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Effects of Biodegradable Plastic Film Mulching on the Global Warming Potential, Carbon Footprint, and Economic Benefits of Garlic Production

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Abstract: This paper clarifies the farm applicability and feasibility of spreading biodegradable plastic film mulching for garlic production to ensure the green and sustainable development of the garlic industry. We set up a field trial of garlic planting with biodegradable plastic film mulching (BM) and plastic film mulching (PM), using no film mulching (CK) as the control, and measured CH_4 and N_2O emissions in the garlic fields. The yield-scaled global warming potential, carbon footprint, and net ecosystem economic benefit (NEEB) were used to assess the comprehensive impact of the different treatments. Compared to the CK, film mulching significantly increased CH_4 absorption, with significantly higher seasonal cumulative CH_4 emissions (20.5%) in BM than PM, but significantly increased N_2O emissions, with significantly lower seasonal cumulative N_2O emissions (23.53%) in BM than PM. Both BM and PM improved garlic yield, with PM significantly increasing garlic yield by 18.86% compared to the CK. Moreover, film mulching significantly decreased the yield-scaled global warming potential (by 52.06% and 40.82% in PM and BM, respectively). PM had a significantly higher carbon footprint than BM. Film mulching improved NEEB by 9.29–11.78%. Considering crop yields and environmental benefits, we propose BM as an effective method for a green and efficient garlic production.

Keywords: biodegradable plastic film; greenhouse gas; garlic yield; carbon footprint; net ecosystem economic benefit

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1. Introduction

Global warming, resulting from significantly increased greenhouse gas (GHG) emissions since the Industrial Revolution, has become a major global problem [1] (Wang et al., 2017). The Intergovernmental Panel on Climate Change [2] (IPCC 2022) has estimated that the Earth's surface will warm by 1.5–1.6 °C by approximately 2040. Global warming has also changed precipitation patterns and increased the frequency of drought events [3] (Xu and Lan, 2017). These climate changes affect crops on multiple levels, including molecular function, developmental processes, morphological characteristics, and physiological biochemistry, posing significant challenges to global agricultural production and food security [4] (Hu et al., 2023). Agriculture is the main source of GHG emissions, with CH_4 and N_2O emissions from agricultural land accounting for more than 37.8% and 65.1% of global anthropogenic emissions, respectively [5] (Qian et al., 2020). Agricultural management practices, such as straw return, organic manure application, biomass charcoal application, and crop rotation and fallow practices, are common environmental protection measures employed to increase the soil's organic carbon content, which can also reduce the amount of fertilizer application and lower CH_4 and N_2O emissions, thereby improving soil quality

and crop yields [6,7] (Reza and Majid, 2022). Against the background of continuous population growth and increasing food demands, it is increasingly important to develop rational farmland management practices that can achieve the dual goals of increased production and carbon reduction.

China has the largest garlic cultivation area and the highest garlic production in the world [8] (Liu et al., 2023). Garlic (*Allium sativum* L.) is one of the most popular vegetables worldwide and an important export agricultural product for China that generates substantial economic benefits. In 2020, the planted area of garlic in China was 843,000 ha, and the output reached 21.625 million tons, accounting for 50.18% and 67.58% of the world, respectively [9] (Cui et al., 2023). However, garlic grown in open fields in China is susceptible to frost damage and drought owing to low winter temperatures. Therefore, film mulching is a routine management measure in garlic production that promotes long-term growth and development. Recently, biodegradable films have been increasingly used in garlic cultivation to address the problem of film residues.

Film mulching plays a vital role in improving the soil environment. It promotes crop growth, efficient water use, and moisture conservation, which increase yield, particularly in arid and semi-arid regions [10] (Sun et al., 2020). China is the world's largest plastic consumer in terms of the amount of plastic film used and the area covered [11] (Cui et al., 2023). According to the National Bureau of Statistics of China, the coverage area and usage of plastic films in China are predicted to reach 330 million acres and exceed 2 million tons by 2024, respectively. Although helping to guarantee China's food security, the long-term, large-scale, and high-intensity application of plastic films, coupled with the poor degradation and recyclability of these materials, has generated serious plastic film residue pollution [12] (Li et al., 2019). This type of pollution can lead to soil nodulation, water transfer barriers, obstruction of agricultural operations, and a reduction in crop yields by more than 11.3% when the residual film exceeds 240 kg ha^{-1} [13] (Qin et al., 2022). In addition, residual film in the soil releases microplastics under mechanical abrasion and light aging, which can then affect soil health [14] (Yang et al., 2022). Therefore, the use of traditional plastic films has become an important obstacle to the green and low-carbon development of agriculture in China [15] (Du et al., 2022).

In the past 30 years, along with the production and development of film pollution, the pollution control of agricultural plastic films has gradually become a policy concern and academic research hotspot [16,17] (Kumar et al., 2020; Uzamurera et al., 2023). The Chinese government has issued a series of policy documents to manage land film pollution. Since 2014, the Central Government Document No. 1 has proposed to strengthen the management of agricultural film pollution each year. In 2019, the Ministry of Agriculture and Rural Development, the National Development and Reform Commission, and six other departments jointly issued the Opinions on Accelerating the Prevention and Control of Pollution by Agricultural Land Films, which further clarified the overall requirements, institutional measures, critical tasks, and policy guarantee. Strengthening the management of agricultural film pollution has become an important initiative to promote the green development of agriculture.

In contrast, biodegradable films are considered an effective way to mitigate the 'white pollution' that has attracted substantial international research attention [18] (Wang et al., 2019). Biodegradable films are made of low permeability polysaccharides and decompose into harmless water and carbon dioxide [19] (Vox and Schettini, 2007), which enables their direct incorporation into the soil and biodegradation by soil microorganisms after harvest [20] (Scarascia-Mugnozza et al., 2004). To date, biodegradable film mulching has been similarly effective to plastic films at increasing soil temperature and moisture, accelerating crop growth, and enhancing crop yields [21] (Kang et al., 2013), with no significant difference between the two [22] (Yin et al., 2019).

Film mulching also improves the soil hydrothermal conditions, leading to CH_4 and N_2O production during soil organic carbon decomposition, fermentation, nitrification, and denitrification processes, and ultimately contributes to global warming [23] (Yu et al., 2021).

Indeed, plastic film mulching reduces soil O_2 levels and creates an anaerobic environment that promotes CH_4 production, thereby increasing the CH_4 emissions in the field [24] (Cuello et al., 2015). Film mulching can also increase the soil water content, reduce soil aerobic conditions, promote denitrification, and increase N_2O emissions. However, film mulching does not always have a significant effect on N_2O emissions [25] (Chen et al., 2019) and may even reduce N_2O emissions from drylands [26] (Berger et al., 2013). Compared to plastic film mulching, biodegradable film mulching can improve soil aeration, reduce the abundance of soil methanogens, and increase the abundance of methanotrophic bacteria, thereby reducing CH_4 emissions from paddy fields [27] (Hu et al., 2020), while increasing the abundance and diversity of ammonia-oxidizing bacteria and the concentration of N_2O, which significantly reduces N_2O emissions [28] (Qin et al., 2021). Nevertheless, GHG emissions under a mulch cover can vary according to the regional climate, soil properties, and farming system [29] (Guo et al., 2021). Previous studies have shown the effects of plastic film mulching on soil physicochemical properties, organic carbon pools, and the GHG emissions of major crops. There have also been studies on the effects of biodegradable film mulching on soil organic carbon and the GHG emissions of agricultural soils. The impact of the varied mulching measures on GHG emissions from agricultural soils is a multifaceted and intricate subject, and there is no consistent conclusion yet.

Life cycle assessment (LCA) is a research methodology that assesses the potential environmental impacts of a product, service, or technology throughout its life cycle from the cradle to the grave [30] (Maeseele and Roux, 2021). Carbon footprint is the total amount of greenhouse gas (GHG) emissions of a product or activity over its life cycle [31] (Ji et al., 2023). LCA has been gradually applied to agriculture to evaluate environmental pollution and resource consumption in agricultural production [32] (Hu et al., 2019). Feng et al. (2017) [33] evaluated the carbon sequestration capacity of wheat–jade rotational cropping farmland under different mulching methods using carbon footprint indicators, and the results showed that the carbon sequestration capacity of full-film mulching and monopoly mulching was significantly higher. Luo (2019) [34] conducted a study on the impact of straw mulching and regular mulching on the carbon footprint of a winter wheat–summer corn cropping system. The study found that the carbon footprint of half-film mulching, full-film mulching, and ridge mulching was significantly higher compared to no mulching. Therefore, LCA considers the GHG emissions during the product's whole life cycle, which can quantify the GHG produced by various management measures during crop production under different farmland management measures and is helpful to clarify the carbon sequestration and emission reduction potential of different farmland management measures.

In recent years, the academic community has also paid sufficient attention to the economic benefits of the mulching planting mode [35,36] Meng et al. (2018) studied the impact of different monopoly cropping methods on the economic benefits of potatoes in rainfed areas, and the results showed that the net return of potatoes under the treatment of two monoculture rows of complete black film mulching was the highest. Zhao et al. (2017) [37] analyzed the economic benefits of one film for two years under different irrigation levels, and the results showed that the one-film-for-two-years mulching mode under low irrigation levels of water stress reduced cost inputs, improved the production/input ratio, and was a new technology of mulching farmland management suitable for the Northwest Oasis Irrigation Zone. Li et al. (2021) [38] explored the impact of different mulching planting modes on the economic benefits of Houma (*Sesamum indicum*). The results showed that the old direct film mode could alleviate the pollution caused by the residual film waste and have significant economic benefits. The high cost and extensive input of biodegradable plastic films compared to plastic films has a particular impact on the economic benefits of garlic and farmers' willingness to adopt it, ultimately affecting the government's decision-making process. However, more literature needs to focus on the impact of biodegradable film mulching on the economic benefits of garlic, which is lacking in the existing studies.

Therefore, the feasibility of biodegradable films replacing plastic film covers in garlic production requires further expansion in the following areas: (1) How does biodegradable

film mulching affect the GHG emissions of garlic fields? (2) How does biodegradable film mulching affect the carbon footprint of garlic fields? (3) What are the economic, environmental, and comprehensive benefits for garlic fields of using polyethylene and biodegradable films? The objectives of this study are as follows: (1) to compare the effects of different film covers (none, plastic, and biodegradable plastic) on GHG (CH_4 and N_2O) emissions and garlic yields; (2) to assess the impacts of the different film covers on the carbon footprint and economic outputs of garlic production; and (3) to determine the optimal film cover method for garlic fields with regards to maximizing the film cover effect and maintaining crop yields. This research clarifies carbon sequestration and provides technical support for achieving the green and low-carbon development of the garlic industry. Thus, it provides a scientific basis for exploring green technologies in agriculture that combine the benefits of stabilizing production and supply, reducing emissions, and sequestering carbon.

2. Materials and Methods

2.1. Experimental Site and Treatments

The field experiment was conducted from October 2021 to May 2022 during the garlic season at the Pizhou Research Station for the Garlic Industrial Technology Cluster of Jiangsu Agricultural Technology Extension Station in Jiangsu Province, China (117°35′50″–118°10′40″ E, 34°07′–34°40′48″ N). This region has a warm temperate semi-humid monsoon climate with four distinct seasons, significant monsoon, sufficient light and rainfall, an annual average temperature of 14.0 °C, an annual average precipitation of 867.8 mm, and an annual average sunshine hours of 2318.6 h. The daily maximum and minimum air temperature and rainfall values during the experimental period are shown in Figure 1. The previous crop in the experimental field was rice. After the rice was harvested, all straw was returned to the field by rotary tillage. The soil at the experimental field is classified as flavor-aquic soil. The basic soil properties (0–20 cm depth) were as follows: the soil organic matter of 16.82 g kg^{-1}, total nitrogen of 0.85 g kg^{-1}, nitrate nitrogen of 16.55 mg kg^{-1}, ammonium nitrogen of 0.99 mg kg^{-1}, available phosphorus of 32.30 mg kg^{-1}, available potassium of 274.03 mg kg^{-1}, and pH of 7.89.

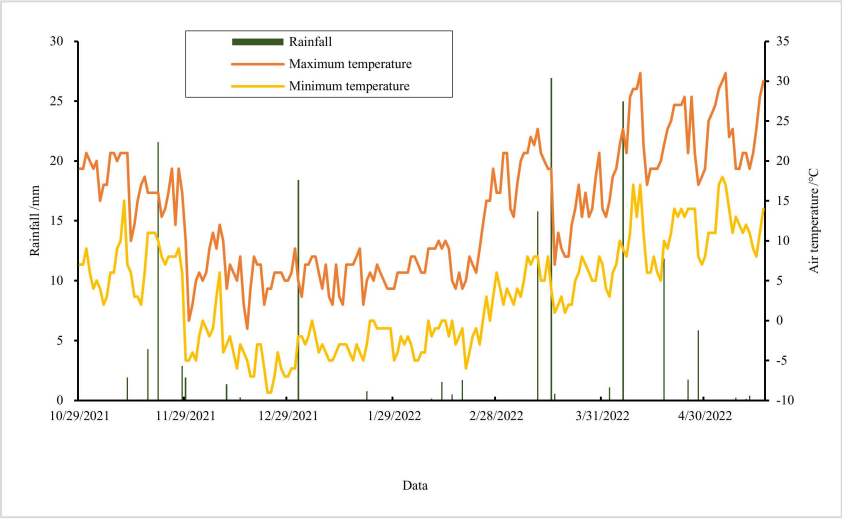

Figure 1. Daily maximum and minimum mean air temperature and rainfall values during the garlic growth period.

Furthermore, a single-factor random block design with three treatments was conducted in this experiment, namely no plastic film mulching (CK), plastic film mulching (PM), and biodegradable plastic film mulching (BM). Each treatment was repeated three times, with a total of 9 plots. Each plot area was 30 m^2, and a 0.5 m protection row was set between the small plots. The common plastic film was mainly composed of polyethylene plastic (PE) and was white translucent, 2 m wide, and 0.01 mm thick. The main component of the

biodegradable film was polybutylene terephthalate (PBAT) and was white translucent, 2 m wide, and 0.01 mm thick. The degradation products were mainly water and CO_2. The garlic was planted artificially and cultivated in the field with 22 × 15 cm row-hill spacing, and the sowing number per hectare was 2.0×10^4. On the next day after sowing, the border surface was sprayed with herbicide and covered with the plastic film, and the edge of the plastic film was pressed with a soil block. After the emergence of the garlic, artificial film breaking was carried out to make the garlic seedling completely exposed to the film. Before sowing, a compound fertilizer as the base fertilizer was applied with 270 kg ha^{-1} of N, 180 kg ha^{-1} of P_2O_5, and 150 kg ha^{-1} of K_2O, and urea as topdressing was applied with 150 kg ha^{-1} of N on 6 March 2022 (the regreening stage of garlic) [39] (Liu et al., 2021). The garlic was watered twice in the whole growth period in combination with soil moisture. The field management of diseases, pests, and weeds were the same as the local garlic high-yield management. The material input list of the different treatments is shown in Table 1.

Table 1. Inputs under the different management treatments of the garlic fields.

Treatment	Diesel (kg ha^{-1})	Diesel Combustion (kg ha^{-1})	Electricity for Irrigation (k Wh ha^{-1})	N Fertilizer (kg ha^{-1})	P Fertilizer (kg ha^{-1})	K Fertilizer (kg ha^{-1})	Herbicide (kg ha^{-1})	Insecticides (kg ha^{-1})	Fungicides (kg ha^{-1})	Film (kg ha^{-1})	Garlic Seeds (kg ha^{-1})	Labor Force (per ha^{-1})
CK	97.5	97.5	75	420	180	150	4.5	4.5	3	0	1500	135
PM	97.5	97.5	45	420	180	150	4.5	4.5	1.8	67.5	1500	240
BM	97.5	97.5	45	420	180	150	4.5	4.5	1.8	67.5	1500	210

Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching. Data source: Growers of the Pizhou Experimental Land.

2.2. Gas Sampling and Measurement

The CH_4 and N_2O fluxes were continuously sampled during the garlic growing season by the static opaque chamber-gas chromatograph (GC) method [40] (Zou et al., 2005). The flux chambers were 50 × 50 × 50 cm. Each plot was installed with a chamber. Every chamber was equipped with a fan that ensured thorough gas mixing. The chambers were also insulated and covered in aluminum foil to reduce the temperature changes within. The gas samples were generally collected from 13:00 to 16:00 from the garlic sowing to harvest, and more frequently after precipitation and fertilizer application events. For each gas flux sampling, four gas samples were collected from the chamber using a 60 mL syringe at 5, 10, 15, and 20 min after covering the chambers.

The gas concentrations of CH_4 and N_2O were measured using a gas chromatograph (Agilent 7890A, Shanghai, China). The device was equipped with a flame ionization detector (FID) and an electron capture detector (ECD). The ECD detector was maintained at 300 °C, while the column temperature was set at 40 °C. The oven and FID were operated at 50 °C and 300 °C, respectively. Any sample sets that did not yield a linear regression value of $r^2 > 0.90$ were rejected. The average fluxes and standard errors of CH_4 and N_2O were calculated from triplicate plots. The seasonal amounts of CH_4 and N_2O were determined linearly from the emissions between every two adjacent intervals of the measurements [40] (Zou et al., 2005).

The GWP was estimated as the CO_2 equivalent (CO_2-eq) over a span of 100 years, employing the radioactive forcing potential of 28 for CH_4 and 265 for N_2O [41] (IPCC 2013). The mathematical equation utilized in this calculation is presented below:

$$\text{GWP (kg } CO_2\text{-eq ha}^{-1}\text{ yr}^{-1}) = 28 \times CH_4\text{ (kg ha}^{-1}\text{ yr}^{-1}) + 265 \times N_2O\text{ (kg ha}^{-1}\text{ yr}^{-1})$$

To assess the GWP based on crop production, the GWP per unit grain yield (kg CO_2-eq Mg $grain^{-1}$), namely yield-scaled GWP (GHGI), was calculated by referring to van [42] Landman (2010).

2.3. Soil Sampling and Measurements

At the seedling, flower bud differentiation, and mature stages of the garlic season from 2021 to 2022, soil samples (0–20 cm) were collected from five points using a screw drill with

a diameter of 5 cm. The fresh soil samples were passed through a 2 mm sieve and stored at 4 °C. The aim was to determine the concentration of soil dissolved organic carbon (DOC), ammonium-nitrogen (NH_4^+–N), and nitrate-nitrogen (NO_3^-–N). The soil DOC content was extracted from 10 g of moist soil with a 1:2.5 ratio of soil to water at 25.8 °C [43] (Jiang et al., 2006). Soil NH_4^+–N and NO_3^-–N in 10 g soil samples were extracted with 25 mL 0.5 M K_2SO_4 and determined by the Shan et al. (2013) [44] method. The sum of NH_4^+–N and NO_3^-–N concentrations reflected the soil mineral N content.

2.4. Carbon Footprint

In this study, the LCA evaluation method was used to establish the system boundary (Figure 2): (1) agricultural inputs; (2) agricultural management [45–47] (Xia et al., 2016; Li et al., 2021); and (3) soil non-CO_2 greenhouse gas emissions (N_2O and CH_4). The above carbon emission factors were converted into the CO_2 equivalent, and the carbon footprint was calculated. The calculation formula of the carbon footprint per unit area is as follows:

$$CF = \sum_{i=1}^{n} Q_I \times C_i + GWP$$

In the formula, *CF* represents the carbon footprint per unit area of garlic field (kg CO_2-eq ha^{-1} yr^{-1}), *n* refers to the use of agricultural products in the production process, Q_i is the input per unit area of garlic field (kg ha^{-1} yr^{-1}), and C_i refers to the carbon emission factor of the input (kg CO_2-eq ha^{-1} yr^{-1}). The carbon emission coefficients of the different materials for agricultural production involved in the study are shown in Table 2.

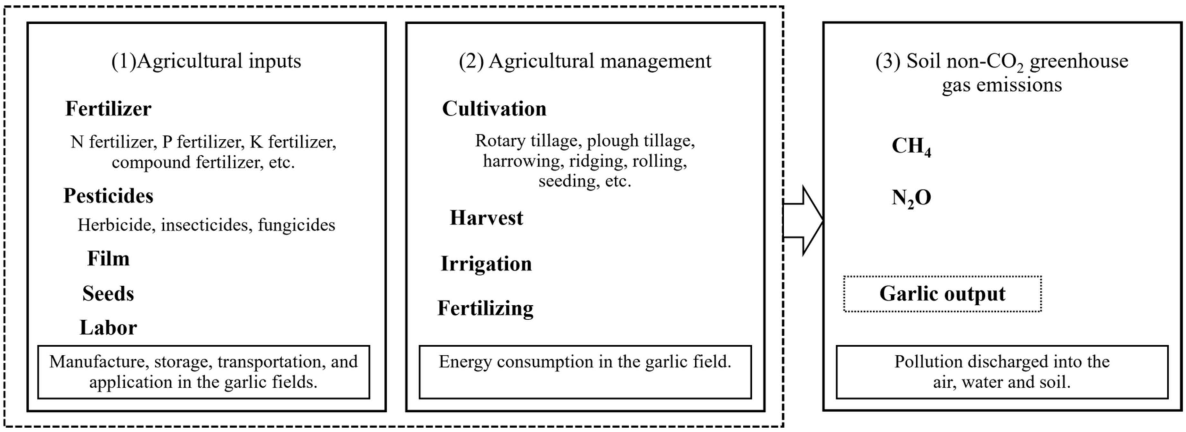

Figure 2. The system boundary of the garlic fields.

Table 2. Coefficients of the carbon emissions of the different materials for agricultural production.

Inputs	Carbon Emission Coefficient	Data Source
Diesel	0.89 kgCO2-eq kg−1	CLCD 0.7
Diesel combustion	4.10 kgCO2-eq kg−1	CLCD 0.7
Electricity for irrigation	0.82 kgCO2-eq kg−1	CLCD 0.7
N fertilizer	1.53 kgCO2-eq kg−1	CLCD 0.7
P fertilizer	1.63 kgCO2-eq kg−1	CLCD 0.7
K fertilizer	0.65 kgCO2-eq kg−1	CLCD 0.7
Herbicide	10.15 kgCO2-eq kg−1	Ecoinvent 2.2
Insecticides	16.61 kgCO2-eq kg−1	Ecoinvent 2.2
Fungicides	10.57 kgCO2-eq kg−1	Ecoinvent 2.2
Film	2.49/6.91 kgCO2-eq kg−1	CPCD 2023
Garlic seeds	0.18 kgCO2-eq kg−1	CPCD 2023
Labor force	0.86 kgCO2-eq d−1	Liu et al., 2013 [48]

Note: CLCD 0.7, China Life Cycle Database 0.7; Ecoinvent 2.2, International Life Cycle Inventory Database 2.2; CPCD 2023, China Product Life Cycle Greenhouse Gas Emission Coefficient Database.

2.5. Economic Benefit

The economic benefit is the yield of garlic minus the production cost. The net ecosystem economic benefit (NEEB) is calculated by the following formula:

$$\mathrm{NEEB} = C_{garlic} - C_{production} - C_{GWP}$$
$$C_{GWP} = \mathrm{GWP} \times P_{carbon}$$

The garlic income is the product of garlic yield and the garlic purchase price. The production cost includes the cost of agricultural materials (pesticides, fertilizers, seeds, mulch, etc.), labor cost (CNY 60 for one person per day), and field operation cost (land preparation and irrigation). The GWP cost is the carbon cost of greenhouse gases directly generated in the production process; the carbon price was 66 CNY/t CO_2-eq.

2.6. Grain Yield Measurement (The Weight of Garlic Bulbs)

The garlic yield was determined by weighing every plot at maturity. After garlic harvest, 50 garlic plants representing the average growth of the plot were randomly selected. Thus, the roots, pseudostems, and leaves of the garlic were cut off, and the garlic bulbs were weighed. The weight measured by manual measurement was converted into yield per unit area (t ha^{-1}).

2.7. Data Analysis

The research study utilized both the SPSS 16.0 analytical software package and Excel 2010 to conduct the statistical analysis. The data were carefully checked to confirm that they fitted a normal distribution. The statistical technique called one-way ANOVA was utilized to determine if there were any significant differences in the emissions of CH_4 and N_2O, garlic yield, and the other variables (DOC, MBC, NH_4^+-N, and NO_3^--N) during different seasons and years among the three treatments. The test was conducted at a significance level of $p < 0.05$, and the means were separated using the least significant difference (LSD). The Origin 2021 software was used for mapping.

3. Results

3.1. GHG Emission Characteristics of the Garlic Fields under Different Treatments

3.1.1. CH_4

As shown in Figure 3, the CH_4 fluxes during the garlic season show similar temporal trends under all treatments, and CH_4 was not emitted at all times during the garlic season. The CH_4 fluxes ranged from −0.21 to 0.08 mg m^{-2} h^{-1}, with the seasonal emission peak occurring on approximately half a month after fertilization, followed by a sharp decline. The seasonal cumulative CH_4 emissions showed negative values for all treatments (Figure 4), indicating that CH_4 was absorbed during the garlic growing season. The cumulative CH_4 emissions during the season were highest in CK and were significantly higher compared to those of BM. Moreover, the seasonal cumulative CH_4 emissions were significantly higher in BM than in PM. Compared to CK, the PM and BM treatments significantly increased CH_4 absorption by 94.74% and 54.74%, respectively (Figure 4).

3.1.2. N_2O

N_2O fluxes exhibited no clear trends under the different treatments during the garlic season. The N_2O fluxes ranged from −0.03 to 0.05 mg m^{-2} h^{-1}. In general, N_2O fluxes first increased and then decreased, with the seasonal N_2O emission peak appearing on 23 March 2022 (Figure 5). Compared to CK, the PM and BM treatments both significantly increased the seasonal cumulative N_2O emissions by 126.67% and 73.33%, respectively (Figure 4). Compared with PM, BM reduced the seasonal cumulative N_2O emissions by 23.53%.

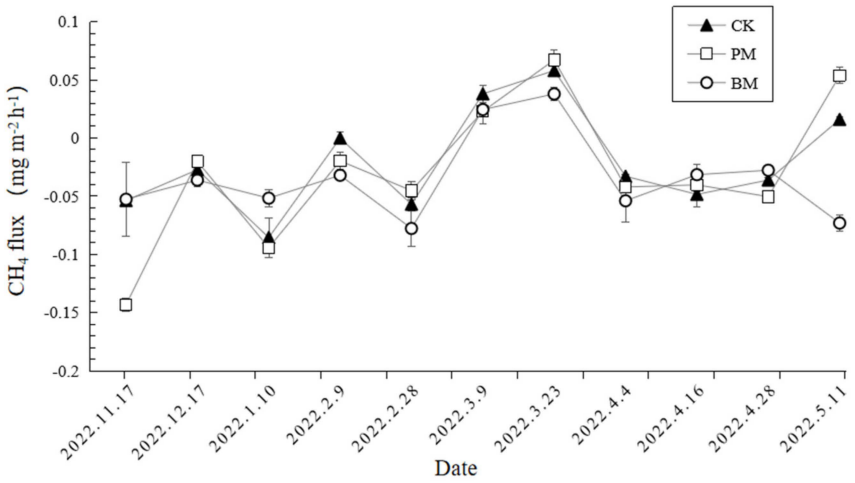

Figure 3. Monthly variations in CH_4 fluxes during the garlic season from November 2021 to May 2022. Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching.

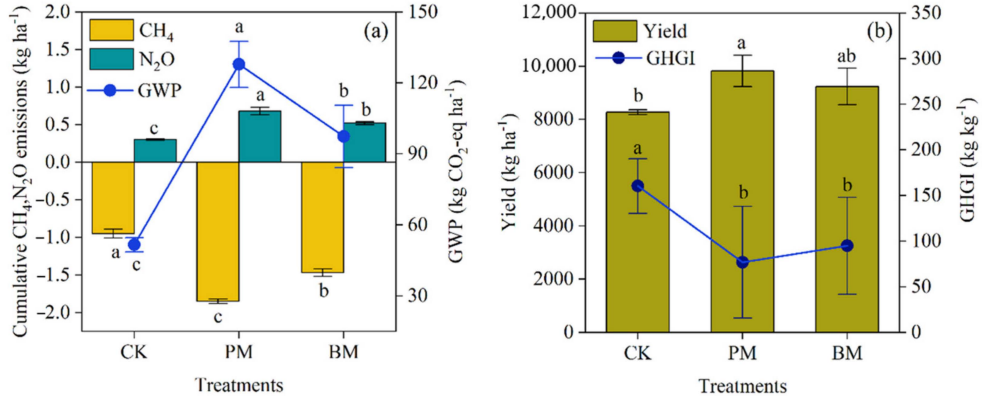

Figure 4. Cumulative emissions of the different film mulching treatments on CH_4 and N_2O, GWP (**a**), garlic yield, and GHGI (**b**) during the garlic season. Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching; GWP, global warming potential; GHGI, yield-scaled greenhouse gas intensity. Different lowercase letters indicate significant differences in GHG contents at the $p < 0.05$ level.

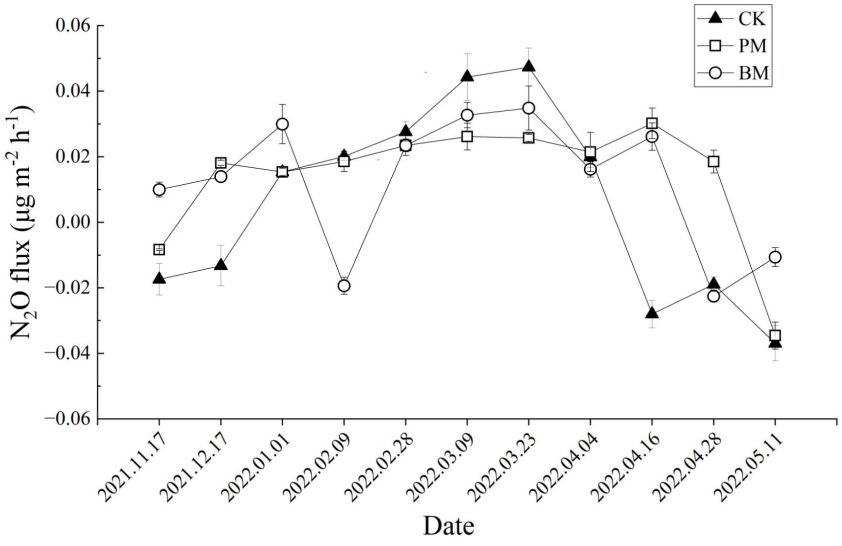

Figure 5. Monthly variations in N_2O fluxes during the garlic season from November 2021 to May 2022. Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching.

3.1.3. Yield and GHGI

Compared to the CK, PM and BM significantly improved the garlic yield by 18.86% and 11.73%, respectively; however, the garlic yield did not differ significantly between BM and PM (Figure 4). Throughout the garlic growth season, the GWP was mainly attributed to N_2O emissions, with CH_4 and N_2O emissions under all treatments ranging from 51.58 to 127.89 kg CO_2 eq ha^{-1} (Figure 4). Compared to the CK, film mulching significantly increased GWP, with increases of 147.95% and 88.79% in PM and BM, respectively. The GWP was significantly higher in PM than in BM. The GHGI under both film mulching treatments was significantly lower than that under the CK. Compared to PM, BM increased GHGI by 23.45%; however, this difference was not significant (Figure 4).

3.1.4. Soil Organic Carbon and Nitrogen Contents

As shown in Figure 6a, the soil DOC content varied in the three growth stages under the different treatments. Over the growth period, the DOC content increased continuously in BM and PM, whereas that under the CK decreased during the flower bud differentiation stage (within a week of topdressing). During the maturation period of garlic, the soil DOC content was significantly higher in BM and the CK than in PM. With the continued growth of garlic, the soil mineral N content first increased, then decreased, and reached its highest level after topdressing (Figure 6b). In the seeding period, the soil mineral N content was higher in the CK than in PM and BM. During the flower bud differentiation period of garlic, the soil mineral N content was significantly higher in PM than in the CK or BM. During garlic maturation, no significant differences were observed among the three treatments.

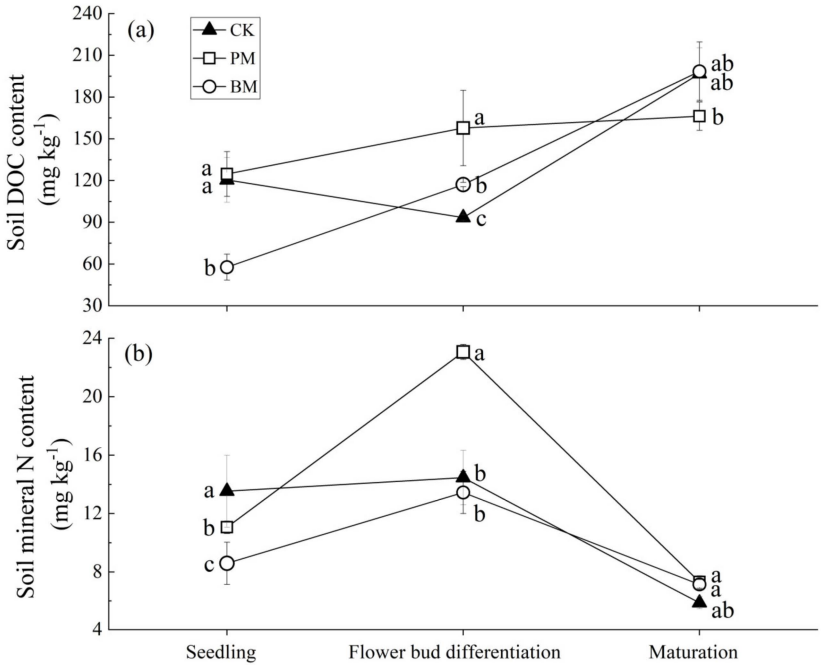

Figure 6. Soil DOC and mineral N content in the different phenological stages of garlic. Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching. Different lowercase letters indicate significant differences in the soil DOC and mineral N content at the $p < 0.05$ level. Due to the limitations of the experimental methodology, the values can be subjected to a certain level of uncertainty.

3.2. Indirect Carbon Emissions of Garlic Production under Different Treatments

The indirect GHG emissions from garlic fields were higher in the film mulching treatments than in the CK, and the contributions of agricultural inputs to CO_2 emissions were 2639.20, 2315.05, and 2119.76 kg CO_2-eq ha^{-1} in PM, BM, and the CK, respectively (Figure 7). Among them, the GHG emissions attributed to nitrogen fertilizer inputs represented the

most significant contribution to the total GHG emissions from agricultural inputs (24.35%, 27.76%, and 30.31% in PM, BM, and the CK, respectively). GHG emissions from different forms of synthetic fertilizers decreased in the following order: nitrogen > phosphate > potassium fertilizers. The diesel fuel input was the second largest source of indirect GHG emissions, accounting for 18.43%, 21.02%, and 22.95% of the total indirect emissions in PM, BM, and the CK, respectively. The GHG emissions from agricultural film production ranked third in PM, accounting for 17.67%, but were only 7.26% in BM. The proportions of GHGs produced by garlic seeds in PM, BM, and the CK were 10.23%, 11.66%, and 12.74%, respectively. The proportions of GHGs caused by pesticides in PM, BM, and the CK were 8.26%, 9.41%, and 10.28%, respectively. The GHG emissions caused by artificial inputs were low, that is, 7.82%, 7.80%, and 5.48% in PM, BM, and the CK, respectively. The irrigation power consumption made the smallest contribution to GHG emissions, that is, 36.90, 36.90, and 61.50 kg CO_2-eq ha^{-1} in PM, BM, and the CK, respectively.

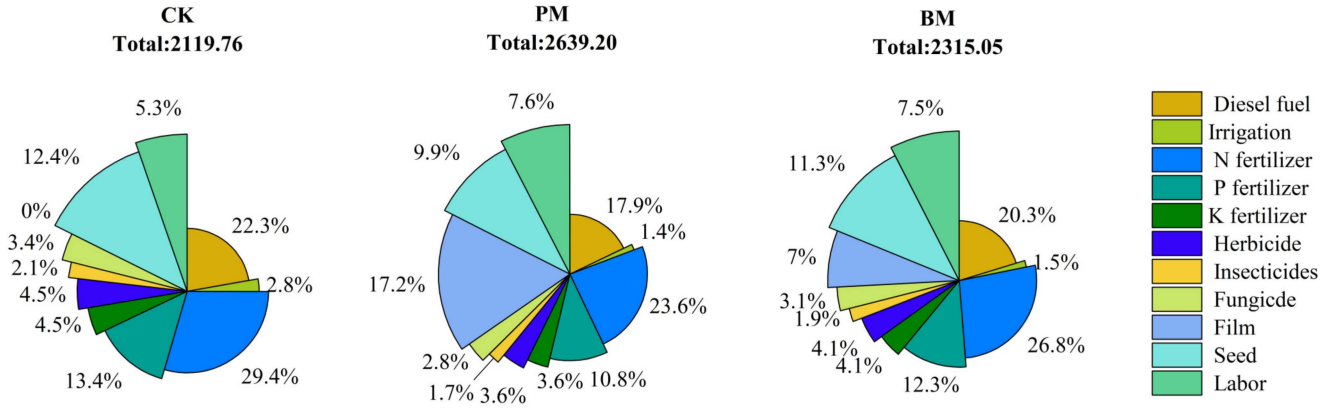

Figure 7. Characteristics of indirect carbon emissions under different film mulching treatments on diesel fuel, irrigation, N fertilizer, P fertilizer, K fertilizer, herbicides, insecticides, fungicide, film, seed, and labor in the garlic fields. Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching.

3.3. Carbon Footprint Composition under Different Treatments

The annual GHG emissions under the three treatments were 2171.34–2767.09 kg CO_2-eq ha^{-1} and those in BM and PM were significantly lower than those in the CK (Table 3). According to the composition of the carbon footprint, agricultural inputs were the largest contributor to the carbon footprint in garlic fields, accounting for 95.38%, 95.96%, and 97.62% of the total emissions in PM, BM, and CK, respectively. N_2O was the second largest contributor to the total carbon footprint, accounting for 6.51%, 5.71%, and 3.76% of the total emissions in PM, BM, and the CK, respectively. CH_4 emissions had a negligible effect on the carbon footprint. Compared to the CK, PM significantly increased the carbon footprint by 7.69%; however, the increase in BM was not significant.

Table 3. Composition of the carbon footprint under the different film mulching treatments in garlic production.

Item	Unit	CK	PM	BM
CH_4 emissions	kg CO_2-eq ha^{-1}	−26.60 ± 1.35 a	−51.80 ± 1.55 c	−41.16 ± 0.92 b
N_2O emissions	kg CO_2-eq ha^{-1}	79.50 ± 1.49 c	180.2 ± 2.66 a	137.80 ± 3.22 b
Agriculture input	kg CO_2-eq ha^{-1}	2119.76 ± 0 c	2639.20 ± 0 a	2,315.05 ± 0 b
Garlic yield	kg CO_2-eq ha^{-1}	8270.00 ± 90 b	9830.00 ± 590 a	9240.00 ± 690 ab
GHG emissions	kg CO_2-eq ha^{-1}	2171.34 ± 0 c	2767.09 ± 0 a	2412.43 ± 0 b
Carbon footprint	kg CO_2-eq ha^{-1}	0.26 ± 0.04 b	0.28 ± 0.03 a	0.26 ± 0.03 b

Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching. Different lowercase letters indicate significant differences in carbon footprint contents at the $p < 0.05$ level.

3.4. Net Ecosystem Economic Benefit of Garlic Production under Different Treatments

The yield income and production cost of garlic were significantly higher in the film mulching treatments than in the CK and significantly higher in PM than in BM (Table 4). The final result is that the NEEB is significantly higher in the film mulching treatments than in the CK, by 11.78% and 9.29% in PM and BM, respectively; however, the NEEB does not differ significantly between PM and BM.

Table 4. Net ecosystem economic budget under the different film mulching treatments in garlic production.

Treatment	Production (kg ha^{-1})	Production Costs (CNY ha^{-1})	Production Costs (CNY ha^{-1})	GWP Costs (CNY ha^{-1})	NEEB (CNY ha^{-1})
CK	8270.00 ± 90 b	62,025 ± 0 c	28,950 ± 0 c	3.40 ± 0.20 c	33,071.60 ± 86 b
PM	9830.00 ± 590 a	73,725 ± 0 a	36,750 ± 0 a	8.44 ± 0.64 a	36,966.56 ± 590 a
BM	9240.00 ± 690 ab	69,300 ± 0 b	33,150 ± 0 b	6.43 ± 0.87 b	36,143.57 ± 635 a

Note: CK, no film mulching; PM, plastic film mulching; BM, biodegradable plastic film mulching; GWP, global warming potential; NEEB, net ecosystem economic benefit. Different lowercase letters indicate significant differences in net ecosystem economic budget contents at the $p < 0.05$ level.

4. Discussion

4.1. GHG Emission Characteristics under Different Film Mulching Treatments in Garlic Production

4.1.1. CH_4

In this study, there were slight fluctuations in CH_4 fluxes between emission and adsorption (Figure 3); Nonetheless, all treatments showed a net absorption of CH_4, as demonstrated in Figure 4. These results are consistent with prior research and indicate that the net absorption of CH_4 is not uncommon [49] (Jiang et al., 2022). It has been observed that dryland soils serve as effective sinks for atmospheric CH_4 due to the presence of methanotrophs that oxidize CH_4 under dry conditions [50] (Dalal et al., 2007). The film mulching treatments increased CH_4 absorption (Figure 4) in this study, probably because the process of film mulching impeded gas exchange by serving as a barrier between the soil and the atmosphere. The result is that less than 10% of the soil area remains in direct contact with the atmosphere [51] (Meng et al., 2020). Under film mulching, a higher soil temperature and moisture cause methanotrophic microorganisms to be absorbed and oxidized [52] (Chen et al., 2021). Yu et al. (2021) [53] proposed that the usage of plastic film mulching causes a decrease in CH_4 absorption and an increase in CH_4 emissions. However, the results of our study contradict this finding. The difference in results may be due to the impact of different environmental factors on the rate of methane oxidation. The physicochemical properties of the soil in the test plots differed significantly from those of other studies and may have been influenced by farmland management practices and climatic differences [25] (Chen et al., 2019).

Compared to PM, BM exhibited significantly higher seasonal cumulative CH_4 emissions and reduced CH_4 absorption (by 20.5%) (Figure 5). This may be because the progressive degradation of BM resulted in a better permeability than that of PM, enabling atmospheric CH_4 to diffuse into the soil. However, a previous study reported that BM leads to lower seasonal cumulative CH_4 emissions than PM (Guo et al., 2021) [29], probably because PM cuts off the exchange of gases between the soil and the atmosphere throughout the garlic growth period. This results in an increased soil moisture content due to reduced evaporation and maintained water in the topsoil (Zhang et al., 2017) [54], resulting in reduced methanotroph activity and anaerobic conditions for the incomplete oxidation of organic matter to form CH_4 [24] (Cuello et al., 2015). The seasonal emission peaks on 23 March 2022 (approximately half a month after fertilization) indicate that CH_4 emissions are closely linked to fertilization. Fertilization increases the secretion of plant roots by promoting crop growth and photosynthesis, which improves methane production and enhances CH_4 emissions.

4.1.2. N_2O

Dryland soils are typically sources of atmospheric N_2O (Li et al., 2022) [55]. After fertilization, soil N_2O fluxes were found to have high emissions, according to the findings of this study (9 March 2022), and the seasonal N_2O emission peak appeared approximately half a month after fertilization (23 March 2022) in all three treatments (Figure 5). This is in line with the findings of earlier research [29] (Guo et al., 2021), suggesting that the application of nitrogen fertilizer is the most significant contributing factor to soil N_2O emissions. It is probable that the high emissions of N_2O from the soil are caused by denitrification occurring at a fast pace and longer nitrification because of the elevated levels of rapidly available nutrients after N fertilizer application, which provide the substrates to form N_2O [56] (Li et al., 2015). According to Figure 4, film mulching significantly increased N_2O emissions when compared to CK. This increase can be attributed to the improved soil temperature, moisture, and N availability under film mulching [57] (Kim et al., 2017). The key factors that affect the mineralization processes and microbial metabolic activities are soil moisture and temperature. These factors have the potential to promote N_2O emissions from the soil; thus, there is no shortage of mineral N [58] (Liu et al., 2014). Moreover, Jiang et al. (2022) [49] suggested that N_2O fluxes through mulch were higher than N_2O fluxes that diffused horizontally, and the permeability of N_2O through mulch was enhanced by an increase in the soil temperature, which led to increased N_2O emissions under film mulching.

Nitrification and denitrification are fundamental microbial processes that play a crucial role in natural N_2O production. The availability of NH_4^+-N and NO_3^--N is essential for these processes to occur [59] (Pajares and Bohannan, 2016). In this study, film mulching led to an increase in NH_4^+-N, NO_3^--N, and DOC contents (Figure 6), and the outcomes further demonstrated a noteworthy association among NH_4^+-N, NO_3^--N, and N_2O emissions, thereby suggesting that available C and N are the key factors driving N_2O emissions under film mulching. Moreover, a characteristic pattern of higher N_2O emissions from straw return and film mulching during the garlic growth stage, as well as lower N_2O emissions toward the reproductive growth stage of garlic (Figure 5), coincided with the positive correlation between the available N content in the soil and the flower bud differentiation stage. However, this correlation weakened during the mature period of garlic growth, as the available N content decreased (Figure 6b). The benefits of straw return for soil improvement, combined with the favorable conditions (i.e., increased soil temperature and moisture) under film mulching, may speed up the decomposition of plant residues, which enhances the DOC content in the soil and increases N_2O emissions under film mulching [57] (Kim et al., 2017). Contrary to these findings, several studies have suggested that film mulching in drylands does not significantly affect N_2O emissions, probably because it inhibits soil penetration by rainfall or irrigation. Furthermore, a higher soil temperature and moisture increased N_2O emissions, which are offset by lower soil mineral N contents due to increased mineralization and plant N uptake under film mulching [26] (Berger et al., 2013). Compared to PM, BM exhibited significantly lower seasonal cumulative N_2O emissions (by 23.53%) (Figure 4), probably because the higher soil mineral N content (Figure 6b), soil temperature [53] (Wang et al., 2019), and moisture content [25] (Chen et al., 2019) of PM enabled soil nitrification with favorable conditions to enhance N_2O emissions.

4.2. Effects of Different Plastic Film Mulching Treatments on the Garlic Yield and GHGI

4.2.1. Yield

Compared to CK, film mulching markedly increased the garlic yield (Table 1), which is consistent with previous research [60] (Li et al., 2018); film mulching is better for potato management measures and there is potential to improve the yield in the Loess Plateau. Fang et al. [61] (2022) reported that film mulching may inhibit moisture evaporation and facilitate the movement of water from deep into the surface soil, which increases the moisture of the surface soil to promote crop growth and increase crop yields. Moreover, a high nitrogen use efficiency under film mulching treatments corresponds to high crop yields [48] (Liu et al., 2013). In addition, straw return can increase soil microbial biomass

and enzyme activity [62] (Zhang et al., 2016), thereby providing a supplement to soil organic matter, improving soil structure, and ensuring nutrient supplementation for crop growth under microbial decomposition [63] (Hui and Zhang, 2022).

The effect of PM and BM on the crop yield did not differ significantly in this study, similar to that for various other crops, including maize [49] (Jiang et al., 2022), wheat [29] (Guo et al., 2021), sunflower [63] (Hui and Zhang, 2022), and winter rapeseed [64] (Shi et al., 2017). Therefore, our results confirm the findings of previous reports [65] (Zhou et al., 2019) that biodegradable plastic film mulching cover degrades and disappears in the late reproductive stage of crops, avoiding white pollution, improving soil structure and keeping heat and moisture, accelerating the growth process of crops, and increasing yields as significantly as plastic film mulching. During the early growth stage of garlic, BM and PM play the same role in thermal insulation and moisture retention. When the degradants of biodegradable plastic films are absorbed and used by soil microorganisms in the late growth stage of garlic, BM enhances the soil microbial activity [66] (Yan et al., 2016). Furthermore, BM mitigated the issues of root decay, soil physical properties' degradation, and poor permeability, which were caused by a high soil temperature in the late growth stage of garlic, which is attributed to the difficulty in degrading plastic film mulch, thereby providing favorable conditions for garlic growth and accelerating the uptake of water and nitrogen by garlic. This indicates that biodegradable plastic film mulching matches the yield-increasing effects of plastic film mulching. Li et al. [67] (2003) also demonstrated that plastic film mulching over the entire crop season may not be beneficial for the semi-arid Loess Plateau of China. However, the study revealed that film mulching for only 60 or 65 days can significantly increase the yield of spring wheat and potato, respectively.

4.2.2. GHG and GHGI

Film mulching increases dryland crop yields, but leads to various environmental problems. Considering that film mulching practices are widely used for dryland crops [26] (Berger et al., 2013), this is an important area of research. As one of the most important indicators for determining whether agricultural management practices are consistent with sustainable development, GWP is a useful indicator to comprehend the effects of agricultural practices on climate change [24] (Cuello et al., 2015). In this study, the GWP coefficients of 28 and 265 were used for CH_4 and N_2O, respectively, over a 100-year horizon [41] (IPCC 2013) to assess the impact of different mulching treatments on CH_4 and N_2O. Compared to the CK, the GWP was significantly increased under the film mulching treatments (Figure 4), which is consistent with previous research [68] (Lee et al., 2019). The GWP emissions of PM were affected by the specific cultivation measures, as reflected by the increased N_2O emissions caused by a high N fertilizer application, straw mulching, and plastic mulching in the fields, with residual N nutrients and straw from the rice planting left in the soil during garlic planting.

Finding sustainable methods to meet food demands and mitigate climate change requires environmentally friendly agricultural practices that do not compromise crop productivity [69] (Grassini and Cassman, 2012). The GHGI is a potential indicator of agricultural practices' impact on global warming [41] (IPCC 2013). Recent studies have shown that increasing crop yields can efficiently decrease the GHGI [58] (Liu et al., 2014). In this study, we showed that the film mulching treatment slightly increased GWP and significantly increased crop yield. The GHGI of garlic fields decreased by 52.06% and 40.82% in PM and BM, respectively, although the difference between PM and BM was not significant (Figure 4). Therefore, our results agree with a previous study that reported that film mulching can increase crop productivity [29] (Guo et al., 2021), although negative environmental impacts were also reported. Compared to BM, PM may cause environmental problems in terms of the effect of plastic film residue on the soil's chemical and physical characteristics [70] (Lal 2007). Biodegradable plastic film mulch can increase crop yield while avoiding most of the aforementioned constraints. Therefore, considering its effect on crop yields and environmental benefits, BM is the optimum mulching method for balancing

crop production and GHGI emissions in the study area, as well as potentially in other dryland areas.

4.3. Effects of Different Film Mulching Treatments on the Carbon Footprint and NEEB of Garlic Production

The total GHG emissions from the studied garlic fields in China ranged from 2171.34 to 2767.09 kg CO_2-eq ha^{-1} (Table 3). These values are lower than the weighted average GHG emissions from the production of other vegetables in China (6244 kg) and lower than those of four terrestrial vegetables (tomato, cucumber, Chinese cabbage, and radish) [71] (Zhang et al., 2020). This is mainly due to the fact that more fertilizers are added to the cultivation of fruits and vegetables in addition to chemical fertilizers. A large amount of organic fertilizer was also applied, which generated more N_2O during the production process [55] (Li et al., 2022) and contributed to indirect GHG emissions [72] (Li et al., 2020). Furthermore, melons and vegetables have higher yields and labor inputs. The results of this study suggest that the high consumption of agricultural inputs (fertilizers, pesticides, agricultural films, and diesel fuel) during garlic field production leads to significant carbon emissions [73] (Yoon et al., 2012). Among these inputs, chemical fertilizer made the largest contribution (Figure 7) of more than 24% under all treatments, consistent with previous studies' results [74] (He et al., 2021). This result was attributed to the large amount of chemical fertilizer input during the garlic cultivation process, and the fact that chemical fertilizer production requires large fossil energy inputs, resulting in substantial GHG emissions. In terms of the carbon footprint composition, CH_4 emissions and N_2O emissions contribute less to the carbon footprint, which is inconsistent with the results of previous studies. Possible reasons for this may be the different reference values of carbon emission coefficients, in addition to the different inputs of agricultural production materials.

The indirect GHG emissions of the three treatments ranged from 2119.76 to 2639.20 kg CO_2-eq ha^{-1} (Table 3). Differences among the treatments were mainly attributed to the use of agricultural films and labor inputs. The carbon footprint of agricultural films in PM was 466.43 kg CO_2-eq ha^{-1}, which was 2.76 times higher than that in BM. The carbon footprint of agricultural films includes their production and application, with average GHG emissions of 22.72 kg CO_2-eq ha^{-1} generated from the consumption of plastic films during crop cultivation [75] (Wang et al., 2015). The difference in the carbon footprints of plastic films under PM and BM conditions reflects differences in the production of plastic films. The total GHG emissions during the production of ordinary polyethylene are 2590 kg CO_2-eq ha^{-1} [76] (Lee et al., 2021). The production of polyethylene consumes more fossil energy than biodegradable mulch, which is a plastic mulch produced from biomass that predominantly includes polylactic acid, polyalkanoic acid, and polyglutamic acid, which can reduce the consumption of traditional fossil fuels, such as oil. The carbon footprint of the labor input followed the order of PM > BM > CK. As the main raw materials of PM are refractory polymer compounds, the plastic film under the PM must be removed manually at the crop maturity stage to minimize plastic film residue. In contrast, BM decomposes completely into water and carbon dioxide through the action of environmental microorganisms and can be plowed directly without manual picking after the garlic has matured.

In this study, the carbon footprint per unit yield was in the range of 0.26–0.28 kg CO_2-eq kg^{-1} (Table 3); it was significantly higher in PM than in BM and the CK, but not significantly different between BM and CK. This is due to the garlic yield being significantly higher in BM than in the CK, yet the GHG emissions were the same. The garlic yield in BM was not significantly different from that in PM, but agricultural film and labor use were higher in PM than in BM, and farmland N_2O emissions were significantly higher, resulting in a significantly higher carbon footprint for PM. Therefore, BM had lower annual GHG emissions and higher garlic production, making it the most productive and efficient model among the three treatments.

The decisive factor in farmers' adoption of agricultural management measures is often the economic benefits [77] (Zhang et al., 2015), which describes the combined effect of production expenditure, warming potential, and crop yield [78] (Xu et al., 2022), and directly affects the enthusiasm of farmers to participate [56] (Li et al., 2015). In this study, although BM increased costs through film mulching and PM led to higher production costs because of the requirement to manually remove and transport the residual plastic film (Table 3), plastic film mulching significantly reduced CH_4 emissions and increased crop yield. Therefore, film mulching significantly increased the NEEB of garlic production. Farmers' willingness to adopt biodegradable mulch while promoting biodegradable mulch in China is low [29] (Guo et al., 2023). Although biodegradable mulch can provide considerable yield benefits compared to no mulch and has specific emission reduction effects compared to ordinary mulch, the purchase of biodegradable mulch in agricultural production dramatically increases the farmers' upfront input costs, which restricts the purchase and use of biodegradable mulch by farmers. Therefore, reducing the cost of biodegradable film is the primary countermeasure to eliminate the bottleneck of its promotion. Firstly, reducing the cost using the innovation of raw materials and processing methods as well as expanding the scale of production is the essential means to promote the application widely. Secondly, the government must provide appropriate subsidies to promote the popularization and application of biodegradable films. Thirdly, selecting biodegradable films with different specifications according to different uses can stabilize crop yield, reduce investment, and improve economic benefits.

5. Conclusions

Dryland soils are typically sinks for atmospheric CH_4 and sources of atmospheric N_2O. In terms of direct GHG emissions, the film mulching treatments significantly increased CH_4 absorption compared to the control treatments, and BM had significantly higher (20.5%) seasonal cumulative CH_4 emissions than PM. Moreover, film mulching treatments significantly increased N_2O emissions, and BM had significantly lower (23.53%) seasonal cumulative N_2O emissions than PM. The film mulching treatments also significantly increased the GWP and garlic yield. The GHGI decreased by 52.06% and 40.82% in PM and BM, respectively, but did not differ significantly between PM and BM. In terms of indirect GHG emissions, the film mulching treatments significantly increased the indirect carbon footprint, and PM had significantly higher carbon emissions (14.70%) than BM. BM did not lead to a significant difference in the carbon footprint per unit yield, whereas PM had a 7.69% higher carbon footprint per unit yield than BM. Finally, the film mulching treatments significantly increased the cost input, CH_4 absorption, and garlic yield, thereby improving NEEB by 9.29–11.78%. Although the NEEB did not differ significantly between PM and BM, considering the crop yields and environmental benefits, we propose BM as an effective method for the green and efficient production of garlic.

Several policy recommendations can be put forward based on this research:

(1) The sustainable management of agricultural plastic film should be emphasized to achieve the China's GHG emissions reduction target since the biodegradable plastic films can generate lower carbon footprint per unit yield than plastic films.

(2) Biodegradable films still need to improve, such as low tensile strength, poorly controllable degradation rate, significant differences between crops, and low acceptance by farmers, which hinder the large-scale popularization and demonstration of biodegradable films. The government should increase special funds to gradually expand the scope of implementation of demonstration sites for fully biodegradable films and, at the same time, build a platform of "government, research and enterprise" to enhance the controllability and cutting-edge research and development of fully biodegradable films.

(3) Promoting biodegradable films still faces many problems, the most important of which are high prices, farmers' unwillingness to use them, and difficulty promoting them. The government should develop and utilize abundant and inexpensive biological resources according to the local conditions and build film production enterprises to reduce

transportation costs, lowering the unit price and enhancing farmers' willingness to buy and use to achieve the promotion of biodegradable films truly.

Moreover, long-term field trials are still required to quantify the GHG emissions (the CO_2e of CH_4, N_2O, and soil organic carbon changes) caused by different film mulching in garlic fields. The carbon footprint of incorporating mulch microplastics and waste mulch can be considered to be added as the measurement indicators in studying the impact of different mulch treatments on carbon footprint.

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References

1. Wang, C.; Shen, J.; Tang, H.; Inubushi, K.; Guggenberger, G.; Li, Y.; Wu, J. Greenhouse gas emissions in response to straw incorporation, water management and their interaction in a paddy field in subtropical central China. *Arch. Agron. Soil Sci.* **2017**, *63*, 171–184. [CrossRef]
2. [IPCC] Intergovernmental Panel on Climate Change. *Climate Change 2022: Impacts, Adaptation and Vulnerability*; Cambridge University Press: Cambridge, UK, 2022.
3. Xu, X.; Lan, Y. Spatial and temporal patterns of carbon footprints of grain crops in China. *J. Clean. Prod.* **2017**, *146*, 218–227. [CrossRef]
4. Hu, Y.; Su, M.; Jiao, L. Peak and fall of China's agricultural GHG emissions. *J. Clean. Prod.* **2023**, *389*, 136035. [CrossRef]
5. Qian, H.; Huang, S.; Chen, J.; Wang, L.; Hungate, B.A.; Van Kessel, C.; Zhang, J.; Deng, A.; Jiang, Y.; Van Groenigen, K.J. Lower-than-expected CH4 emissions from rice paddies with rising CO_2 concentrations. *Glob. Chang Biol.* **2020**, *26*, 2368–2376. [CrossRef]
6. Reza, K.A.; Majid, D. Sustainability assessment of corn production in conventional and conservation tillage systems. *J. Clean. Prod.* **2022**, *351*, 131508.
7. Wang, H.; Shen, M.; Hui, D.; Chen, J.; Sun, G.; Wang, X.; Lu, C.; Sheng, J.; Chen, L.; Luo, Y.; et al. Straw incorporation influences soil organic carbon sequestration, greenhouse gas emission, and crop yields in a Chinese rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system. *Soil Tillage Res.* **2019**, *195*, 104377. [CrossRef]
8. Liu, G.W.; Ren, Y.Y.; Zhang, L.P.; Gao, Y.Y.; Li, S.Q.; Zhu, C.Y.; Tan, H. Application of biodegradable mulching film in garlic cultivation. *Hunan Agric. Sci.* **2023**, *3*, 36–39+45. (In Chinese) [CrossRef]
9. Cui, Z.; Liu, X.; Chen, Y.; Guan, C.; Yang, Y.; Xu, B. Status quo, problems and countermeasures of the whole mechanized production of garlic in China. *Chin. J. Agric. Mech. Chem.* **2023**, *44*, 239–243+250. [CrossRef]
10. Sun, D.; Li, H.; Wang, E.; He, W.; Hao, W.; Yan, C.; Li, Y.; Mei, X.; Zhang, Y.; Sun, Z.; et al. An overview of the use of plastic-film mulching in China to increase crop yield and water-use efficiency. *Natl. Sci. Rev.* **2020**, *7*, 1523–1526. [CrossRef] [PubMed]
11. Cui, J.X.; Xu, J.Z.; Bai, R.H.; Liu, Q.; He, W.Q.; Yan, C.R. Investigation on plastic film application and recycling treatment behavior of farmers in typical regions of our country. *J. Agric. Resour. Environ.* **2023**, 1–16. (In Chinese) [CrossRef]
12. Li, Z.; He, W.Q.; Liu, E.K.; Zhou, J.L.; Liu, Q.; Yan, C.R. Research progress on the degradation process and mechanism of polyethylene film. *J. Agric. Environ. Sci.* **2019**, *38*, 268–275. (In Chinese)
13. Qin, Y.; Chai, Y.; Li, R.; Li, Y.; Ma, J.; Cheng, H.; Chang, L.; Chai, S. Evaluation of straw and plastic film mulching on wheat production: A meta-analysis in Loess Plateau of China. *Field Crop. Res.* **2022**, *275*, 108333. [CrossRef]
14. Yang, Y.; Li, Z.; Yan, C.; Chadwick, D.; Jones, D.L.; Liu, E.; Liu, Q.; Bai, R.; He, W. Kinetics of microplastic generation from different types of mulch films in agricultural soil. *Sci. Total Environ.* **2022**, *814*, 152572. [CrossRef] [PubMed]
15. Du, Y.; Sun, J.; Wang, Z.; Zhang, Q.; Cui, B.; Niu, W. Effect of ridge film mulching and nitrogen application rate on seed quality, oil yield and nitrogen-use efficiency of winter oilseed rape in northwest China. *Arch. Agron. Soil Sci.* **2022**, *68*, 1385–1397. [CrossRef]
16. Kumar, S.; Gaikwad, S.; Shekdar, A.; Kshirsagar, P. Singh Estimation method for national methane emission from solid waste landfills. *Atmos. Environ.* **2004**, *38*, 3481–3487. [CrossRef]

17. Uzamurera, A.G.; Wang, P.-Y.; Zhao, Z.-Y.; Tao, X.-P.; Zhou, R.; Wang, W.-Y.; Xiong, X.-B.; Wang, S.; Wesly, K.; Tao, H.-Y.; et al. Thickness-dependent release of microplastics and phthalic acid esters from polythene and biodegradable residual films in agricultural soils and its related productivity effects. *J. Hazard. Mater.* **2023**, *448*, 130897. [CrossRef] [PubMed]
18. Wang, Z.; Wu, Q.; Fan, B.; Zhang, J.; Li, W.; Zheng, X.; Lin, H.; Guo, L. Testing biodegradable films as alternatives to plastic films in enhancing cotton (*Gossypium hirsutum* L.) yield under mulched drip irrigation. *Soil Tillage Res.* **2019**, *192*, 196–205. [CrossRef]
19. Vox, G.; Schettini, E. Evaluation of the radiometric properties of starch-based biodegradable films for crop protection. *Polym. Test.* **2007**, *26*, 639–651. [CrossRef]
20. Scarascia-Mugnozza, G.; Schettini, E.; Vox, G. Effects of solar radiation on the radiometric properties of biodegradable films for agricultural applications. *Biosyst. Eng.* **2004**, *87*, 479–487. [CrossRef]
21. Kang, H.; Ao, L.L.; Qin, L.Z.; Su, H.J. Field degradation process of biodegradable mulching film and its effect on maize growth. *Chin. Agric. Sci. Bull.* **2013**, *9*, 54–58. (In Chinese)
22. Yin, M.; Li, Y.; Fang, H.; Chen, P. Biodegradable mulching film with an optimum degradation rate improves soil environment and enhances maize growth. *Agric. Water Manag.* **2019**, *216*, 127–137. [CrossRef]
23. Yu, Y.; Zhang, Y.; Xiao, M.; Zhao, C.; Yao, H. A meta-analysis of film mulching cultivation effects on soil organic carbon and soil greenhouse gas fluxes. *Catena* **2021**, *206*, 105483. [CrossRef]
24. Cuello, J.P.; Hwang, H.Y.; Gutierrez, J.; Kim, S.Y.; Kim, P.J. Impact of plastic film mulching on increasing greenhouse gas emissions in temperate upland soil during maize cultivation. *Appl. Soil. Ecol.* **2015**, *91*, 48–57. [CrossRef]
25. Chen, S.-J.; Jiang, C.-S.; Ni, X.; Li, X.-X.; Hao, Q.-J. Effect of plastic film mulching on greenhouse gas emissions from rice-rapeseed rotation in cropland. *Chin. J. Environ. Sci.* **2019**, *40*, 4213–4220. (In Chinese)
26. Berger, S.; Kim, Y.; Kettering, J.; Gebauer, G. Plastic mulching in agriculture—Friend or foe of N_2O emissions. *Agric. Ecosyst. Environ.* **2013**, *167*, 43–51. [CrossRef]
27. Hu, Y.; Ma, P.; Duan, C.; Wu, S.; Feng, H.; Zou, Y. Black plastic film combined with straw mulching delays senescence and increases summer maize yield in northwest China. *Agric. Water Manag.* **2020**, *231*, 106031. [CrossRef]
28. Qin, M.; Chen, C.; Song, B.; Shen, M.; Cao, W.; Yang, H.; Zeng, G.; Gong, J. A review of biodegradable plastics to biodegradable microplastics: Another ecological threat to soil environments? *J. Clean. Prod.* **2021**, *312*, 127816. [CrossRef]
29. Guo, Y.T.; Luo, X.Q.; Wang, R.; Chen, H.X.; Feng, H. Effects of biodegradable plastic film mulching on greenhouse gas emissions under wheat-maize rotation system in the Guanzhong Plain. *Chin. J. Environ. Sci.* **2021**, *43*, 2788–2801. (In Chinese)
30. Maeseele, C.; Roux, P. An LCA framework to assess environmental efficiency of water reuse: Application to contrasted locations for wastewater reuse in agriculture. *J. Clean. Prod.* **2021**, *316*, 128151. [CrossRef]
31. Ji, G.; Ji, H.; Cheng, K.; Liu, M.; Jiang, M.; Hu, Z.; Zhang, Y.; Hu, N.; Hu, F. Comprehensive evaluation of the carbon footprint and economic benefits of rice cultivation in Jiangsu. *Soil Sci. J.* **2024**, 1–15. Available online: http://kns.cnki.net/kcms/detail/32.1119.P.20230423.1726.004.html (accessed on 15 February 2024).
32. Hu, N.; Chen, Q.; Zhu, L. Life cycle environmental impact assessment of rice-wheat rotation system in the middle and lower reaches of the Yangtze River—A case study of Nanjing, Jiangsu. *Yangtze River Basin Resour. Environ.* **2019**, *28*, 1111–1120.
33. Feng, H.; Liu, J.J.; Zhang, A.F.; Zou, S.Y.; Chen, H.S. Effects of mulching method on net carbon sinks in wheat-corn rotation farmland ecosystems. *J. Agric. Mach.* **2017**, *48*, 180–189.
34. Luo, X. Characteristics of Greenhouse Gas Emissions and Carbon Footprint of Farmland under Different Mulching Measures. Master's Thesis, Northwest Agriculture and Forestry University, Xianyang, China, 2019.
35. Guo, B.; Yang, Z.; He, W.; Liu, J. Application effects and problems of biodegradable mulch. *China Agric. Meteorol.* **2023**, *44*, 977–994.
36. Meng, Y.; He, W. Effects of different ridge cropping methods on water utilization efficiency and economic benefits of potato in rainfed areas. *J. Henan Agric. Univ.* **2018**, *52*, 506–513. [CrossRef]
37. Zhao, C.; Chen, G.; Chai, Q.; Yin, W.; Liu, C. Analysis of soil moisture and economic benefits of corn farmland covered by one film for two years under different irrigation levels. *Arid. Reg. Agric. Res.* **2017**, *35*, 1–6.
38. Li, P.; Wu, B.; Gao, Y.; Niu, J.; Chen, Y.; Ling, P.; Li, Y. Impact analysis of mulching planting mode on economic benefits of dryland huisache—A comprehensive evaluation based on entropy weighted gray correlation coupling. *Arid. Zone Resour. Environ.* **2021**, *35*, 180–188. [CrossRef]
39. Liu, C.Y.; Yang, F.; Lu, X.J.; Zhao, Y.Q.; Zhang, B.W.; Fan, J.D. Effects of organic and inorganic fertilizers on growth, yield, and quality of garlic. *Hunan Agric. Sci.* **2021**, *12*, 40–43. (In Chinese)
40. Zou, J.W. A Study on Greenhouse Gas (CO2, CH4, and N2O) Emissions from Rice-Winter Wheat Rotations in Southeast China. Ph.D. Thesis, Nanjing Agricultural University, Nanjing, China, 2005.
41. [IPCC] Intergovernmental Panel on Climate Change. *Climate Change 2013: The Physical Science Basis*; Cambridge University Press: Cambridge, UK, 2013.
42. Landman, W. Climate change 2007: The physical science basis. *S. Afr. Geogr. J.* **2010**, *92*, 86–87. [CrossRef]
43. Jiang, P.; Xu, Q.; Xu, Z.; Cao, Z. Seasonal changes in soil labile organic carbon pools within a Phyllostachys praecox stand under high rate fertilization and winter mulch in subtropical China. *For. Ecol. Manag.* **2006**, *236*, 30–36. [CrossRef]
44. Shan, H.; Zhang, Q.; Zhang, X.; Han, R.; Feng, Z. Effects of preservation, analysis method on determination of nitrate in soils. *J. Instr. Anal.* **2013**, *32*, 1466–1471.
45. Xia, L.; Ti, C.; Li, B.; Xia, Y.; Yan, X. Greenhouse gas emissions and reactive nitrogen releases during the life-cycles of staple food production in China and their mitigation potential. *Sci. Total Environ.* **2016**, *556*, 116–125. [CrossRef]

46. Li, S.-H.; Guo, L.-J.; Cao, C.-G.; Li, C.-F. Integrated assessment of carbon footprint, energy budget and net ecosystem economic efficiency from rice fields under different tillage modes in central China. *J. Clean. Prod.* **2021**, *295*, 126398. [CrossRef]
47. Hillier, J.; Hawes, C.; Squire, G.; Hilton, A.; Wale, S.; Smith, P. The carbon footprints of food crop production. *Int. J. Agric. Sustain.* **2009**, *7*, 107–118. [CrossRef]
48. Liu, C.; Wang, K.; Zheng, X. Effects of nitrification inhibitors (DCD and DMPP) on nitrous oxide emission, crop yield and nitrogen uptake in a wheat–maize cropping system. *Biogeosciences* **2013**, *10*, 2427–2437. [CrossRef]
49. Jiang, H.-L.; Lei, Q.; Zhang, B.; Wu, S.-F. Effects of mulching and application of organic and chemical fertilizer on greenhouse gas emission and water and nitrogen use in summer maize farmland. *Chin. J. Environ. Sci.* **2022**, *44*, 3426–3438. [CrossRef]
50. Dalal, R.C.; Allen, D.E.; Livesley, S.J.; Richards, G. Magnitude and biophysical regulators of methane emission and consumption in the Australian agricultural, forest, and submerged landscapes: A review. *Plant Soil* **2007**, *309*, 43–76. [CrossRef]
51. Meng, C.; Wang, F.; Yang, K.; Shock, C.C.; Engel, B.A.; Zhang, Y.; Tao, L.; Gu, X. Small wetted proportion of drip irrigation and non-mulched treatment with manure application enhanced methane uptake in upland field. *Agric. For. Meteorol.* **2020**, *281*, 107821. [CrossRef]
52. Chen, N.; Li, X.; Šimůnek, J.; Shi, H.; Hu, Q.; Zhang, Y. Evaluating the effects of biodegradable and plastic film mulching on soil temperature in a drip-irrigated field. *Soil Tillage Res.* **2021**, *213*, 105116. [CrossRef]
53. Wang, Z.L.; Bai, J.; Li, Y.; Li, S.Q. Effects of nitrogen application and plastic film mulching on nitrogen uptake and allocation in dry-land spring maize. *Plant. Nutr. Fert. Sci.* **2019**, *25*, 74–84. (In Chinese)
54. Zhang, K.L.; Hao, Q.J.; Feng, D.; Shi, J.L.; Shi, X.J.; Jiang, C.S. Effect of plastic film mulching on methane emission from a vegetable field. *Chin. J. Environ. Sci.* **2017**, *38*, 3451–3462. (In Chinese)
55. Li, Y.; Wu, W.; Yang, J.; Cheng, K.; Smith, P.; Sun, J.; Xu, X.; Yue, Q.; Pan, G. Exploring the environmental impact of crop production in China using a comprehensive footprint approach. *Sci. Total Environ.* **2022**, *824*, 153898. [CrossRef]
56. Li, B.; Fan, C.H.; Zhang, H.; Chen, Z.; Sun, L.; Xiong, Z. Combined effects of nitrogen fertilization and biochar on the net global warming potential, greenhouse gas intensity and net ecosystem economic budget in intensive vegetable agriculture in southeastern China. *Atmos. Environ.* **2015**, *100*, 10–19. (In Chinese) [CrossRef]
57. Kim, G.W.; Das, S.; Hwang, H.Y.; Kim, P.J. Nitrous oxide emissions from soils amended by cover-crops and under plastic film mulching: Fluxes, emission factors and yield-scaled emissions. *Atmos. Environ.* **2017**, *152*, 377–388. [CrossRef]
58. Liu, J.; Zhu, L.; Luo, S.; Bu, L.; Chen, X.; Yue, S.; Li, S. Response of nitrous oxide emission to soil mulching and nitrogen fertilization in semi-arid farmland. *Agric. Ecosyst. Environ.* **2014**, *188*, 20–28. [CrossRef]
59. Pajares, S.; Bohannan, B.J.M. Ecology of nitrogen fixing, nitrifying, and denitrifying microorganisms in tropical forest soils. *Front. Microbiol.* **2016**, *7*, 1045. [CrossRef] [PubMed]
60. Li, Q.; Li, H.; Zhang, S. Yield and water use efficiency of dryland potato in response to plastic film mulching on the Loess Plateau. *Acta Agric. Scand. Sect.* **2018**, *68*, 175–188. [CrossRef]
61. Fang, H.; Li, Y.; Gu, X.; Yu, M.; Chen, P.; Li, Y.; Liu, F. Optimizing the impact of film mulching pattern and nitrogen application rate on maize production, gaseous N emissions, and utilization of water and nitrogen in northwest China. *Agric. Water Manag.* **2022**, *261*, 107350. [CrossRef]
62. Zhang, Z.X.; Nie, T.Z.; Wang, D. The coupling effect of water, N and P with drip irrigation under plastic film on maize yield in semi-arid region of western Heilongjiang Province. *China Rural. Water Hydropower* **2016**, *2*, 1–4. (In Chinese)
63. Hui, S.J.; Zhang, J.X. Effects of different mulching patterns and irrigation quotas on soil hydrothermal, nutrients and yield of sunflower farmland in Hexi Oasis. *Agric. Res. Arid. Areas.* **2022**, *40*, 212–223. (In Chinese)
64. Shi, J.-L.; Hao, Q.-J.; Feng, D.; Zhang, K.-L.; Shi, X.-J.; Jiang, C.-S. Effects of plastic film mulching on methane and nitrous oxide emissions from a rice-rapeseed crop rotation. *Environ. Sci.* **2017**, *38*, 4790–4799. [CrossRef]
65. Zhou, L.; Wang, F.; Zhao, W.L.; Zeng, Z.W.; Yang, D.L. Research progress of crop mulching cultivation. *Hubei Agric Sci.* **2019**, *58*, 75–81. (In Chinese)
66. Yan, C.; He, W.; Xue, Y.; Liu, E.; Liu, Q. Application of biodegradable plastic film to reduce plastic film residual pollution in Chinese agriculture. *Chin. J. Biotech.* **2016**, *32*, 748–760.
67. Li, S.Q.; Li, D.F.; Li, F.M.; Bai, H.Y.; Ling, L.; Wang, J. Soil ecological effects of plastic film mulching in semiarid agro-ecological system. *J. Northwest AF Univ.* **2003**, *31*, 21–29. (In Chinese)
68. Lee, J.G.; Cho, S.R.; Jeong, S.T.; Hwang, H.Y.; Kim, P.J. Different response of plastic film mulching on greenhouse gas intensity (GHGI) between chemical and organic fertilization in maize upland soil. *Sci. Total Environ.* **2019**, *696*, 133827. [CrossRef] [PubMed]
69. Grassini, P.; Cassman, K.G. High-yield maize with large net energy yield and small global warming intensity. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 1074–1079. [CrossRef]
70. Lal, R. Constraints to adopting no-till farming in developing countries. *Soil Tillage Res.* **2007**, *94*, 1–3. [CrossRef]
71. Zhang, F.; Cheng, T.-H.; Chen, X.-P.; Wang, X.-Z. Greenhouse gas emissions for typical open-field vegetable production in China. *Environ. Sci.* **2020**, *41*, 3410–3417. (In Chinese)
72. Li, C.; Xiong, Y.; Huang, Q.; Xu, X.; Huang, G. Impact of irrigation and fertilization regimes on greenhouse gas emissions from soil of mulching cultivated maize (*Zea mays* L.) field in the upper reaches of Yellow River, China. *J. Clean. Prod.* **2020**, *259*, 120873. [CrossRef]
73. Yoon, S.Y.; Kim, Y.R.; Kim, T.H.; Park, J.H.; Ahn, S.W. Study of garlic's carbon footprint though LCA. *Korean J. Org. Agric.* **2012**, *20*, 161–172.

74. He, X.; Chen, J.; Li, Y.; Chen, Y.; Zhao, G.; Ren, K.; Hu, M.; Hu, B.; Chen, Y.; Xu, Z.; et al. Seasonal dynamics of soil aggregates and associated C and N stocks in different fertilizer managements. *Arch. Agron. Soil Sci.* **2021**, *68*, 1305–1321. [CrossRef]
75. Wang, Z.-B.; Wen, X.-Y.; Zhang, H.-L.; Lu, X.-H.; Chen, F. Net energy yield and carbon footprint of summer corn under different N fertilizer rates in the North China Plain. *J. Integr. Agric.* **2015**, *14*, 1534–1541. [CrossRef]
76. Lee, J.G.; Chae, H.G.; Hwang, H.Y.; Kim, P.J.; Cho, S.R. Effect of plastic film mulching on maize productivity and nitrogen use efficiency under organic farming in South Korea. *Sci. Total Environ.* **2021**, *787*, 147503. [CrossRef] [PubMed]
77. Zhang, D.B.; Yao, P.W.; Zhao, N.; Wang, Z.; Yu, C.W.; Cao, Q.H.; Cao, W.D.; Gao, Y.J. Responses of winter wheat production to green manure and nitrogen fertilizer on the Loess Plateau. *Agron. J.* **2015**, *107*, 361–374.
78. Xu, Y.; Liang, L.; Wang, B.; Xiang, J.; Gao, M.; Fu, Z.; Long, P.; Luo, H.; Huang, C. Conversion from double-season rice to ratoon rice paddy fields reduces carbon footprint and enhances net ecosystem economic benefit. *Sci. Total Environ.* **2022**, *813*, 152550. [CrossRef]

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