical additives (plasticizers) used in the production process of agricultural materials were released into the environment along with the emission of exhaust gases and wastewater. This exacerbated soil and water pollution, causing adverse effects on the ecosystem. Phase 3 (farming production) was the main contributor to global warming potential, environmental acidification, eutrophication, and human health, accounting for 52.84%, 70.04%, 56.20%, and 95.63% of the total endpoint results, respectively. This was due to the fact that agricultural activities such as tillage, fertilizer, and pesticide application and film mulching during crop production generated substantial greenhouse gas emissions and could lead to the formation and release of toxic chemicals containing heavy metals. Phase 1 (energy exploitation) made the most substantial contribution to resource consumption among the six endpoint damage categories. This was due to the fact that diesel and electricity production consumes a large amount of fossil energy sources such as coal, oil, and natural gas, as well as water and mineral resources. Additionally, inefficient extraction practices for energy and primary raw materials in China further intensified the energy consumption issues in Phase 1 (energy exploitation). Phase 4 (agricultural waste disposal) impacted all six endpoint damage categories, but only minimally, contributing 3.45%, 6.50%, 10.34%, 5.24%, 4.37%, and 0.54% to the total endpoint results, respectively.

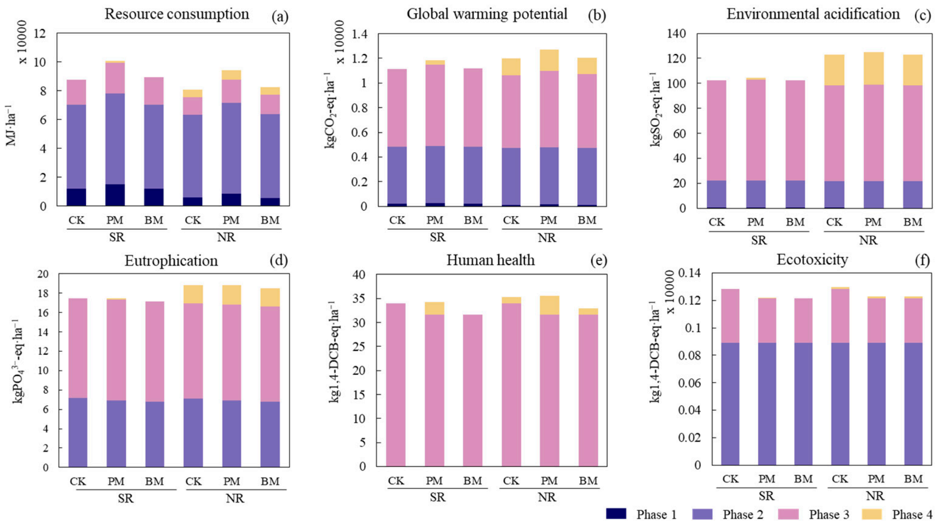


Figure 2. The comparison of six endpoint damage categories per hectare (area-scaled functional unit) among the six cultivation methods. Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching. (**a**) The comparison of resource consumption damage per hectare (area-scaled functional unit) among the six cultivation methods; (**b**) The comparison of global warming potential damage per hectare (area-scaled functional unit) among the six cultivation methods; (**c**) The comparison of environmental acidification damage per hectare (area-scaled functional unit) among the six cultivation methods; (**d**) The comparison of eutrophication damage per hectare (area-scaled functional unit) among the six cultivation methods; (**e**) The comparison of human health damage per hectare (area-scaled functional unit) among the six cultivation methods; (**f**) The comparison of ecotoxicity damage per hectare (area-scaled functional unit) among the six cultivation methods.

3.2. The Impact of Straw Return or Plastic Film Mulch on the Six Endpoint Damages per Hectare

Figure 3 presented the percentage effects (based on unit area scale) of straw return or film mulch on the six endpoint damage types. Compared to the SR-CK and NR-CK treatments, the impact potentials per hectare for the three endpoint damage categories of resource consumption, global warming potential, and environmental acidification were significantly higher for SR-PM, SR-BM, NR-PM, and NR-BM, while they were significantly lower for the eutrophication and ecotoxicity categories. The mean of the six endpoint damages per hectare increased by 3.27% in the SR-PM treatment compared to the SR-CK treatment under the straw return. Specifically, the SR-PM treatment had a greater impact on the damage categories of resource consumption and global warming potential, with resource consumption and global warming potential values under the SR-PM treatment being 15.15% and 6.43% higher than those in the SR-CK treatment, respectively. The mean values of the six endpoint damages were reduced by 1.88% in the SR-BM treatment compared to SR-CK. The resource consumption, global warming potential, and environmental acidification impact potentials in the SR-BM treatment were higher by 1.82%, 0.57%, and 0.09%, respectively, while the eutrophication, human health, and ecotoxicity impact potentials were reduced by 1.92%, 6.71%, and 5.13% compared to SR-CK. The mean values of the six endpoint damages per hectare in the NR-PM treatment increased by 3.41% under the non-returned straw conditions compared to NR-CK, where the resource consumption and global warming potential values in the NR-PM treatment were higher than NR-CK by 16.82% and 5.98%, respectively. The mean values of the six endpoint impairments in the NR-BM treatment were reduced by 1.73% compared to NR-CK, with eutrophication, human health, and ecotoxicity impact values reduced by 1.77%, 6.47%, and 1.73%, respectively. Compared to the NR-CK, NR-PM and NR-BM treatments, per hectare, the SR-CK, SR-PM and SR-BM treatments exhibited significantly higher impact potentials for the two endpoint damage categories of resource consumption and environmental acidification, and significantly lower impact potentials for the four endpoint damage categories of global warming potential, eutrophication, human health and ecotoxicity. The global warming potential, eutrophication, human health and ecotoxicity impact values per hectare of the SR-BM treatment were reduced by 6.96%, 4.53%, 3.64% and 1.03% compared to NR-BM.

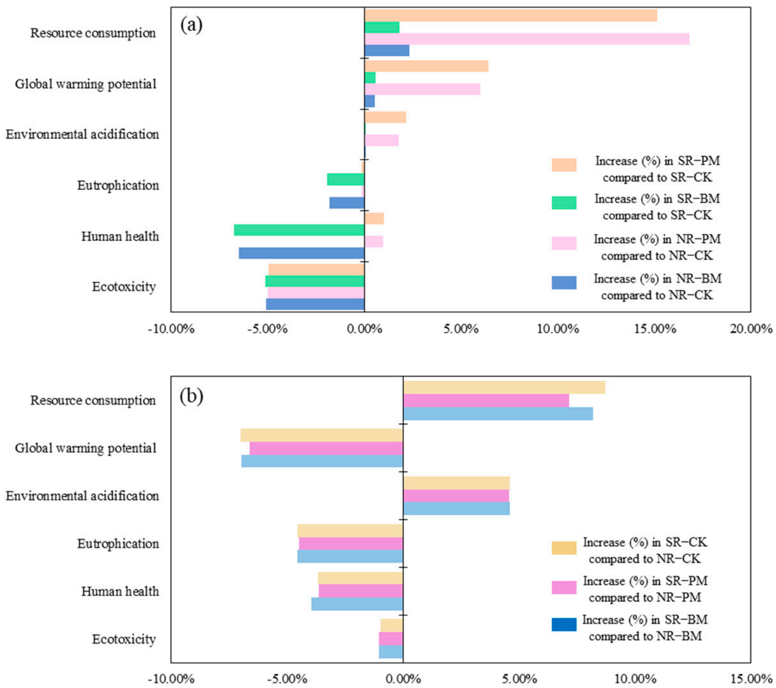


Figure 3. The percentage increase of the six endpoint damage categories per hectare (area-scaled functional unit) between different mulching films or straw returning. (**a**) The percentage increase in PM

or BM mulching films compared to CK in different straw returning. (**b**) The percentage increase in SR system compared to NR system in different mulching films. Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching.

3.3. Life Cycle Environment Impact Indexes and Evaluation Results of Straw Returning or Film Mulching on the Six Endpoint Damages per Hectare

Table 3 presented the standardized post-impact index and weighted post-impact index (based on unit area scales) of the impact potential of the six endpoint damage categories per hectare under straw return and film mulching. The environmental impacts of the six endpoint damages on garlic cropping system were ranked as ecotoxicity, eutrophication, environmental acidification, global warming potential, human health, and resource consumption. Among them, the highest impact potential value of ecotoxicity in the NR-CK treatment was 27.8, the highest impact potential values of eutrophication, environmental acidification, global warming potential, and human health in the NR-PM treatment were 1.20, 0.34, 0.22, and 0.03, the highest impact potential value of resource consumption in the SR-PM treatment was 0.01. Phase 2 (production of materials) was a major contributor to the environmental impacts of ecotoxicity, while Phase 3 (farming production) was a major contributor to eutrophication, environmental acidification, and global warming potential. The composite index of life cycle environmental impact per hectare was significantly lower for the SR-PM, SR-BM, NR-PM, and NR-BM treatments, with values of 27.75, 27.68, 28.18, and 28.11, respectively, compared to the SR-CK and NR-CK treatments.

Table 3. Weighted analysis of life cycle environmental impact potential values of the garlic system among six cultivation methods.

Impact Category	Stage	SR-CK	SR-PM	SR-BM	NR-CK	NR-PM	NR-BM
Resource consumption	Phase 1	7.03×10^{-4}	8.69×10^{-4}	6.92×10^{-4}	3.37×10^{-4}	5.03×10^{-4}	3.26×10^{-4}
	Phase 2	3.36×10^{-3}	3.66×10^{-3}	3.38×10^{-3}	3.34×10^{-3}	3.66×10^{-3}	3.38×10^{-3}
	Phase 3	1.02×10^{-3}	1.24×10^{-3}	1.11×10^{-3}	7.01×10^{-4}	9.23×10^{-4}	7.89×10^{-4}
	Phase 4		8.48×10^{-5}		2.92×10^{-4}	3.77×10^{-4}	2.92×10^{-4}
	Total	5.08×10^{-3}	5.85×10^{-3}	5.17×10^{-3}	4.67×10^{-3}	5.46×10^{-3}	4.78×10^{-3}
Global warming potential	Phase 1	4.11×10^{-3}	4.40×10^{-3}	4.02×10^{-3}	2.12×10^{-3}	2.41×10^{-3}	2.03×10^{-3}
	Phase 2	8.02×10^{-2}	8.10×10^{-2}	8.05×10^{-2}	8.02×10^{-2}	8.10×10^{-2}	8.05×10^{-2}
	Phase 3	1.10×10^{-1}	1.15×10^{-1}	1.11×10^{-1}	1.04×10^{-1}	1.08×10^{-1}	1.05×10^{-1}
	Phase 4		6.76×10^{-3}		2.33×10^{-2}	3.00×10^{-2}	2.33×10^{-2}
	Total	1.95×10^{-1}	2.07×10^{-1}	1.96×10^{-1}	2.09×10^{-1}	2.22×10^{-1}	2.10×10^{-1}
Environmental acidification	Phase 1	2.11×10^{-3}	1.99×10^{-3}	1.80×10^{-3}	1.12×10^{-3}	1.00×10^{-3}	8.11×10^{-4}
	Phase 2	5.73×10^{-2}	5.75×10^{-2}	5.79×10^{-2}	5.73×10^{-2}	5.75×10^{-2}	5.79×10^{-2}
	Phase 3	2.15×10^{-1}	2.16×10^{-1}	2.15×10^{-1}	2.05×10^{-1}	2.07×10^{-1}	2.05×10^{-1}
	Phase 4		3.96×10^{-3}		6.57×10^{-2}	6.96×10^{-2}	6.57×10^{-2}
	Total	2.74×10^{-1}	2.80×10^{-1}	2.74×10^{-1}	3.29×10^{-1}	3.35×10^{-1}	3.30×10^{-1}
Eutrophication	Phase 1	3.21×10^{-3}	3.49×10^{-3}	3.15×10^{-3}	1.47×10^{-3}	1.74×10^{-3}	1.41×10^{-3}
	Phase 2	4.53×10^{-1}	4.38×10^{-1}	4.31×10^{-1}	4.53×10^{-1}	4.38×10^{-1}	4.31×10^{-1}
	Phase 3	6.58×10^{-1}	6.64×10^{-1}	6.58×10^{-1}	6.28×10^{-1}	6.34×10^{-1}	6.28×10^{-1}
	Phase 4		7.25×10^{-3}		1.20×10^{-1}	1.27×10^{-1}	1.20×10^{-1}
	Total	1.11×10^{0}	1.11×10^{0}	1.09×10^{0}	1.20×10^{0}	1.20×10^{0}	1.18×10^{0}
Human health	Phase 1						
	Phase 2						
	Phase 3	2.41×10^{-2}	2.25×10^{-2}	2.25×10^{-2}	2.41×10^{-2}	2.25×10^{-2}	2.25×10^{-2}
	Phase 4		1.86×10^{-3}		9.20×10^{-4}	2.78×10^{-3}	9.20×10^{-4}
	Total	2.41×10^{-2}	2.44×10^{-2}	2.25×10^{-2}	2.50×10^{-2}	2.53×10^{-2}	2.34×10^{-2}
Ecotoxicity	Phase 1						
	Phase 2	1.98×10^{1}	1.98×10^{1}	1.98×10^{1}	1.98×10^{1}	1.98×10^{1}	1.98×10^{1}
	Phase 3	7.75×10^{0}	6.34×10^{0}	6.34×10^{0}	7.75×10^{0}	6.34×10^{0}	6.34×10^{0}
	Phase 4		2.44×10^{-2}		2.77×10^{-1}	3.01×10^{-1}	2.77×10^{-1}
	Total	2.75×10^{1}	2.61×10^{1}	2.61×10^{1}	2.78×10^{1}	2.64×10^{1}	2.64×10^{1}

Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching.

3.4. Six Endpoint Damage Categories per t

Figure 4 presented the six endpoint damage categories per t (based on unit yield scales) for 2022 and 2023 under straw return and film mulching. The results showed that in 2022 and 2023, there was a significant reduction in the impact potential of the damage category for the six endpoints per t in the SR-PM, SR-BM, NR-PM, and NR-BM treatments compared to SR-CK and NR-CK. In terms of resource consumption, the straw-return system showed a significantly higher impact potential compared to the straw non-returned system, with the NR-BM treatment exhibiting the lowest average impact value at 3227.69 MJ$\cdot$t^{-1}. For global warming potential, environmental acidification, and eutrophication, the SR system recorded significantly lower mean values of 500.71 kgCO_2-eq$\cdot$t^{-1}, 4.54 kgSO_2-eq$\cdot$t^{-1} and 0.76 kg$PO_4{}^{3-}$-eq$\cdot$t^{-1}, respectively, compared to the NR system. The SR-BM treatment had the lowest global warming potential, recorded at 4444.53 kgCO_2-eq$\cdot$t^{-1}. The SR-PM treatment recorded the lowest values for environmental acidification and eutrophication at 3.94 kgSO_2-eq$\cdot$t^{-1} and 0.66 kg$PO_4{}^{3-}$-eq$\cdot$t^{-1}, respectively. In terms of human health, CK > PM > BM was demonstrated under both straw-returned and non-returned treatments, with the SR-BM treatment showing the lowest human health impact potential at 125 kg1,4-DCB-eq$\cdot$t^{-1}. In terms of ecotoxicity, CK > BM > PM was exhibited under both straw-returned and non-returned treatments, with the SR-PM treatment showing the lowest ecosystem impact potential at 45.78 kg1,4-DCB-eq$\cdot$t^{-1}.

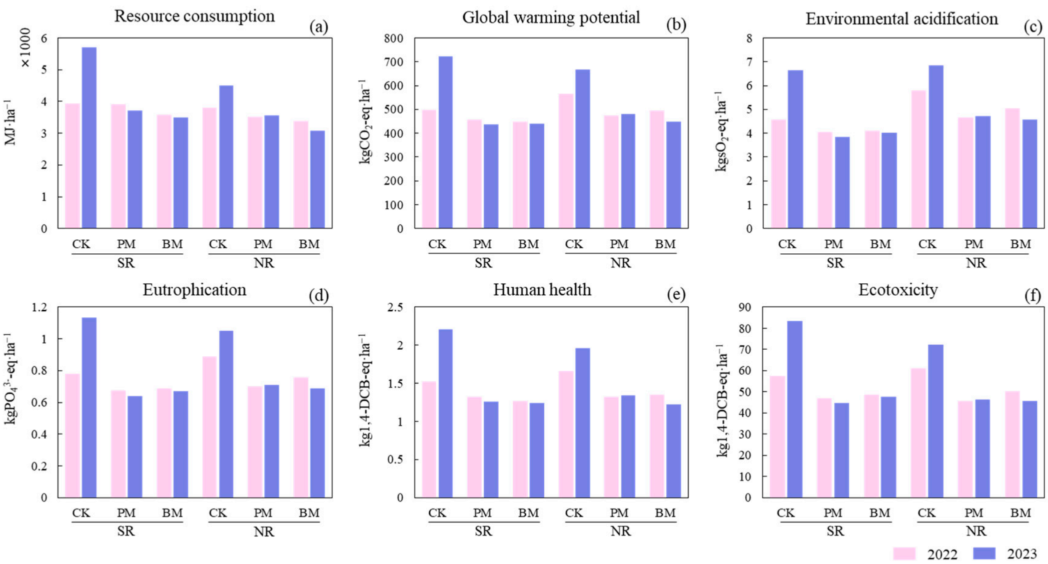


Figure 4. The comparison of the six endpoint damage categories per t of yield produced (yield-scaled functional unit) in year 2022 and 2023 among six cultivation methods. Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching. (**a**–**f**). (**a**) The comparison of resource consumption damage per t of yield produced (yield-scaled functional unit) in year 2022 and 2023 among six cultivation methods; (**b**) The comparison of global warming potential damage per t of yield produced (yield-scaled functional unit) in year 2022 and 2023 among six cultivation methods; (**c**) The comparison of environmental acidification damage per t of yield produced (yield-scaled functional unit) in year 2022 and 2023 among six cultivation methods; (**d**) The comparison of eutrophication damage per t of yield produced (yield-scaled functional unit) in year 2022 and 2023 among six cultivation methods; (**e**) The comparison of human health damageper t of yield produced (yield-scaled functional unit) in year 2022 and 2023 among six cultivation methods; (**f**) The comparison of ecotoxicity damage per t of yield produced (yield-scaled functional unit) in year 2022 and 2023 among six cultivation methods.

3.5. The Impact of Straw Return and Film Mulching on the Six Endpoint Damages per t

Figure 5 presented the percentage impact of different straw return and film mulch on the six endpoints damage (based on unit yield scales) in 2022 and 2023. In 2022 and 2023, the impact potential for the six endpoint damage categories per t in the SR-PM, SR-BM, NR-PM, and NR-BM treatments were significantly lower compared to SR-CK and NR-CK. The mean values of the six endpoint damages per t were reduced by 26.31% and 26.43% in the SR-PM and SR-BM treatments compared to SR-CK under straw return. The mean values of the six endpoint damages per t for NR-PM and NR-BM were reduced by 24.10% and 24.54% under non-straw returned conditions compared to the NR-CK treatment. In 2022 and 2023, there was a significant increase in the impact potential for the resource consumption damage category, along with a notable decrease in the impact potential for the environmental acidification damage category per t in the SR-CK, SR-PM, and SR-BM treatments compared to NR-CK, NR-PM, and NR-BM.

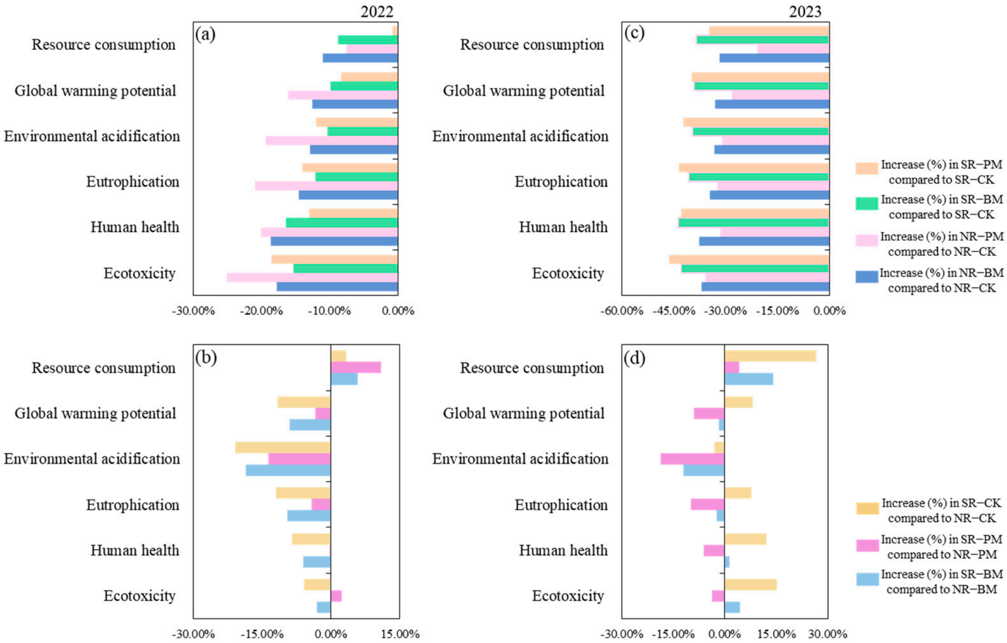


Figure 5. The percentage increase of the six endpoint damage categories per t of yield produced (yield-scaled functional unit) in year 2022 and 2023 between different mulching films or straw returning. Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching. (**a**–**d**). (**a**) The percentage increase in PM or BM mulching films compared to CK in different straw returning in 2022. (**b**) The percentage increase in SR system compared to NR system in different mulching films in 2022. (**c**) The percentage increase in PM or BM mulching films compared to CK in different straw returning in 2023. (**d**) The percentage increase in SR system compared to NR system in different mulching films in 2023.

3.6. The Cost–Benefit Assessment of Straw Return and Film Mulching on the Six Endpoint Damages

Minimizing input costs while maximizing economic returns remains the primary goal in agricultural production. Table 4 presented the effects of straw return and film mulch on economic benefits (based on unit area and yield scales) in 2022 and 2023. The cost input for PM was the highest, while CK had the lowest cost input across both straw-returned and non-returned treatments. In 2022, economic benefits showed no significant difference across the six treatments. However, in 2023, returns per hectare significantly increased for the SR-PM, SR-BM, NR-PM, and NR-BM treatments compared to SR-CK and NR-CK. Additionally, there was no significant difference between PM and BM in the SR and NR system. The economic efficiency based on unit yield was highest for the SR-BM treatment at 3691.03 CNY·t^{-1}, exceeding that of the SR-CK treatment by 7.26%.

Table 4. The cost–benefit assessment of the garlic system among the six cultivation methods.

Treatment	All Cost/CNY $10^4 \cdot ha^{-1}$	Income in 2022/CNY $10^4 \cdot ha^{-1}$	Benefit in 2022/CNY $10^4 \cdot ha^{-1}$	Income in 2023/CNY $10^4 \cdot ha^{-1}$	Benefit in 2023/CNY $10^4 \cdot ha^{-1}$	Benefit/CNY$\cdot t^{-1}$
SR-CK	5.94	11.35 ± 0.25 b	8.38 ± 0.25 a	7.70 ± 0.82 b	4.73 ± 0.82 b	3441.23 ± 91.74 b
SR-PM	6.96	12.96 ± 0.11 ab	9.42 ± 0.11 a	13.60 ± 0.42 a	10.07 ± 0.42 a	3670.42 ± 17.57 ab
SR-BM	6.6	12.46 ± 0.49 ab	9.16 ± 0.49 a	12.75 ± 0.03 a	9.45 ± 0.03 a	3691.03 ± 25.61 a
NR-CK	6.06	11.63 ± 1.04 ab	8.53 ± 1.04 a	8.97 ± 0.86 b	5.86 ± 0.86 b	3493.18 ± 133.55 ab
NR-PM	7.08	13.41 ± 0.23 a	9.75 ± 0.23 a	13.24 ± 0.06 a	9.57 ± 0.06 a	3624.55 ± 12.07 ab
NR-BM	6.72	12.20 ± 0.15 ab	8.76 ± 0.15 a	13.45 ± 0.47 a	10.02 ± 0.47 a	3661.04 ± 27.33 ab

Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching. Different lowercase letters indicate that there are significant differences among the treatments by LSD's new multiple range test ($p < 0.05$). Values are expressed as mean ± standard error (SE; $n = 3$).

3.7. Detailed Contribution Analysis of Inventory Items for Each of the Six Endpoint Damage Categories per Hectare

Figure 6 showed the detailed contribution of each stockpile item, along with its associated upstream and downstream processes to the six endpoint damage categories across the straw return and different mulch treatments. Fertilizer inputs were the major contributors to resource consumption, global warming potential, environmental acidification, eutrophication, and ecosystems impacts, with respective contributions of 61.29%, 78.31%, 85.06%, 67.60%, and 71.12%. Crop protection was the primary contributor to human health, accounting for 76.63%. Seeding was the second largest contributor to human health and ecosystems with contributions of 19.53% and 16.10%, respectively. Waste mulch recycling disposal was the third largest contributor to human health in the SR-PM and NR-PM treatments with contributions of 7.64% and 7.36%, respectively. Straw disposal was the second-largest contributor to global warming potential and environmental acidification in the NR system with 5.45% and 9.91%, respectively. Additionally, tillage, mulching, irrigation, and harvesting were significant contributors to resource consumption, accounting for 15.44%, 3.59%, 1.24%, and 5.89%, respectively.

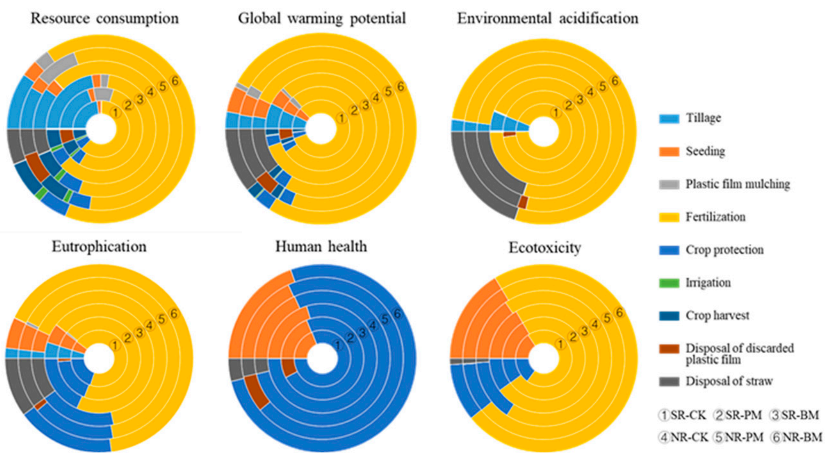
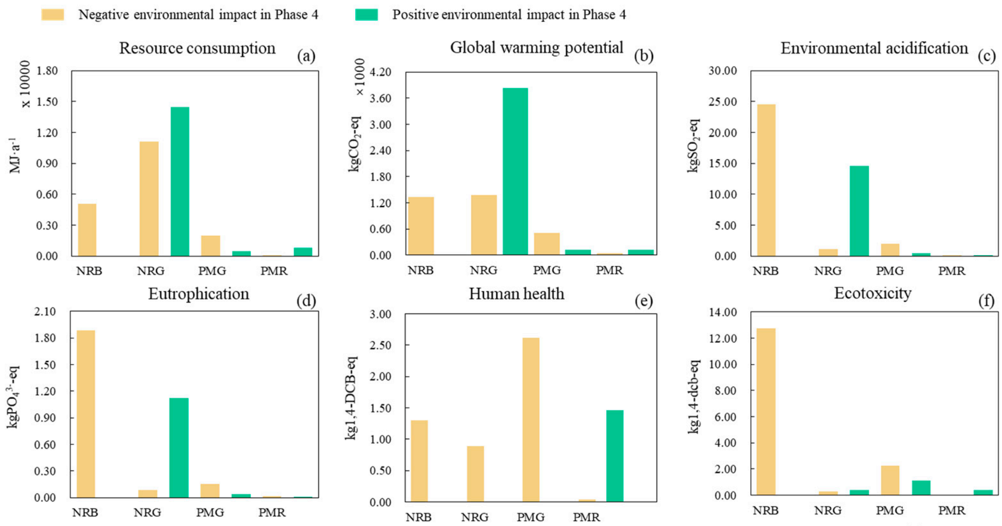


Figure 6. The relative proportion (%) of various inventory items on the six endpoint damage categories per hectare (area-scaled functional unit). Note: SR-CK: straw return without film mulching; SR-PM: straw return with plastic film mulching; SR-BM: straw return with biodegradable film mulching; NR-CK: straw non-return without film mulching; NR-PM: straw non-return with plastic film mulching; and NR-BM: straw non-return with biodegradable film mulching.

3.8. Two Options in the Disposal of Discarded Plastic Films and Straw per Hectare

Figure 7 indicates that in addition to the conventional straw incineration and waste mulch power generation in Phase 4, straw power generation and waste mulch recycling granulation were also evaluated to explore options for reducing environmental impacts. Compared to SI and MPG, SPG and MRG were more favorable offset strategies in terms of resource consumption, global warming potential, environmental acidification, eutrophication, and ecotoxicity, yielding positive environmental benefits. In the SR-PM system, the MRG model significantly reduced the impact potential across the six endpoint damage categories per hectare compared to the MPG. The human health impact potential of the MRG model was decreased by 6.34% compared to MPG. In the NR-PM system, the SPG + MRG model significantly reduced the impact potential across the six endpoint damage categories per hectare compared to the SI + MPG model. In the SPG + MRG model, the impact potentials for global warming potential and environmental acidification were reduced by 33.35% and 31.58%, respectively, compared to SI + MPG.



(g)

Category	Resource consumption	Global warming potential	Environmental acidification	Eutrophication	Human health	Ecotoxicity
Decrease (%) in PMR compared to PMG in SR−PM	2.17	3.99	1.41	0.63	6.34	0.18
Decrease (%) in NRG+PMR compared to NRB+PMG in NR−PM	11.18	33.55	31.58	16.1	7.24	0.18

< 5 5−20 > 20

Figure 7. The comparison of the six endpoint damage categories per hectare (area-scaled functional unit) between the four waste disposal methods: straw incineration, straw power generation, waste mulch power generation, and recycling granulation in Phase 4 (**a**–**f**). The positive environmental benefit in straw and waste mulch power were generated from the electricity recovery converted by heat energy and waste mulch recycling granulation being reused. The percentage decrease of the six endpoint damage categories hectare (area-scaled functional unit) with the improvement of the new method in the SR-PM and NR-PM treatments (**g**). Note: SR-PM: straw return with plastic film mulching; NR-PM: straw non-return with plastic film mulching; SI: straw incineration; SPG: straw power generation; MPG: waste mulch power generation; and MRG: waste mulch recycling granulation.

4. Discussion

4.1. Endpoint Damage Categories per Hectare or per t of Yield Produced Influenced by Different Straw Return and Film Mulching

China is the world's leading rice producer and the largest exporter of garlic [59]. Therefore, balancing agricultural productivity with the environmental impacts of production cycles is crucial. Straw return and mulching, key management practices in modern agricultural production, have been extensively implemented in arid and semi-arid regions, particularly for crops such as maize, cotton, and vegetable crops [9]. Mulching can significantly increase garlic yield by conserving water, raising soil temperature, inhibiting weed growth, and enhancing the physical and chemical properties of the soil [24]. The results of study aligned with this finding, showing that garlic yield was 38.37% and 32.26% higher under the PM and BM treatments compared to the CK treatments. Previous research has also demonstrated that mulching helped to inhibit water evaporation, promotes water movement from deep soil to the surface, increased surface soil moisture, and promotes crop growth [60]. At the same time, returning straw to the field can boost soil microbial biomass and enzyme activity, improve soil structure, and enhance crop yields [10]. There was no significant difference in crop yield observed between the PM and BM treatments for both SR and NR systems. It was consistent with previous studies [61], and the possible reason for this was that both BM and PM served similar roles in heat and moisture retention during the pre-growth period of garlic. In the later stages of garlic growth, the degrading properties of the biodegradable membranes helped mitigate issues such as root rot, soil structure degradation, and poor permeability that were caused by high soil temperatures resulting from the failure of ordinary plastic membranes to degrade [62]. At the same time, the late degradation of biodegradable film can enhance garlic's absorption of soil water and nitrogen, creating favorable conditions for garlic growth [63].

This study broadened life cycle assessments compared to previous research, incorporating factors such as primary energy production, agricultural equipment losses, and disposal of used mulch and straw off-farm. The study results indicated that the six endpoint damages had a greater impact on the garlic life cycle environment were ecosystems, eutrophication, environmental acidification, and global warming potential. Notably, the NR system per hectare significantly increased the damage potentials of the three endpoint categories of global warming potential, environmental acidification, and eutrophication compared to the SR system. This was because direct straw incineration in the NR system releases large amounts of greenhouse gases, which can trigger warming. At the same time, the straw incineration also produced acid gases such as SO_2 and NO_x, which combined with atmospheric water vapor to form acid rain that falls to the ground and acidifies soil and water bodies [64]. Moreover, nutrients such as N and P contained in straw were released into the atmosphere in gaseous form when burned. These nutrients later settle on soil or water bodies, increasing nutrient levels and causing water eutrophication [65]. Therefore, in order to protect the environment and promote sustainable development, straw incineration was replaced with more eco-friendly and sustainable straw utilization methods, such as returning straw to the field, energizations, and resuscitations. Straw pyrolysis, as an important form of comprehensive utilization of straw, had a positive impact on the environment. Straw pyrolysis could reduce a large amount of particulate matter, harmful gases, and carbon emissions from straw incineration. Some studies have shown that straw pyrolysis can adsorb heavy metals and organic pollutants in soil and purify the soil and water environment [66]. The SR-BM treatment caused the least damage to the six endpoints under the straw return system. This was due to higher pesticide application in the SR-CK treatment, which led to increased potentials for environmental acidification, eutrophication, human toxicity, and ecotoxicity. In the SR-PM treatment, producing plastic films and incinerating used films consumed significant energy, while film incineration released toxic gases such as dioxins and polycyclic aromatic hydrocarbons (PAHs), which posed serious health hazards. Additionally, plastic film mulching during the phase of farming production produced more carbon emissions, aligning with findings from previous studies [61]. Enhanced soil hydrothermal processes in film mulching accelerated the decomposition of organic matter, resulting in increased emissions of greenhouse gases. Therefore, the SR-BM treatment was a stable and eco-friendly cultivation practice that helped stabilize and increase garlic yield per unit hectare. Secondly, when considering plastic film mulch, the environmental impact of plastic mulch should be carefully assessed, particularly during production and waste disposal stages.

4.2. Low-Energy, High-Efficiency Garlic Cultivation Model

Higher crop yields and economic efficiency remained the primary goals pursued in agricultural production [67]. To scientifically assess the combined benefits of different treatments in agricultural production applications, both endpoint damage categories per hectare (based on the area scale), in addition to endpoint damage categories per t (based on the area scale), and economic returns per t of yield (based on the yield scale) were assessed. This approach highlighted the importance of boosting crop yields with minimal environmental impacts in order to ensure food security, enhance farm household incomes, and promote sustainable crop production. The results of this study showed that all six endpoint damage categories per t of yield were lower in the PM and BM treatments than the CK treatment, primarily due to the fact that the increase in yield in film mulching was greater than the endpoint damage categories per hectare of yield in film mulching. Compared to the NR-PM and NR-BM treatments, the impact potentials of the damage categories of energy consumption per t in the SR-PM and SR-BM treatment were significantly higher, while the impact potentials of the damage categories of GWP, environmental acidification, and eutrophication were significantly lower. This indicated that the SR-PM and SR-BM treatments can be regarded as potential high-yield strategies that produced more yield with less environmental impact. Additionally, the SR-BM treatment offered the highest economic benefit per unit yield, which was due to the fact that biodegradable mulch does not need to be picked up after use during the garlic cultivation cycle. This reduced the cost of mulch removal and recycling. Furthermore, the natural polymer materials (e.g., starch, cellulose, etc.) in biodegradable mulch can be decomposed by microorganisms into beneficial substances and can improve the structure of the soil, which can be used as fertilizer to promote crop yield [68]. It has also been demonstrated that the external costs of plastic films, resulting from environmental contamination due to improper disposal, must be considered [69]. Therefore, the SR-BM system is a cultivation model that combines low energy consumption per unit of production with high yield potential and high efficiency. Compared with PE film, an important limiting factor for the large-scale popularization and application of biodegradable film was its high cost. The price of raw materials, film thickness, processing technology, and other factors of biodegradable films have resulted in production costs that were much higher than PE films, which could become a barrier for small-scale farmers. Therefore, there is a need to reduce costs through innovations in raw materials and processing methods for biodegradable mulch. At the same time, although Xuzhou City, where the experiment is located, gave a subsidy of 900 CNY ha^{-1} to small farmers using biodegradable film, the price of biodegradable film was still twice as much as that of PE film, and the government should increase the cost compensation or subsidy.

4.3. Major Contributions to the Endpoint Categories

Determining the contributions of different resource inputs per hectare to the six endpoint damage categories is useful for exploring strategies to mitigate environmental impacts. The current study revealed that fertilizer inputs were the largest contributors to resource consumption, global warming potential, environmental acidification, eutrophication, and ecotoxicity, accounting for about 72.80% of the five environmental impacts (Figure 6). The result aligned with previous studies, which demonstrated that >50% of the total environmental impacts under different treatments came from fertilizer [45,70]. This was primarily because fertilizers, as agricultural inputs, require a large amount of energy consumption in the industrial manufacturing process, such as crude coal, crude oil, and natural gas, as well as inputs of diesel and electricity. Therefore, improving fertilizer production technology and increasing fertilizer utilization are effective ways to reduce the environmental impact of the upstream chain. Nitrogen fertilizer application was also a key factor that causes greenhouse gas emissions in cropping production systems. Additionally, the application of nitrogen fertilizer under straw return and film mulching can significantly increase CH_4 and N_2O emissions. This was mainly due to the fact that the application of fertilizer increased the nitrogen content of the soil, which provided essential raw materials such as H_2 and CO_2 for the methanogenic bacteria. Additionally, the straw return and film mulching reduced the frequency of O_2 exchange between the field soil and the outside world, and the soil aeration was poor, leading to poor soil aeration and creating an anaerobic environment favorable for the growth of methanogenic bacteria [71]. Furthermore, the straw return increased the effective carbon substrate concentration, which promotes N_2O emissions [32]. Fertilizer application can also cause environmental acidification and eutrophication in cropping production systems by affecting NH_3 volatilization and N_2O emissions, which is consistent with previous studies [72]. This means that replacing chemical fertilizers with organic fertilizers to reduce NO_x emissions and resource consumption in agricultural fields can be considered as a potential strategy to mitigate environmental impacts [73]. Bu et al. [71] found that substituting organic fertilizers for chemical fertilizers was an effective approach to improving soil fertility and reducing the intensity of greenhouse gas emissions from paddy fields. Substituting organic fertilizers for chemical fertilizers can significantly reduce ammonia volatilization and N_2O emission from paddy fields, providing a sustainable solution to reduce emissions, increase efficiency, and stabilize production in rice–duck symbiosis [74]. Additionally, replacing chemical fertilizers with locally composted organic fertilizers (to minimize long-distance transport) may be environmentally beneficial, as it reduces environmental pollution from transportation [75].

Crop protection was a major contributor to human health, mainly due to heavy metal particles volatilized into the air from pesticide production in industry and pesticide residues entering the air from agricultural practices [76]. In the SR and NR systems, the BM treatments reduced human health impact potentials compared to CK, mainly due to the effectiveness of BM in controlling weeds and reducing pesticide inputs [77]. However, the human health impact potential in the PM treatment remained higher than CK due to the fact that the incineration treatment of waste mulch during Phase 4 not only completely offset the benefits of reduced pesticide inputs, but also generated larger quantities of soot and ash that are hazardous to human health. These include pollutants like PM2.5/10, CO, acid gases, and NO_x, which contribute to severe air pollution and environmental burdens [78]. Therefore, it is important to explore feasible disposal methods for waste mulch that could offset or mitigate the environmental impacts of waste mulch power generation. Additionally, straw disposal was the second largest contributor to the global warming potential and environmental acidification in the NR system. Therefore, it is crucial to explore feasible methods for optimizing straw disposal to mitigate environmental impacts.

4.4. Better Options in the Disposal of Discarded Plastic Films and Straw per Hectare for Mitigation of Plastic Film and Straw Pollution

4.4.1. Discarded Plastic Films

As a key tool in agricultural production in China, effectively preventing and controlling residual pollution is crucial for managing agricultural and rural pollution and the promotion of green agricultural development [79]. While plastic mulch plays an important role in safeguarding China's food security, it's long-term, large-scale and high-intensity application, coupled with delays in recycling practices among farmers, results in mulch film residual pollution problems [49]. Waste mulch recycling and processing enterprises can utilize various resource recovery methods, including regeneration granulation, fuel extraction, fuel power generation, and wood-plastic production. Currently, waste mulch reuse methods primary include incineration for power generation and recycling granulation. This study showed that compared to waste mulch power generation, recycling granulation of waste mulch was a more favorable offset strategy in terms of resource consumption, global warming potential, environmental acidification, eutrophication, and ecotoxicity, producing positive environmental benefits. This is primarily because recycling discarded plastic films reduced white pollution and enables recycled plastic films to be reused in new products. The results differ from the study of Zhang et al. [69], mainly due to the inconsistency in the life cycle boundaries of plastic film mulch. China is a major user of agricultural films, generating a substantial number of used films every year. Currently, there are two main technologies in China to prevent and control pollution from used agricultural films. The first is product substitution technology. The adoption of biodegradable films to replace PE films for agricultural use is an inevitable trend in development. The second is the waste agricultural film recycling technology. This involves adopting machinery (artificial) to remove used agricultural films from the soil and then, according to specific situations, using appropriate recycling technology to achieve resource recycling, to solve the "last kilometer" problem. The recycling and reuse of used agricultural films can establish a true closed-loop agricultural film circular economy industry chain of "agricultural films, used agricultural films, renewable resources". This process helps reduce environmental pollution and promotes the green and sustainable development of agriculture.

4.4.2. Straw

China has a large total agricultural output and abundant straw resources. In 2022, China's annual crop straw production was approximately 700 million tons, with 301 million tons of collectible resources [5]. Transforming straw into valuable assets and vigorously promoting its comprehensive utilization as high-quality renewable biological resources are conducive to improving agricultural waste management, minimizing the adverse impact of agricultural production waste on the agricultural production environment, as well as promoting the green development of agriculture [15,69]. Therefore, the study also evaluated the method of straw incineration for power generation compared to direct straw incineration. Straw incineration for power generation, as a method of energy utilization, is the common method of straw treatment in China, alongside its use in fertilizer and feed, accounting for 8.3% of the total straw utilization [80]. This study found that compared to straw incineration, straw incineration for power generation produced positive environmental benefits in resource consumption, global warming potential, environmental acidification, eutrophication, human health, and ecotoxicity. The six endpoint damage categories under the SPG + MRG model were significantly reduced; especially the impact potentials of the two endpoint damage categories, global warming potential and environmental acidification, were reduced compared to that of SI + MPG by 33.35% and 31.58%. This was due to the fact that straw power generation produced electricity, which helped to reduce the reliance on fossil fuels. It has also been demonstrated that straw incineration for electricity generation instead of direct incineration significantly reduces atmospheric particulate matter levels. Specifically, particulate matter emissions were reduced by about 99% relative to direct combustion, while NO_x emissions were relatively low [52]. Therefore, the approach of waste mulch recycling granulation and straw power generation is the most effective strategy for offsetting and mitigating all six endpoint damage categories per hectare.

4.5. Limitations and Implications

Although the study employed a scientific and systematic LCA method to evaluate the endpoint damage categories of various mulch covers and straw return, the current LCA method still has limitations. Firstly, due to the lack of information in the database, plant equipment, construction facilities, etc. were not considered to cause a certain amount of resource consumption and pollutant emission. As a result, the study's findings were significantly lower than those of the actual production. Secondly, the carbon sequestration effect under various farmland management techniques (e.g., straw return to the field, mulching, organic and inorganic fertilizer application, etc.) were not considered. Some studies have shown that straw return to the field can increase the soil organic matter, promote the soil microbial activity, and increase carbon fixation. Additionally, combining straw return with nitrogen fertilizers can affect the soil carbon and nitrogen ratio, enhance the microbial utilization of nitrogen, and reduce N_2O emissions. Film mulch can change soil microbial communities and ecological functions, thereby accelerating organic carbon mineralization [81]. Thirdly, since most of the collected inventory data were based on foreign research results, there was a certain deviation from the actual situation in China, leading to unavoidable uncertainty. Therefore, future efforts should focus on enhancing China's LCA database to cover all scenarios across the entire industrial chain, enabling a comprehensive and integrated evaluation of the life of different agricultural production systems in China.

This study indicated that while most of the used plastic film was collected and transferred for waste disposal, some plastic film residues have been remained in the topsoil. Although the system boundary of LCA does not account for soil-based plastic film residues, these residues present a potentially complex environmental threat [82]. Some studies have shown that crop yields can decrease by over 11.3% when the amount of residual film exceeds 240 kg ha^{-1}. At the same time, the residual film in the soil can adsorb heavy metals, antibiotics and other pollutants, change the soil physical and chemical properties (e.g., pH and weight etc.), affect the development of soil animals such as earthworms, reduce the activity of key microorganisms involved in the soil nutrient cycling process, and ultimately harm the soil environment. The research, development and testing of fully biodegradable mulch films offer potential solutions to residual film pollution. Currently, the composition of fully biodegradable mulch film products is mainly based on polyesters such as PBAT (polybutylene terephthalate adipate), PLA (polylactic acid), and PBS (polybutylene succinate), which are degraded into water and carbon dioxide without releasing toxic chemicals into the environment [83]. However, studies have shown that biodegradable mulches still release microplastics into the soil system, which may alter soil microbial communities and ecological functions [84]. Therefore, it is essential to develop double-degradable agricultural films, such as light biodegradable agricultural films, to ensure timely and complete degradation. The production process of double-degradable agricultural films is complex and costly, making the simplification of production and cost reduction a key challenge for their future application. In addition, the negative impacts of microplastics from biodegradable films on crop yield, soil aggregate nutrients, water cycling, and C, N, and P transformation are similar to those of non-biodegradable plastics [83]. Therefore, the mechanism of action of microplastics in biodegradable films remains a key focus of current research, aimed at further minimizing their environmental impacts on sustainable agriculture.

This study thoroughly explored the environmental impacts of returning straw to the field, straw incineration, and straw power generation. However, in order to more accurately assess the optimal utilization of straw, future studies could consider its potential use as feed or feedstock.

5. Conclusions

In terms of unit area, the results indicated that the environmental impacts of the six endpoint damages in garlic cropping system were ranked as ecotoxicity, eutrophication, environmental acidification, global warming potential, human health, and resource consumption. The SR-BM treatment had the lowest life cycle environmental impact composite index at 27.68 per unit area, primarily due to the significant reduction damage in Phase 4. The six endpoint damage categories per t of yield were the lowest under the SR-BM treatment and had the highest economic benefits at 3691.03 CNY·t^{-1}, exceeding that of SR-PM by 0.56%. This was mainly because the yield increased under the mulch treatment outweighed the endpoint damage categories per hectare of yield, and BM reduced the cost of mulch pickup and recycling treatment compared to PM. Therefore, the SR-BM system can be used as a highly productive and eco-friendly cultivation practice for garlic. Fertilizer inputs were the largest contributor to resource consumption, global warming potential, environmental acidification, eutrophication, and ecotoxicity, accounting for about 72.80% of the five environmental impacts. Crop protection also significantly affected human health, and garlic mulching helped minimize pesticide use, thereby reducing potential health impacts. Compared to straw incineration and waste mulch power generation, straw power generation, and waste mulch recycling granulation offered positive environmental benefits and were more effective offset strategies. In conclusion, straw return with biodegradable mulch is a synergistic cultivation measure that offers both environmental and economic benefits. For straw return with plastic film mulch, environmental impacts can be reduced by waste mulch recycling granulation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14122993/s1, Table S1: The operative methods (machinery or manual) and facilities for each field operation; Table S2: Summary of the data sources within the four phases of the life cycle for evaluating four phases' damage categories in garlic production; Table S3: Normalized values and weights for the six impact categories.

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