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Impact of Management Strategies on Reducing of Mulching Film Residues Pollution in Arid Regions

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Abstract: Plastic pollution caused by mulching film residues (MFRs) is escalating in arable lands, which affects the function of agricultural ecosystems, and poses a serious obstacle to agricultural sustainable development in arid regions. Internationally, increasing recycling rate of polyethylene (PE) film and adopting biodegradable films are recommended strategies to mitigate plastic pollution in farmland, aiming to increase agricultural sustainability and food security. However, impacts of the future of these strategies remain underexplored. This study estimated MFRs accumulation over the next 50 years under varying PE and polybutylene adipate terephthalate (PBAT) film recovery scenarios: no recovery, and recovery rates increased to 80%, 85%, 90%, and 95%. Additionally, cumulative ecological effects (CEEs) of MFR pollution were assessed based on historical MFRs accumulations of 75 kg hm^{-2}, 160 kg hm^{-2}, 220 kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2}, by evaluating direct and indirect ecological effects. The findings revealed that (1) with no recovery, PE film residues could increase by 480 kg hm^{-2}, whereas achieving a 95% recovery rate could limit residues increasing to below the national threshold of 75 kg hm^{-2}, outperforming the 80%, 85%, and 90% recovery rates. On the other hand, using PBAT film would maintain the increasing MFRs below 75 kg hm^{-2} regardless of recovery rate. (2) Without PE film recovery, CEEs would intensify significantly, as both the direct and indirect effects increase notably, while the CEEs of MFRs could maintain the current status or decrease under the strategy of 95% recovery rate of PE film and using PBAT film, similar to the variation of direct effects. However, indirect effects would persist due to ongoing microplastics (MPs) and phthalate esters (PAEs) released from residual films. Overall, a 95% PE film recycling rate and PBAT film usage emerged as particularly effective strategies for minimizing MFRs accumulation and mitigating ecological impacts over the next 50 years. Further research should prioritize the indirect ecological effects of MFRs, given their persistence despite reduction efforts. The results could provide a theoretical support for agricultural sustainable development in arid regions.

Keywords: plastic pollution; mulching film residues (MFRs); ecological effects; microplastic (MPs); mitigation strategies; agricultural sustainable development

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1. Introduction

Mulching film is an essential material in modern agriculture, providing benefits such as weed suppression, reduced water evaporation, enhanced plant growth, and increased crop yields [1,2]. This practice is especially prevalent in both arid and humid regions [1,3]. However, poor recycling rates over the past decades have led to an accumulation of plastic debris in soils [4–6]. The rising plastic pollution from mulching film residues (MFRs) in farmland has become a major barrier to sustainable agricultural development [7–9].

Many studies have quantified MFRs levels in soils and identified factors influencing their accumulation across humid to arid regions. These studies indicate that MFRs concentrations are significantly higher in arid regions, typically accumulating in the topsoil layer (0–30 cm), with average levels ranging from 136.7 to 259.1 kg hm^{-2} [6,10,11]. In some areas, the residues have reached up to 502.2 kg hm^{-2} [12]. As an essential material for crop production in arid areas, mulch would continue to be used; however, research on variation of MFRs accumulation in the future is limited domestically and internationally [13,14].

MFR pollution poses direct and indirect threats to agricultural ecosystems, presenting a long-term environmental challenge [7,9]. Directly, residual plastics lead to continuous soil degradation, causing damage to soil structure, altering soil bulk density, reducing soil porosity, and disrupting the vertical penetration and horizontal transport of soil water [8,15–17]. These effects negatively impact seed emergence, root growth, biomass accumulation, and crop yields [8,18,19]. Indirectly, MFRs release microplastics (MPs, $\leq$5 mm in size) and plastic additives during degradation, causing a series of hazards [20–22]. MPs can reduce water and nutrient uptake by blockage of pores in seed coat or roots, inhibiting plant growth [22,23]. Moreover, MPs can be absorbed and transported to other plant organs by transpiration, and can accumulate in higher animal bodies through the food chain, potentially harmful to human health [22,24–26]. Phthalic acid esters (PAEs), as the main ingredient in plastic additives, also pose threats to crops, microbes in soil, animals, and humans [27,28].

Assessing the long-term ecological impacts of MFRs on agricultural ecosystems is essential, and comprehensive studies on the overall impacts of MFRs remain sparse [7,18,19]. This gap underscores the limited understanding of MFR pollution as an environmental issue [7,13]. To mitigate MFR pollution, the Food and Agriculture Organization (FAO) has proposed global strategies for improving agricultural plastic management [29]. In China, government initiatives aim to address this issue by targeting a recovery rate of over 80% for polyethylene (PE) films and encouraging using biodegradable films [30], and polybutylene adipate terephthalate (PBAT) film is a relatively common biodegradable film in the market [31,32]. However, further research is needed to assess the effectiveness of these measures [3,7,33,34].

This study estimates the accumulation of MFRs over the next 50 years under strategies involving increased PE film recovery and the use of PBAT film. Additionally, it evaluates the cumulative ecological effects (CEEs) of MFR pollution under different historical accumulation levels to assess the impact of these strategies [9]. This research aims to offer valuable insights into the prevention and relief of residual film pollution in agricultural ecosystems, promoting agricultural sustainable development.

2. Materials and Methods

2.1. Scenarios

Investigations demonstrated that MFRs in most fields were greater than the national film residue standard (75 kg hm^{-2}), and even up to 502.2 kg hm^{-2}, increasing with increasing mulching years [10–12]. Accumulations of 75 kg hm^{-2}, 160 kg hm^{-2}, 220 kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2} were chosen as the typical historical accumulation in different mulching years fields [10–12]. In order to better understand the variation of accumulation of MFRs over the next 50 years in those fields under different management strategies, this study established ten strategic scenarios (Table 1).

Table 1. Strategies and historical conditions.

Strategies for Mitigating MFR Pollution						Historical Conditions
Strategies	**Film Type**	**Film Usage (kg hm^{-2})**	**Thickness (TK) (mm)**	**Recycling Rate**	**Value of F_r**	
PE-S0	PE film	60–80	0.010	0	50.7%	HC1: 75 kg m^{-2} accumulated historically HC2: 160 kg m^{-2} accumulated historically HC3: 220 kg m^{-2} accumulated historically HC4: 300 kg m^{-2} accumulated historically HC5: 400 kg m^{-2} accumulated historically
PE-S1	PE film	60–80	0.010	80%	20%	
PE-S2	PE film	60–80	0.010	85%	15%	
PE-S3	PE film	60–80	0.010	90%	10%	
PE-S4	PE film	60–80	0.010	95%	5%	
PBAT-S0	PBAT film	60–80	0.010	0	50.7%	
PBAT-S1	PBAT film	60–80	0.010	80%	20%	
PBAT-S2	PBAT film	60–80	0.010	85%	15%	
PBAT-S3	PBAT film	60–80	0.010	90%	10%	
PBAT-S4	PBAT film	60–80	0.010	95%	5%	

Note: 50.7% refers to "Manual for Mulching Film Residue Coefficient" [35].

2.2. Estimation of Accumulation of Mulching Film Residues

The conceptual model for residual film accumulation is presented as Equation (1):

$$Q = \sum_{i=1}^{n} (F_{mi} \times F_{ri}) \tag{1}$$

where Q represents the amount of MFRs, kg hm^{-2}. The variable n is the years of using mulching film. F_{mi} is the amount of film used in the ith year, kg hm^{-2}. F_{ri} is the residual rate of mulching film in the ith year, % (Table 1).

The increasing amount of residual film (ΔQ) and the cumulative amount of residual film (Q) in the future based on historical accumulations were calculated as Equations (2) and (3):

$$\Delta Q = \sum_{i=1}^{n} F_{mij} F_{rij} (1 - d_j)^{n-1} \tag{2}$$

$$Q = Q_0 + \Delta Q \tag{3}$$

where F_{mij} is the amount of jth film usage in the ith year, kg hm^{-2}. F_{rij} is the residual rate of jth film in the ith year, % (Table 1). d_j is the degradation rate of jth film, where the values of PE film and PBAT film are 2.8% and 45.9%, respectively [36,37]. Q_0 is the historical accumulation of MFRs, kg hm^{-2}.

2.3. Evaluation of Cumulative Ecological Effects of Mulching Film Residues

2.3.1. Evaluation of Cumulative Ecological Effects

Under impact of management strategies, the cumulative amount and type of MFRs in soil are constantly changing [3]. Furthermore, the MPs and additives released from MFRs would continue to accumulate with the tillage, aging, and degradation of MFRs in future [7,33]. As a result, the effects of MFRs, MPs, and additives on agro-ecosystems and organisms continue to change, which is in line with the concept of cumulative ecological effects [7,9,18,38]. This paper draws on the concept of cumulative ecological effects (CEEs) to analyze the variation of ecological effects of MFRs in the future, in order to better understand the impacts of management strategies on mitigating MFR pollution [7,9,13].

To evaluate CEEs of MFRs, an index system was developed based on the direct and indirect ecological effects of MFRs (Table 2) [7]. The direct effects of MFRs on farmland ecosystems were assessed by examining their influence on crop yield and soil physicochemical properties, such as changes in water evaporation, water infiltration, organic matter content, and available phosphorus content in soil [8,18,19]. The indirect effects primarily considered pollution from microplastics (MPs, ≤5 mm in size) and phthalate esters (PAEs) [15–17,38–40]. Plastic additives, including plasticizers, antioxidants, heat stabilizers, lubricants, and colorants, are components of plastic pollution [26]. In this study, the accumulation of PAEs from MFRs was utilized to analyze the risk associated with plastic additives, with PAEs being studied systematically [26,41,42].

Table 2. Index system for evaluating cumulative ecological effects of mulching film residues.

Benchmark Layer	Index Layer	Meaning
Direct ecological effects index (I_{de})	Rate of water evaporation reduction Rate of water infiltration reduction Rate of organic matter reduction Rate of available phosphorus reduction	Impacts of MFRs on soil physicochemical properties
	Rate of crop yield reduction	Obstruction to crop production
Indirect ecological effects index (I_{ie})	Accumulation of microplastics from film	Potential risk from MPs
	Accumulation of plastic additives from film	Potential risk from additives

The cumulative ecological effects index (I_{ce}) were used to represent the CEEs of MFRs, as modeled by Equation (4) below:

$$I_{\rm ce} = I_{de} + I_{ie} \quad (4)$$

When I_{ce} values range from 0 to 0.75, CEEs is considered low; values from 0.76 to 1.50 indicate a medium level, and values from 1.51 to 2.00 suggest high-level CEEs from MFR pollution [43].

2.3.2. Evaluation of Direct Ecological Effects of Mulching Film Residues

The direct ecological effects (I_{de}) of MFRs on farmland ecosystems was evaluated by Equations (5)–(7):

$$I_{de} = \frac{CI_{de\ 0} - CI_{de\ min}}{CI_{de\ max} - CI_{de\ min}} \quad (5)$$

$$CI_{de} = \sqrt[5]{CI_{1j} \times CI_{2j} \times CI_{3j} \times CI_{4j} \times CI_{5j}} \quad (6)$$

$$CI_{ij} = \Delta d_i \times \frac{Q_j}{100} \quad (7)$$

where CI_{ij} is the value of the ith item in jth years, and i is from 1 to 5, covering factors such as water evaporation, water infiltration, organic matter content, available phosphorus content, and crop yield. Q_j represents the accumulation of MFRs in the jth year; Δd_i is the value of change in the ith item with an increase of 100 kg hm^{-2} of MFRs, and the Δd of water evaporation, water infiltration, organic matter content, effective phosphorus content, and crop yield are −2%, −8%, −0.8%, −5%, and −3%, respectively [18]. I_{de} values are standardized from the original data to a range of 0 to 1.0 using the min–max method, where the minimum value is set to 0.

2.3.3. Evaluation of Indirect Ecological Effects of Mulching Film Residues

The indirect ecological effects (I_{ie}) were evaluated using Equations (8)–(10):

$$I_{ie} = \sqrt[2]{I_{ie\ 1} \times I_{ie\ 2}} \quad (8)$$

$$CF_i = {}^{C_i}\!\big/_{C_{oi}} \quad (9)$$

$$I_{ie\ i} = \frac{CF_{i\ 0} - CF_{i\ min}}{CF_{i\ max} - CF_{i\ min}} \quad (10)$$

where CF_i is the pollution coefficient of the ith pollutant item, referring to MPs and PAEs. C_i is the accumulated amount of MPs or PAEs, mg kg^{-1}. C_{0i} is the safe concentration threshold of MPs and PAEs below which there is no impact on organisms. The safety concentration of MPs is less than 1000 mg kg^{-1}, which is safe for soil organisms such as earthworms [39,44]. The limit of PAEs is 5 mg kg^{-1}, according to the United States soil cleanup standards (1994) [45].

(1) The cumulative amount of MPs was calculated as Equations (11)–(13):

$$Q_{mps} = Q_{0\ mps} + Q_{i\ mps} \tag{11}$$

$$Q_{0\ mps} = {}^{Q_0 \times EF_0} \Big/ {}_{D \times \rho \times 10^3} \tag{12}$$

$$Q_{i\ mps} = \sum_{i=1}^{n} {}^{Q_{mi} \times EF_j} \Big/ {}_{D \times \rho \times 10^3} \tag{13}$$

where Q_{mps} is the accumulation amount of MPs in the soil, mg kg^{-1}. $Q_{0\ mps}$ is the historical accumulation of MPs. $Q_{i\ mps}$ is the increasing amount of MPs in the *i*th year, mg kg^{-1}. Q_{mi} is the amount of MFRs in the *i*th year, kg hm^{-2}. D is the soil depth at which MPs appear, which is 0.4 m in this paper. ρ is soil bulk density, which is 1.44 × 10^3 kg m^{-3} [46]. EF_j refers to the factor of releasing microplastics from the *j*th type film in the next 50 years, and EF_0 is the factor of historical PE film.

The microplastics emission resulting from wearing of plastic film is unavoidable in the process of production and use. Ren et al. [47,48] presented an effective approach to quantify the EF of microplastics by mechanical abrasion experiments. Although it still has limitations in the standpoint and range, there is no other reliable method for measuring the EF of microplastics. The calculation formula is shown as Equation (14) [47,48]:

$$EF = \frac{1 - \frac{CLT}{c} exp(-d \times TK) - a}{b} \tag{14}$$

where CLT is the light transmittance of the plastic film. The values for PE film and PBAT film are 90% in the next 50 years. TK is the film thickness of film (Table 1), and the thickness of PE film used in the past was 0.008 mm [10]. The variables a, b, c, and d, are modified parameters [47,48].

(2) The cumulative amount of PAEs was calculated by Equations (13)–(17):

$$Q_{APES} = Q_{0APEs} + Q_{cAPES} \tag{15}$$

$$Q_{0\ APEs} = \sum_{i=1}^{n} \frac{Q_0 \times P_0}{D \times \rho \times 10^4} \tag{16}$$

$$Q_{c\ PAEs} = \sum_{i=1}^{n} \frac{(U_{mi} - Q_i) \times P_j \times k}{D \times \rho \times 10^4}) + \sum_{i=1}^{n} \frac{Q_i \times P_j}{D \times \rho \times 10^4} \tag{17}$$

where Q_{PAEs} refers to the cumulative amount of pollution from PAEs, mg kg^{-1}. Q_{0PAEs} refers to the amount of PAEs released from historical MRFs, mg kg^{-1}. Q_0 is the historical accumulation of MFRs, kg hm^{-2}. P_0 is the amount of PAEs in historical film residues, 245 g kg^{-1} [49]. Q_{cPAEs} refers to the increasing amount of PAEs released from cumulative MRFs in the future, mg kg^{-1}. U_{mi} refers to the amount of plastic film used in year i, kg hm^{-2}. Q_i *is* the amount of MFRs in the soil in the *i*th year, kg hm^{-2}, and i is the mulching time (y) of plastic film, from 1 to n. P_j is the amount of PAEs in film, and they are 13.4 mg kg^{-1} and 32.5 mg kg^{-1} in PE film and PABT film, respectively [49–51]. D is the soil depth at which PAEs appear, which was 0.4; ρ is the soil bulk density, which was 1.44 × 10^3 kg m^{-3} [46]; and k is 16.3%, the coefficient of PAEs emission into the soil [21]. This calculation assumes that all PAEs are released into the soil over time, although this process requires a prolonged period. However, due to the lack of a more accurate estimation method, this approach remains the best available for estimation purposes.

3. Results

3.1. Effects of Management Strategies on Accumulation of Mulching Film Residues in the Future

3.1.1. Significant Differences in Increasing Trends of MFRs Under Different Strategies

The results indicate that the increasing trends of MFRs varied significantly across different policy scenarios over the next 50 years. MFRs increased more markedly with lower recycling rates, both when using PE film and PBAT film (Figure 1a,b). In the PE-S0 scenario, MFRs levels showed a continuous upward trend, surpassing the national standard limit of 75 kg hm^{-2} within five years and reaching over 480 kg hm^{-2} by the 50th year. In contrast, in PE-S1, PE-S2, and PE-S3 scenarios, the increase in MFRs was notably less, with final increasing values of 190 kg hm^{-2}, 142 kg hm^{-2}, 94 kg hm^{-2}, and 47.39 kg hm^{-2}, respectively, over 50 years. For PE-S1, PE-S2, and PE-S3, the 75 kg hm^{-2} limit was exceeded in the 13th, 18th, and 43rd years, respectively. Notably, in PE-S4, MFRs accumulation at year 50 remained at 47 kg hm^{-2}, well below the national threshold (Figure 1a).

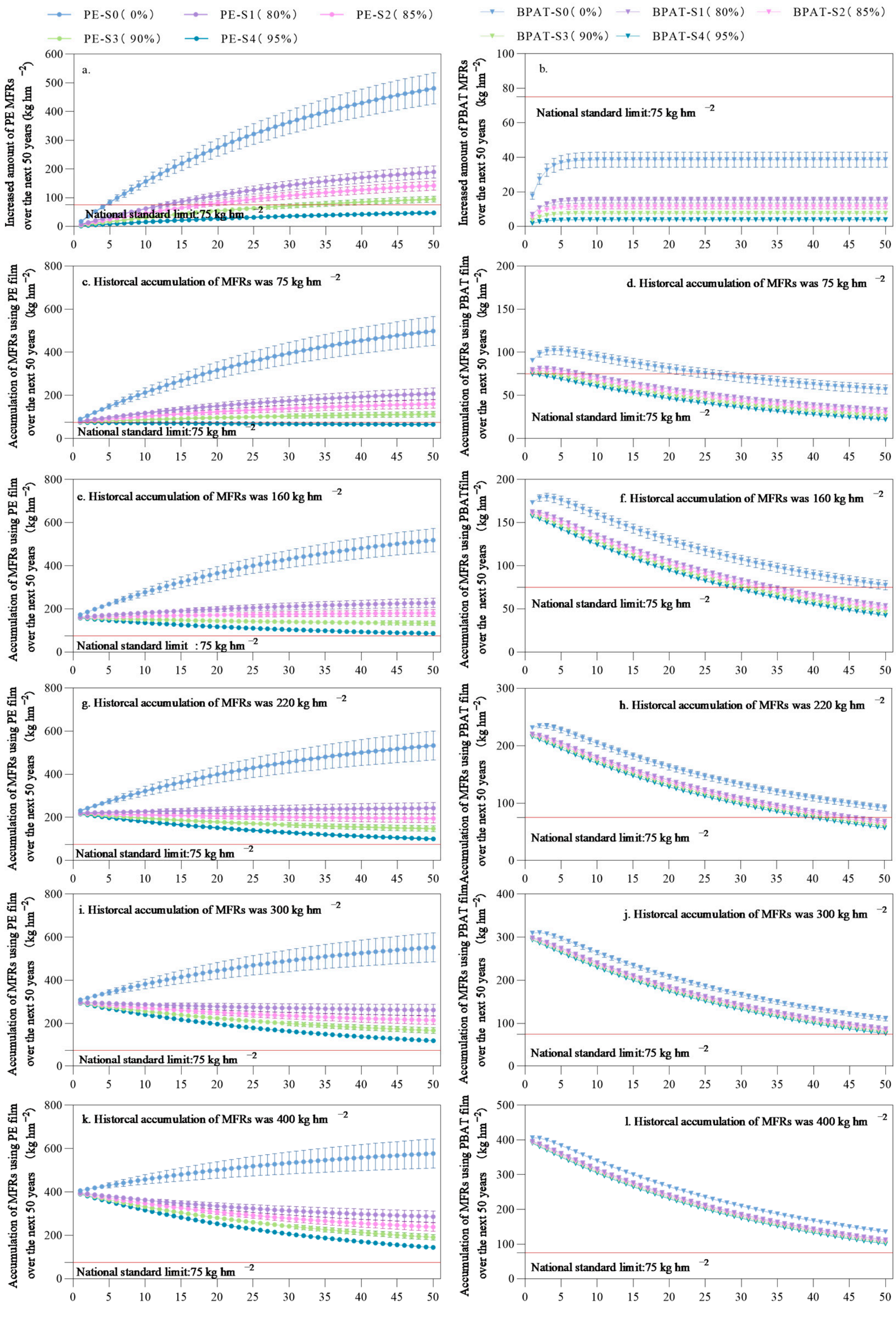


Figure 1. Variation of mulching film residues (MFRs) accumulation in soil over the next 50 years. (**a**) Increased amount of MFRs using PE film with different recycling rates. (**b**) Increased amount

of MFRs using BPAT film with different recycling rates. (**c**) Variation of MFRs accumulation using PE film under 75 kg hm^{-2} historical value. (**d**) Variation of MFRs accumulation using BPAT film under 75 kg hm^{-2} historical value. (**e**) Variation of MFRs accumulation using PE film under 160 kg hm^{-2} historical value. (**f**) Variation of MFRs accumulation using BPAT film under 160 kg hm^{-2} historical value. (**g**) Variation of MFRs accumulation using PE film under 220 kg hm^{-2} historical value. (**h**) Variation of MFRs accumulation using BPAT film under 220 kg hm^{-2} historical value. (**i**) Variation of MFRs accumulation using PE film under 300 kg hm^{-2} historical value. (**j**) Variation of MFRs accumulation using BPAT film under 300 kg hm^{-2} historical value. (**k**) Variation of MFRs accumulation using PE film under 400 kg hm^{-2} historical value. (**l**) Variation of MFRs accumulation using BPAT film under 400 kg hm^{-2} historical value.

In scenarios utilizing PBAT film, MFRs accumulation was substantially lower than in PE film scenarios. In scenarios utilizing PBAT film, the increasing MFRs accumulation was substantially lower than in PE film scenarios, with respective values of 37 kg hm^{-2}, 16 kg hm^{-2}, 12 kg hm^{-2}, 8 kg hm^{-2}, and 4 kg hm^{-2} in PBAT-S0, PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4 scenarios by the 15th year. Additionally, MFRs levels stabilized after 15 years (Figure 1b). Overall, a PE film recycling rate of over 95% effectively reduced MFRs accumulation, though PBAT film use was even more effective.

3.1.2. Effects of Strategies on MFRs Accumulation Under Historical Conditions

The impact of different policies on MFRs accumulation in the future differed substantially depending on historical conditions. Under HC1, PE-S0, PE-S1, PE-S2, and PE-S3 strategies led to an increase in MFRs accumulation, reaching 499 kg hm^{-2}, 208 kg hm^{-2}, 160 kg hm^{-2}, and 113 kg hm^{-2} by the 50th year, respectively. Conversely, PBAT-S0, PBAT-S1, PBAT-S2, and PBAT-S3 strategies initially showed an increase followed by a decline in MFRs accumulation. In PE-S4 and PBAT-S4 strategies, MFRs levels showed a decreasing trend, with final values of 66 kg hm^{-2}, 57 kg hm^{-2}, 33 kg hm^{-2}, 30 kg hm^{-2}, 26 kg hm^{-2}, and 22 kg hm^{-2}, all below the 75 kg hm^{-2} threshold (Figure 1c,d).

In HC2, PE-S0, PE-S1, and PE-S2 strategies led to an accumulation of 519 kg hm^{-2}, 228 kg hm^{-2}, and 180 kg hm^{-2}, respectively. Under PBAT-S0, PBAT-S1, and PBAT-S2 strategies, MFRs accumulation showed an initial increase followed by a reduction, while under PE-S3, PE-S4, PBAT-S3, and PBAT-S4 strategies it displayed a decreasing trend. MFRs accumulations in PE-S3, PE-S4, and PBAT-S0 were, respectively, 133 kg hm^{-2}, 86 kg hm^{-2}, and 77 kg hm^{-2}, higher than 75 kg hm^{-2} in the 50th year, and the accumulations further decreased to 54 kg hm^{-2}, 50 kg hm^{-2}, 46 kg hm^{-2}, and 42 kg hm^{-2} in PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4, respectively (Figure 1e,f).

Under HC3, PE-S0 and PE-S1 strategies caused MFRs to rise to 534 kg hm^{-2} and 243 kg hm^{-2}, respectively. MFRs accumulation initially increased and then decreased in PBAT-S0 and PBAT-S1 strategies, whereas in PE-S2, PE-S3, PE-S4, PBAT-S2, PBAT-S3, and PBAT-S4 strategies it showed decreasing trends, with final accumulations of 195 kg hm^{-2}, 148 kg hm^{-2}, 101 kg hm^{-2}, 92 kg hm^{-2}, 68 kg hm^{-2}, 65 kg hm^{-2}, 65 kg hm^{-2}, 61 kg hm^{-2}, and 57 kg hm^{-2}, respectively, by the 50th year (Figure 1g,h).

Under HC4 and HC5, MFRs accumulation trends were consistent within each strategy. The PE-S0 strategy led to an increase in MFRs, reaching 553 kg hm^{-2} and 577 kg hm^{-2}, respectively. PBAT-S0 strategy showed an initially increasing and then decreasing trend, while other strategies showed a downward trend, with MFRs accumulations remaining above 75 kg hm^{-2} (Figure 1i–l). In summary, the PE-S0 strategy consistently resulted in a significant increase in MFRs under all historical conditions. The effectiveness of other strategies in reducing MFR pollution depended on prior accumulations; with lower historical MFRs levels, the effects of mitigation strategies were more obvious.

3.2. Effects of Strategies on Cumulative Ecological Effects of Mulching Film Residues

3.2.1. Cumulative Ecological Effects of Mulching Film Residues

Results demonstrated significant variations in CEEs under different strategies. In HC1, the CEEs index increased significantly under PE-S0, PE-S1, PE-S2, PE-S3, and PE-S4 strategies, particularly in PE-S0. Conversely, CEEs decreased under PBAT-S0, PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4. Under PE-S0, CEEs rose from the low level to medium level by year 30, whereas in other strategies CEEs remained at the low level over the next 50-year period, as illustrated by index variations in Figure 2a. In HC2, the CEEs had an obvious increase under the PE-S0 strategy, reaching medium levels within 20 years from the low level. The increase under PE-S1, PE-S2, PE-S3, and PE-S4 was less pronounced than under PE-S0, while all PBAT strategies resulted in declines in CEEs, with remaining low levels across all strategies except PE-S0 in the future (Figure 2b). In HC3, CEEs increased to medium levels within 10 years under PE-S0 and reached medium levels under PE-S1 within 30 years. In contrast, CEEs decreased under PE-S3, PE-S4, PBAT-S0, PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4, maintaining at low levels over the next 50 years (Figure 2c). In HC4, the CEEs under PE-S0 rose significantly, reaching the high level in the 40th year, with a smaller increase under PE-S1 and PE-S2. In other strategies, CEEs decreased to low levels in the 20th year (Figure 2d). In HC5, CEEs increased notably under PE-S0, reaching a high level within 20 years from medium levels. CEEs decreased under PE-S2, PE-S3, PE-S4, and PBAT-S0 strategies over the next 50 years, but they remained at medium levels, while under strategies PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4, CEEs decreased to low levels by the 50th year (Figure 2e).

According to the significance analysis, under all historical conditions, there were significant differences in I_{ce} among all PE strategies, with the order being PE-S0 > PE-S1 > PE-S2 > PE-S3 > PE-S4 ($p < 0.05$), and the I_{ce} in PE-S0 was significantly higher ($p < 0.05$) than over the next 50 years. I_{ce} in PBAT-S0 were higher than PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4 ($p < 0.05$). In the 10th year, I_{ce} in PBAT-S1 and PBAT-S2 were higher than PBAT-S3 and PBAT-S4 ($p < 0.05$), while I_{ce} in PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4 had no significance ($p > 0.05$) in the 20th, 30th, 40th, and 50th year. Concerning the difference analysis between PE strategies and PBAT strategies, results showed that I_{ce} in PE-S0, PES-1, and PE-S2 were significantly higher than in all PBAT strategies over the next 50 years ($p < 0.05$). It is worth mentioning that there was no significance between PE-S3 and PBAT-S0 in the 10th year, and no significance between PE-S4 and PBAT-S0 in the 20th, 30th, 40th, and 50th years ($p > 0.05$) (Figure 3) in all historical conditions. In summary, CEEs of MFRs consistently and significantly increased under PE-S0 strategies in all historical conditions over the next 50 years. The effects of PE-S4 on inhibiting CEEs increase was more efficient than PBAT-S0 in the next 10 years, and they had no significance over the next 20 to 50 years.

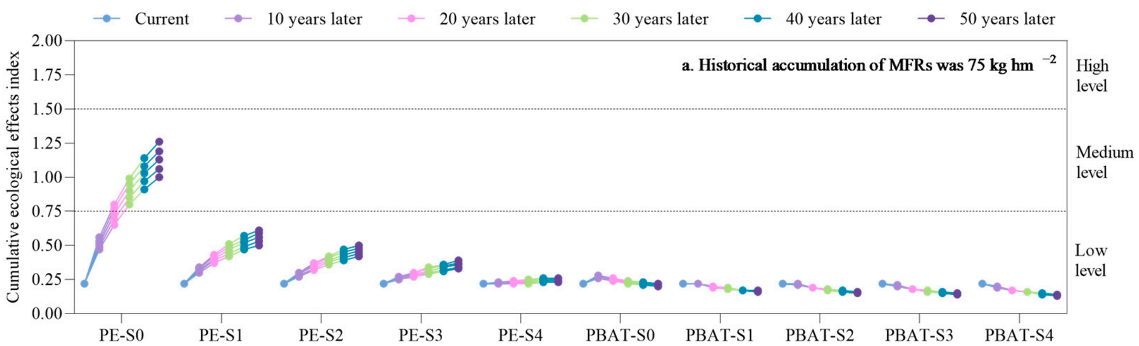


Figure 2. *Cont.*

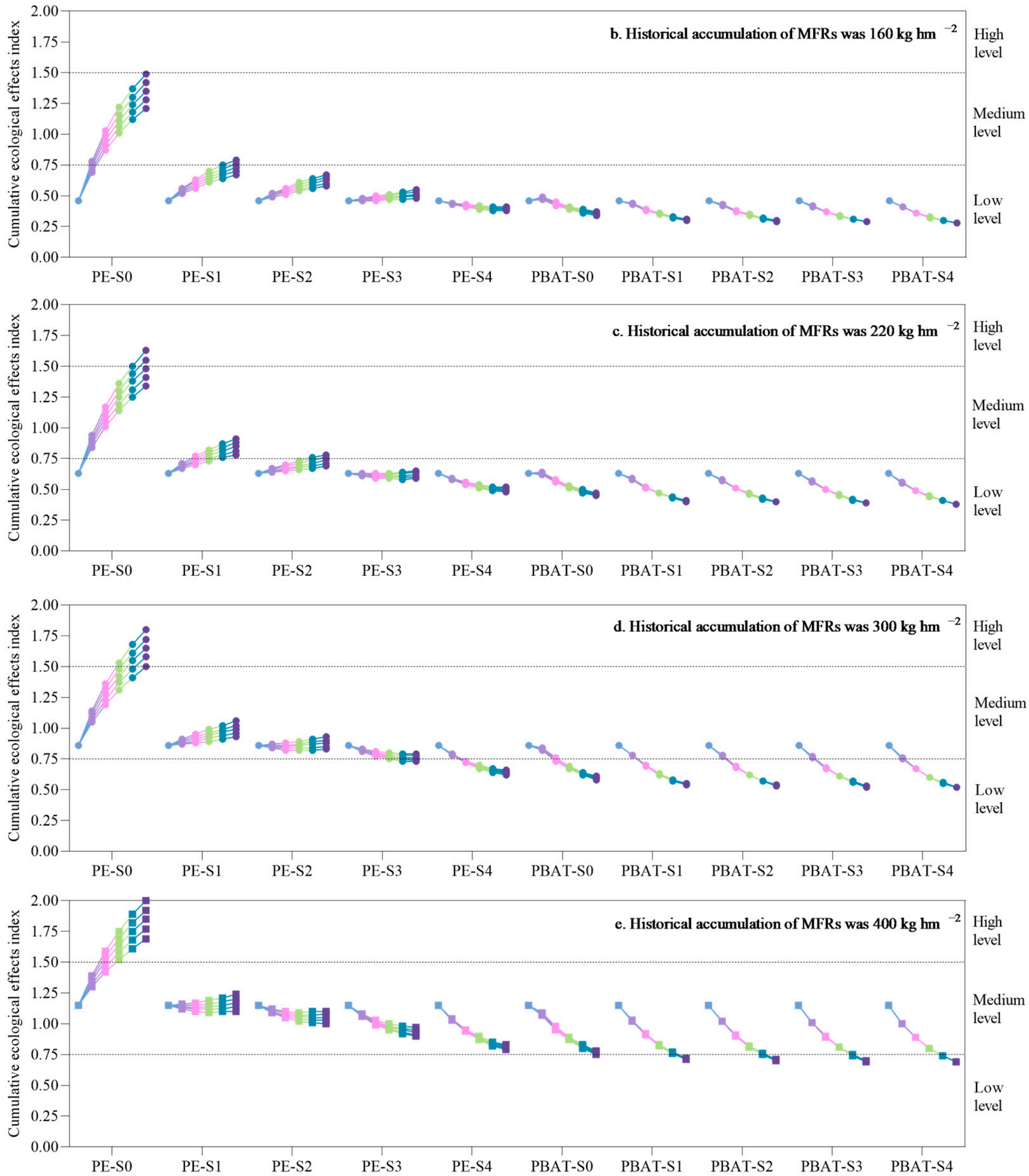
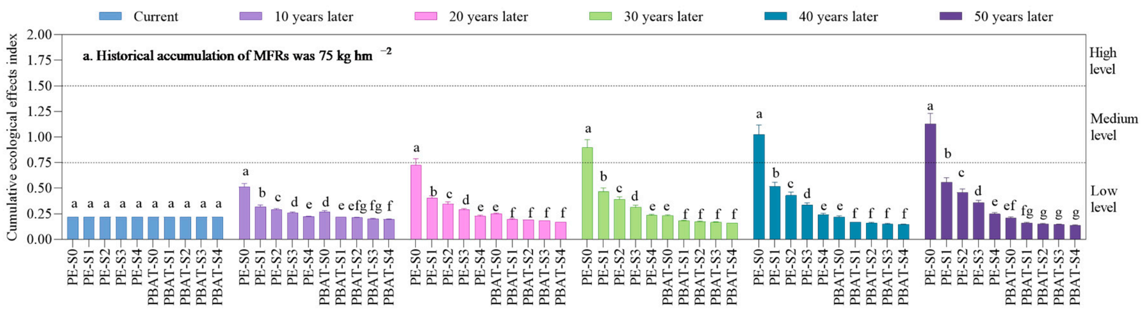


Figure 2. Variation of cumulative ecological effects (CEEs) of mulching film residues in the next 50 years. (**a**–**e**) Variation of CEEs index under historical conditions of 75 kg hm^{-2}, 160 kg hm^{-2}, 220 kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2}.



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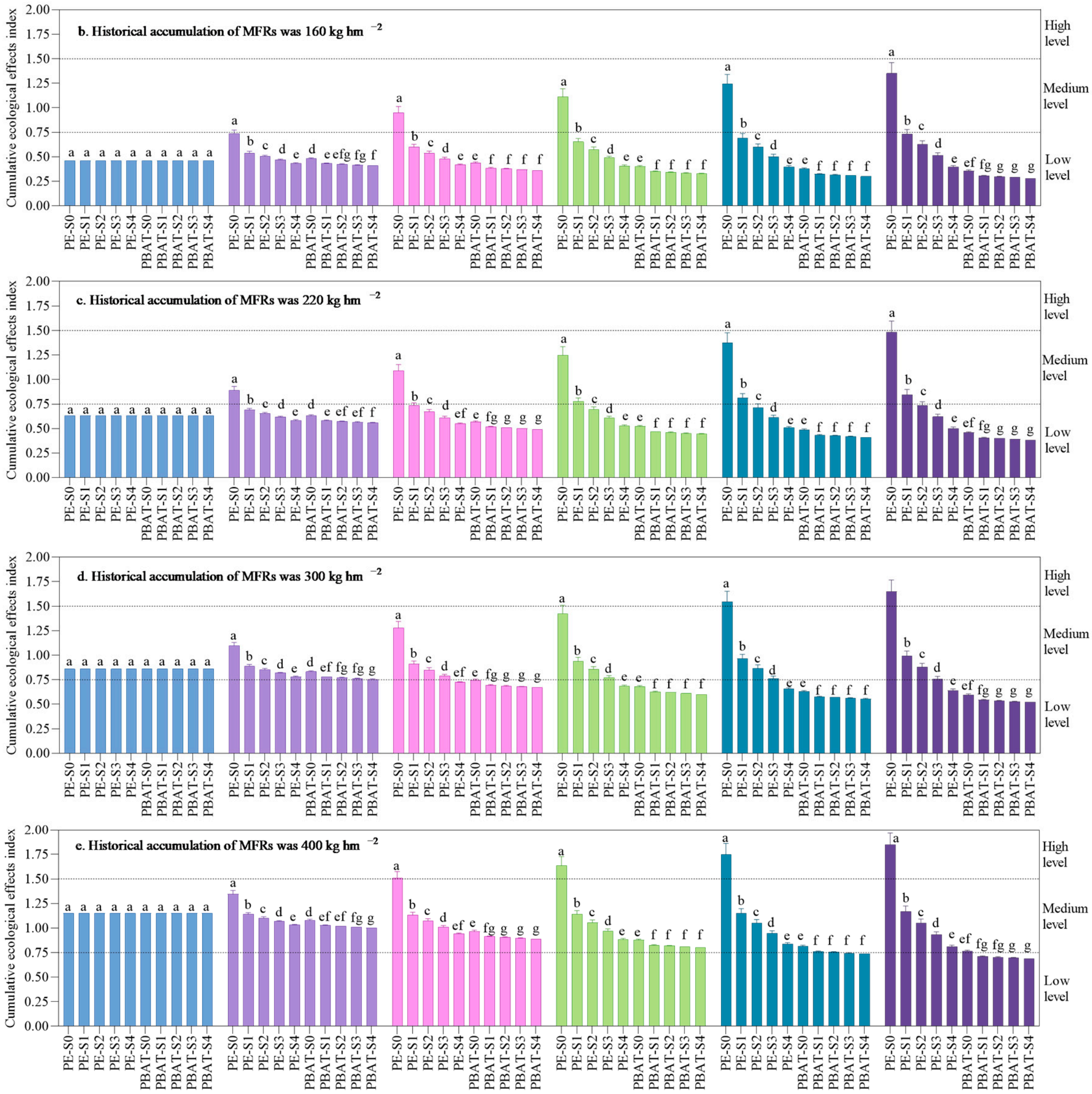


Figure 3. Differences in cumulative ecological effects (CEEs) of mulching film residues among different strategies in the next 10, 20, 30, 40, and 50 years. (**a**–**e**) Differences in CEEs index among different strategies under historical conditions of 75 kg hm^{-2}, 160 kg hm^{-2}, 220 kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2}. Bars with different lowercase letters indicate significant differences among the strategies, $p < 0.05$.

3.2.2. Direct Ecological Effects of Mulching Film Residues

The analysis of direct ecological effects (I_{de}) revealed significant differences across strategies. In HC1, the initial I_{de} value of 0.12 increased by 565%, 177%, 114%, and 51% under PE-S0, PE-S1, PE-S2, and PE-S3, respectively. In PBAT-S0, PBAT-S1, PBAT-S2, and PBAT-S3 scenarios, I_{de} initially increased and then declined, while it showed a consistent decrease under PE-S4 and PBAT-S4, reaching reductions of 23%, 24%, 55%, 61%, 66%, and 71% in year 50 (Figure 4a). In HC2, PE-S0, PE-S1, and PE-S2 strategies led to increases in I_{de}, rising to 0.70 and 0.31 by year 50. Under PE-S3, PE-S4, PBAT-S0, PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4, I_{de} decreased, reaching 0.21, 0.13, 0.12, 0.08, 0.08, 0.07, and 0.07, respectively (Figure 4b). In HC3, I_{de} increased under PE-S0 and PE-S1, reaching 0.83 and 0.38 from 0.34. In other strategies, I_{de} decreased to values of 0.33 (PE-S2), 0.26 (PE-S3), 0.19 (PE-S4), 0.17 (PBAT-S0), 0.14 (PBAT-S1), 0.13 (PBAT-S2), 0.12 (PBAT-S3), and 0.12 (PBAT-S4) by the 50th year (Figure 4c). In HC4 and HC5, I_{de} showed a similar pattern. Under PE-S0, I_{de} rose significantly, reaching 0.86 and 0.89 by the 50th year, increasing from 0.46 in HC4 and 0.62 in HC5. In HC4, reductions under all strategies except PE-S0 ranged from 13% to 75%, while in HC5, reductions were between 28% and 75% across different strategies (Figure 4d,e). In all historical conditions, PE-S0 resulted in an increase in direct ecological effects, while PBAT-S2, PBAT-S3, and PBAT-S4 showed consistent reductions over 50 years.

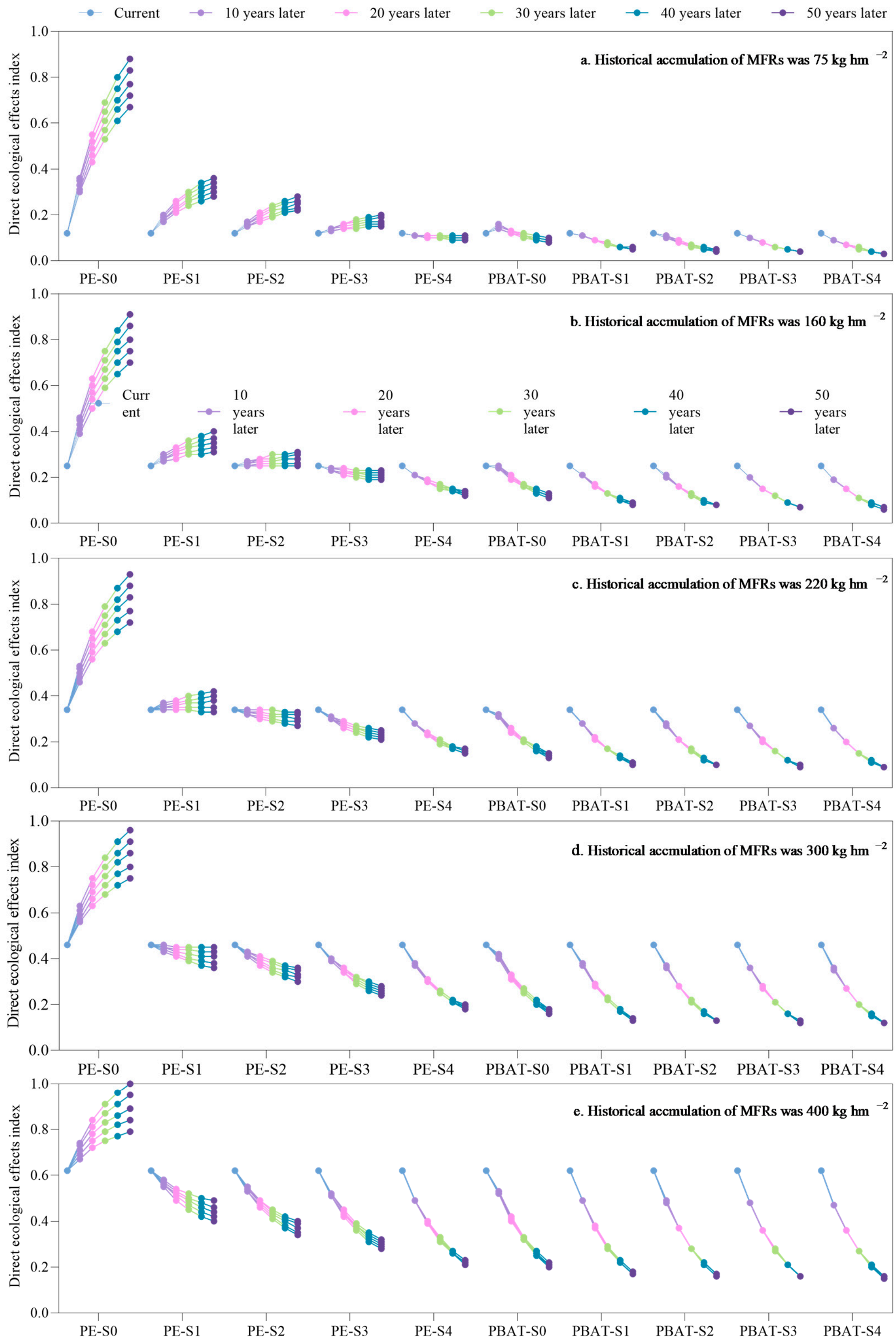
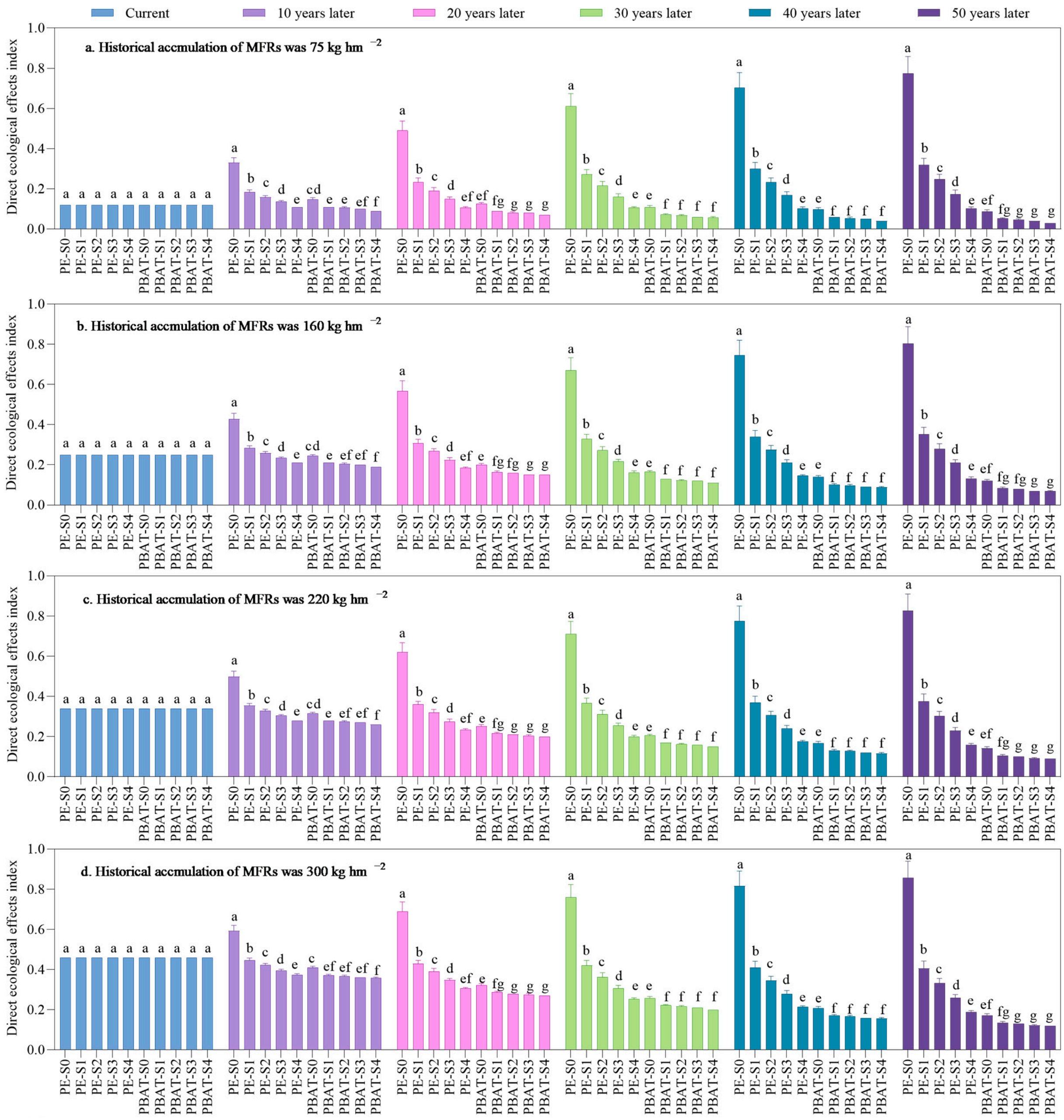


Figure 4. Variation of direct ecological effects index of mulching film residues over the next 50 years. (**a**–**e**) Variation trends of direct ecological effects index with historical value of 75 kg hm^{-2}, 160 kg hm^{-2}, 220 kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2}.

According to the significance analysis, the significant differences in I_{de} were PE-S1 > PE-S2 > PE-S3 > PE-S4 ($p < 0.05$), and the I_{de} in PE-S0 was significantly higher ($p < 0.05$) than them over the next 50 years under all historical conditions. I_{de} in PBAT-S0 was higher ($p < 0.05$) than PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4 ($p > 0.05$) over the next 50 years. Moreover, I_{de} in PE-S0 and PES-1 were significantly higher than in all PBAT strategies over the next 50 years ($p < 0.05$). There was no significance between PE-S2, PE-S3, and PBAT-S0 in HC1, HC2, and HC3, and no significance between PE-S2 and PBAT-S0 in HC4 and HC5 in the next 10 years ($p > 0.05$). In the 20th, 30th, 40th, and 50th years, PE-S4 had no significance with PBAT-S0 ($p > 0.05$) in all historical conditions (Figure 5). Above all, the direct effects of MFRs consistently and significantly increased under PE-S0 strategies in all historical conditions over the next 50 years. The effect of PE-S4 on inhibiting the direct effects of MFRs increasing was better than PBAT-S0 in the next 10 years, and they had no significance over the next 20 to 50 years.



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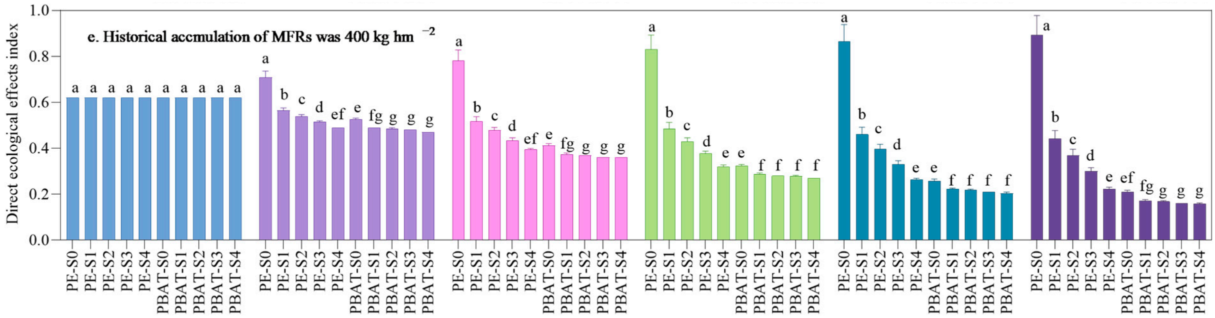


Figure 5. Differences in direct ecological effects index of mulching film residues between different strategies in the next 10, 20, 30, 40 and 50 years. (**a**–**e**) Differences in direct ecological effects index with historical value of 75 kg hm^{-2}, 160 kg hm^{-2}, 220kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2}. Bars with different lowercase letters indicate significant differences among the strategies, $p < 0.05$.

3.2.3. Indirect Ecological Effects of Mulching Film Residues

Trends of indirect ecological effects (I_{ie}) differed from I_{de}, as I_{ie} did not generally decrease across strategies. In HC1, I_{ie}, initially valued at 0.10, increased under all scenarios, with the most substantial rise in using PE film without recovery. By the 50th year, I_{ie} had increased by 260% (PE-S0), 139% (PE-S1), 113% (PE-S2), 83% (PE-S3), and 48% (PE-S4), while PBAT-S0, PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4 resulted in smaller increases of 23%, 10%, 8%, 5%, and 3%, respectively (Figure 6a). In HC2, I_{ie} increased by 5% (PBAT-S1), 3% (PBAT-S2), 2% (PBAT-S3), and 1% (PBAT-S4), respectively. More significant increases were observed under PE-S0 (157%), PE-S1 (79%), PE-S2 (63%), PE-S3 (45%), PE-S4 (25%), and PBAT-S4 (12%) (Figure 6b). In HC3, I_{ie} stabilized at 0.29 under PBAT-S4, with minor increases under PBAT-S0, PBAT-S1, PBAT-S2, and PBAT-S3 strategies. In PE film strategies, I_{ie} increased notably, with values rising by 126%, 62%, 49%, 34%, and 18% (Figure 6c). In HC4, increases of I_{ie} ranged from 100% to 14% under PE-S0 to PE-S4 strategies, while I_{ie} rose by 6% (PBAT-S0), 3% (PBAT-S1), and 2% (PBAT-S2), remaining steady at 0.40 under PBAT-S3 and PBAT-S4 strategies (Figure 6d). In HC5, I_{ie} reached 0.98 from 0.53 under PE-S0, and rose by 37%, 29%, 20%, and 1% across PE film strategies, with PBAT-S0 and PBAT-S1 showing a 5% increase and 2% increase, and other PBAT strategies showing no change, stabilizing at 0.53 (Figure 6e). In conclusion, PBAT film use was more effective than PE film in controlling indirect ecological effects, with higher recycling rates further enhancing its efficacy, However, none of these strategies could reduce the indirect ecological effects.

The significant differences in I_{ie} showed PE-S1 > PE-S2 > PE-S3 > PE-S4 ($p < 0.05$), and the I_{de} in PE-S0 was significantly higher ($p < 0.05$) than them over the next 50 years under all historical conditions. I_{de} in PBAT-S0 was higher ($p < 0.05$) than PBAT-S1, PBAT-S2, PBAT-S3, and PBAT-S4 ($p > 0.05$) in HC1, HC2, and HC3 over the next 50 years and HC4, HC5 over the next 30 years. Further, I_{de} in PE-S0, PE-S1, and PE-S2 were significantly higher than in all PBAT strategies over the next 50 years ($p < 0.05$). There was no significance between PE-S3 and PBAT-S0 in HC1 to HC5 in the next 10 years, and no significance between PE-S4 and PBAT-S0 in the next 20 to 50 years ($p > 0.05$) (Figure 7). Above all, indirect effects of MFRs increased under all strategies in all historical conditions over the next 50 years. The increase in indirect effects under PE strategies was more significant than under PBAT strategies. The effect of PE-S4 on inhibiting the indirect effects of MFRs increasing was better than PBAT-S0 in the next 10 years, and they had no significance over the next 20 to 50 years.

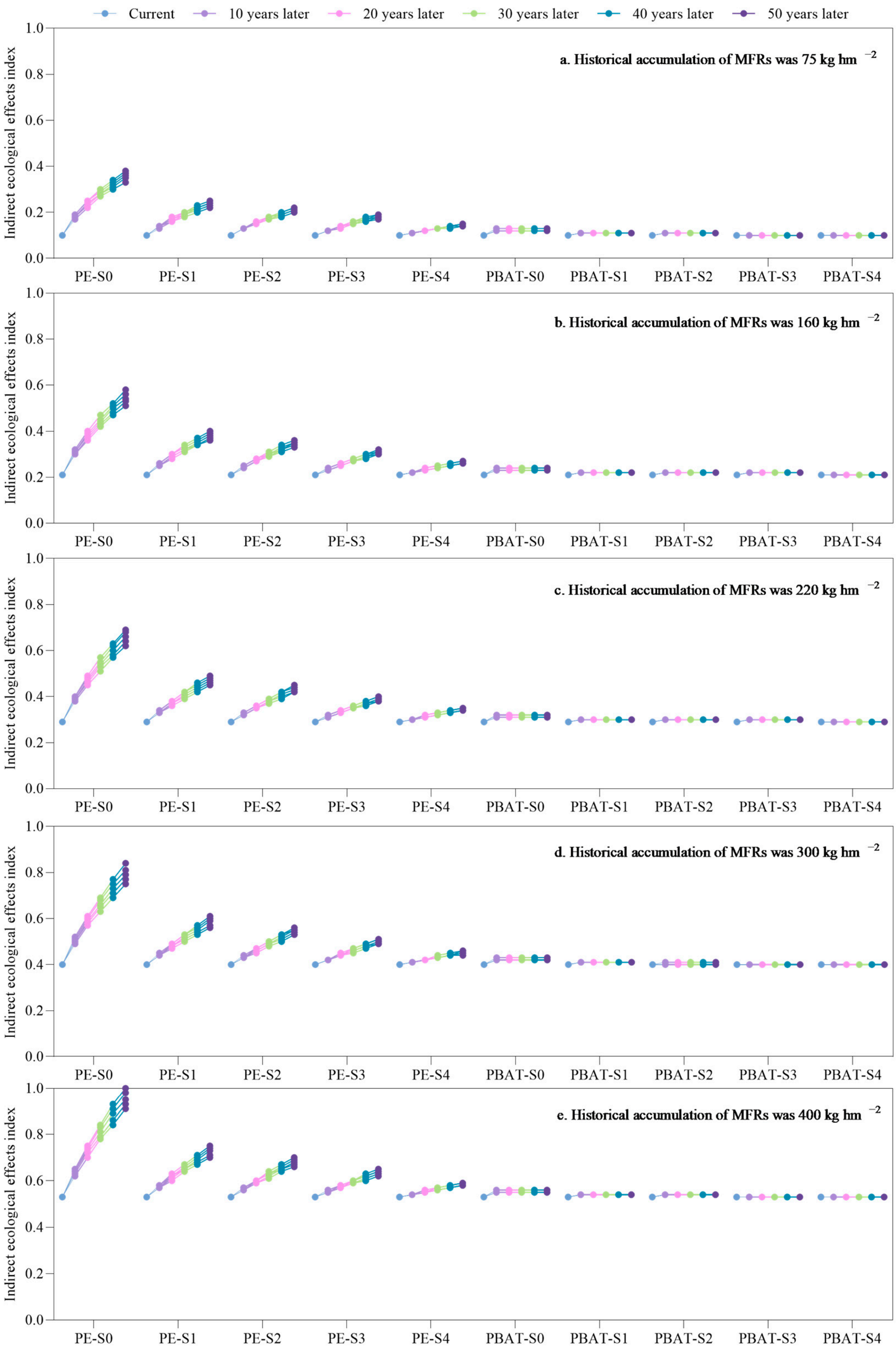


Figure 6. Variation of indirect ecological effects index of mulching film residues over the next 50 years. (**a**–**e**) Variation trends of indirect ecological effects index with historical value of 75 kg hm^{-2}, 160 kg hm^{-2}, 220 kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2}.

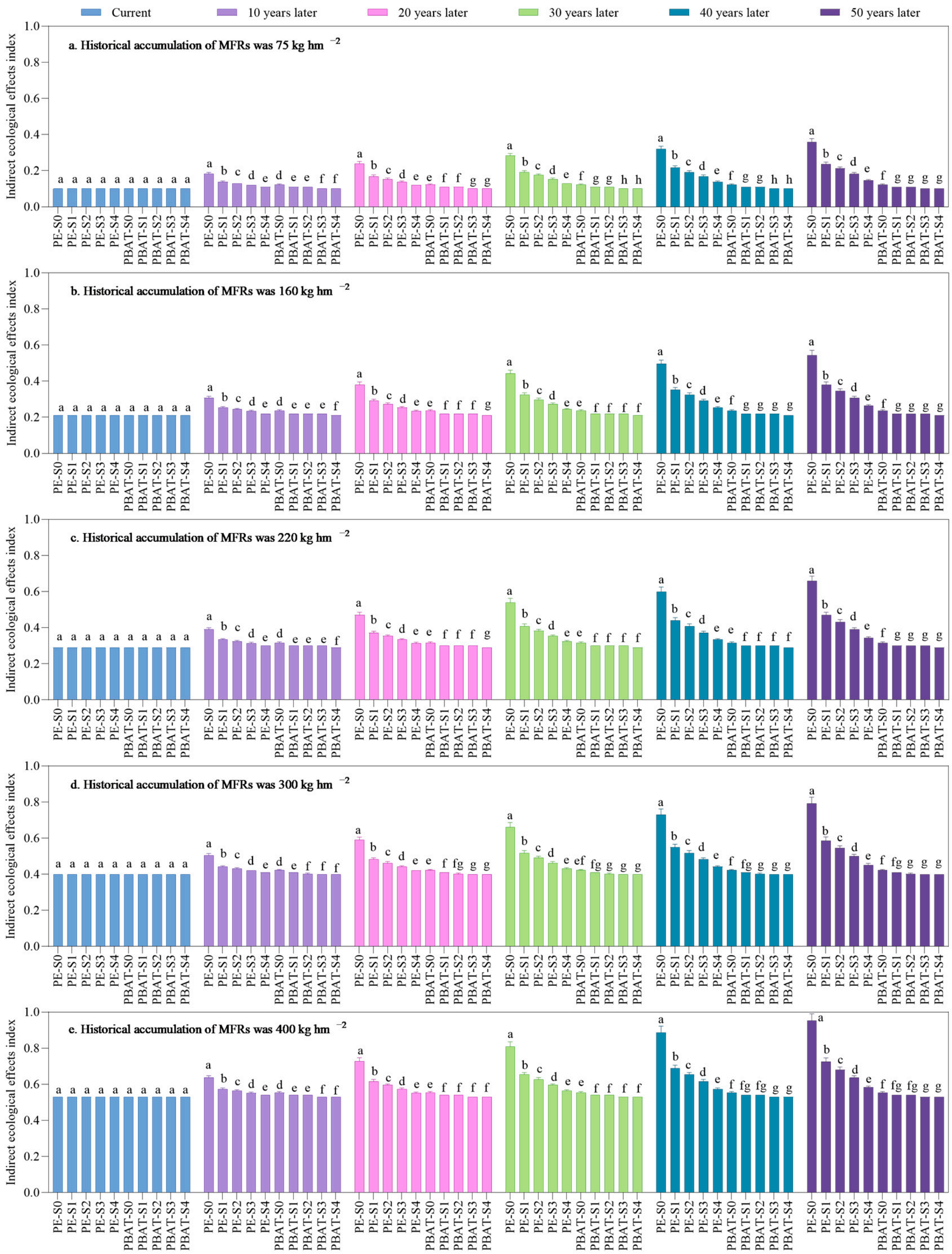


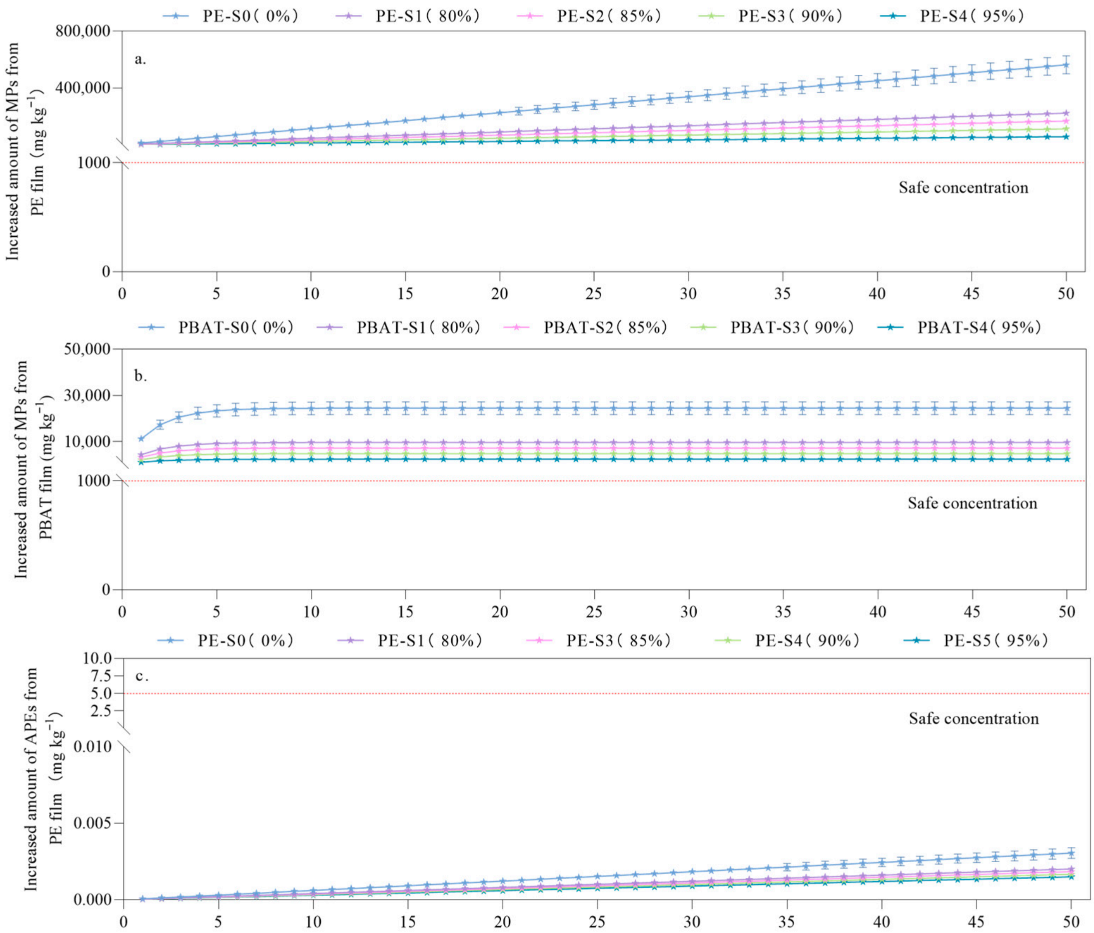
Figure 7. Differences in indirect ecological effects index of mulching film residues among different strategies in the next 10, 20, 30, 40 and 50 years. (**a**–**e**) Differences in indirect ecological effects index with historical value of 75 kg hm^{-2}, 160 kg hm^{-2}, 220 kg hm^{-2}, 300 kg hm^{-2}, and 400 kg hm^{-2}. Bars with different lowercase letters indicate significant differences among the strategies, $p < 0.05$.

4. Discussion

4.1. Effectiveness of Strategies on Mitigating Mulching Film Residues Pollution

The results indicated that both increasing the recycling rate of PE film and utilizing PBAT film effectively curbed MFRs accumulation over the next 50 years, with higher recycling rates yielding better results. When the recycling rate exceeded 95%, the increase in PE MFRs remained below 75 kg hm^{-2}, similar to PBAT film usage. Additionally, MFRs accumulation declined across all historical conditions. Conversely, using PE film without recovery resulted in a yearly increase of 17.74 kg hm^{-2} in residual film, aligning with previous studies [52,53]. However, the total increase in MFRs over the next 50 years would reach 480 kg hm^{-2} without recovery, mainly due to the natural degradation rate of PE film (2.8%) considered in the calculation [30]. That was why total MFRs accumulation over the next 50 years showed decreasing trends in different historical conditions while the yearly increase in MFRs continued.

Moreover, PBAT film appeared to be more effective than higher PE recovery rates both in reducing MFRs accumulation and in the release of MPs and PAEs. As shown in Figure 1a, only when the PE recovery rate exceeded 95% did the MFRs increase amount remain below 75 kg hm^{-2}, while the increase amounts were below this threshold under all PBAT strategies (Figure 1b). Notably, MPs released from PE residues reached as high as 561.9 g kg^{-1} without recovery, whereas PE film with a 95% recovery rate releases 55.4 g kg^{-1} MPs. In contrast, PBAT MPs amount to 24.5 g kg^{-1} without recovery, less than half of released amount of PE MPs at a 95% recycling rate (Figure 8a,b). PAEs released from PBAT residues exceeded those from PE residues but remained within safe concentrations (Figure 8c,d). This aligned with recommendations by numerous countries and organizations advocating biodegradable film adoption [29,40]. This is contingent on PBAT's economic feasibility for farmers. Alternatively, achieving a 95% recycling rate for PE film could effectively keep MFRs levels near threshold in arid areas over the next 50 years.



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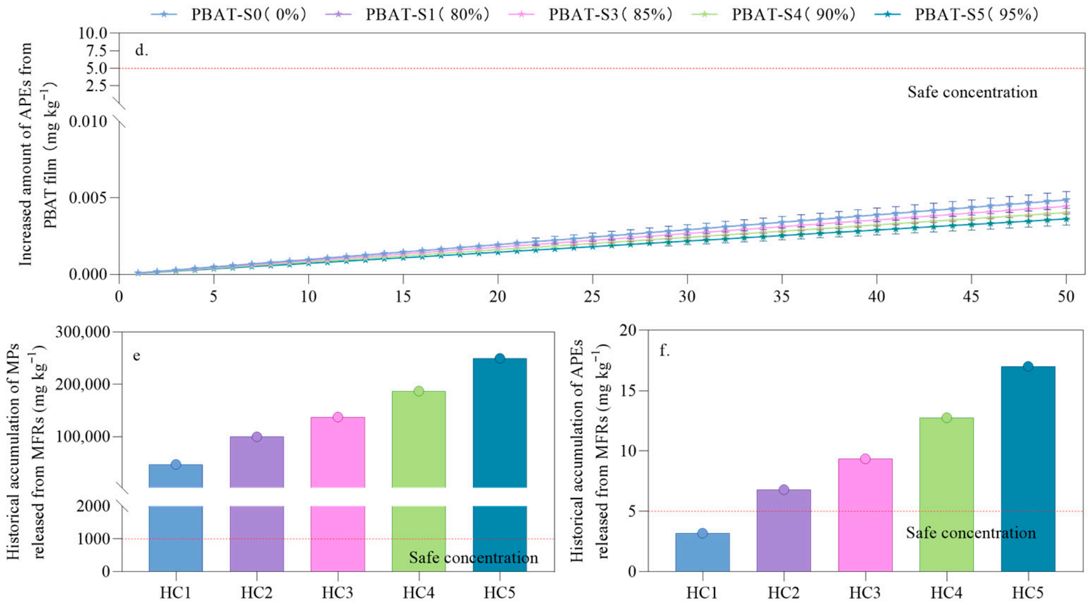

Figure 8. Increased amount of microplastics (MPs) and phthalate esters (PAEs) over the next 50 years. (**a**,**b**) Accumulation of MPs released from PE and PBAT film residues. (**c**,**d**) Accumulation of PAEs released from PE and PBAT film residues. (**e**,**f**) Historical accumulation of MPs and PAEs.

4.2. Indirect Ecological Effects Require More Attention than Direct Effects in the Future

MFRs negatively impact soil health, leading to degradation of soil properties and increased risks. The results suggest that increasing the recycling rate of PE film and utilizing PBAT film measures can alleviate soil property degradation caused by MFRs. Nonetheless, MPs and PAEs pollution from MFRs would increase, either under the strategies of higher PE recycling rates or under using PBAT film strategies. Although MPs concentrations were remarkably out of safe levels when using PBAT, they were notably lower than those from PE film. However, studies by Uzamurera et al. and Zhou et al. suggested that MPs released from biodegradable films may actually exceed those from PE films [54,55]. This discrepancy may stem from differences in calculation methods and parameters. Given this, MPs from PBAT films may be underestimated, warranting further attention in research and production [33]. Unlike MPs, the increase in PAEs from residual films over the next 50 years is much lower and within safe levels across all scenarios (Figure 8c,d). Nevertheless, historical accumulations have already exceeded safe limits, except in HC1, posing persistent risks to the soil environment (Figure 8e,f) [28,41].

Additionally, many studies have shown that micro/nanoplastics can be absorbed and transported to other organs and even edible parts of plants through transpiration [22,24,56]. Furthermore, the "plastisphere" formed by MPs may combine with organic pollutants and heavy metals, thereby contaminating the food chain [20,22,56,57]. This process poses potential risks to crop quality, with possible bioaccumulation in humans and animals [28,58,59]. PAEs also accumulate in crops, with potential transfer along the food chain [41,59]. These results corroborate findings that MFRs would lead to long-term environment hazards, meaning that the indirect ecological effects require more attention in the future [7,32,55].

4.3. Uncertainties and Limitations

In order to simulate the variation in the accumulation of MFRs and assess the ecological effects of MFRs over the next 50 years under different management strategies, this study used a simple and direct method to calculate the accumulation of MFRs [60]. However, there are some uncertainties in the parameters. The parameter F_r includes current and ideal values. The current value of F_r referred to "Manual for Mulching Film Residue Coefficient", which was obtained through field sampling by the Compilation Committee of the First National Pollution Source Census [35], and it was considered to be reliable. However, the ideal values of F_r (20%, 15%, 10%, and 5%) are the values that managers and farmers are trying to achieve through various measures aiming to reduce residual film pollution in farmland and promote the agriculture sustainability [30]. Another uncertain parameter is F_m, which is mainly due to the quality of film from different producers, and related to the subjectivity of farmers in its usage. We used the commonly used amounts of 60 kg hm^{-2}, 65 kg hm^{-2}, 70 kg hm^{-2}, 75 kg hm^{-2}, and 80 kg hm^{-2} as replications in order to make the results more reliable [10,31,32]. In addition, the degradation rates of PE and PBAT film residue were considered in the calculation of MFRs accumulation, and the d_r used referred to the ideal value in the standard manual [36,37], while the real d_r may differ in different regions and environments [54,61,62]. Those uncertainties should be analyzed and assessed to determine how they influence the results in the future [7,55]. Further, the estimation model calculating the amount of MFRs could be optimized by optimizing these parameters.

A comprehensive assessment of MFRs impacts can help inform policy decisions and management strategies. This study developed an evaluation index system for CEEs of MFRs to assess the impacts of MFRs on farmland ecosystems [9]. Key indicators included changes in soil water evaporation, water infiltration, organic matter content, effective phosphorus content, and crop yield reduction rates to represent direct ecological effects [8,9,18,19,21], while MPs and PAEs accumulations were used to reflect indirect ecological effects [9,28,40]. This dual-index approach enhances assessment accuracy. However, there are limitations in evaluating the CEEs of MFRs. First, soil biology and enzyme activities, significant ecological factors influenced by MFRs, were not included, mainly because of divergences among different research results [59,60,63]. Secondly, the indirect effects of MFRs are supposed to encompass MPs generated during MFRs degradation and the "plastisphere effect" due to the release or adsorption of organic matter and heavy metals [64–66]. Although there has been a lot of laboratory research conducted in these fields, those conclusions are significantly different, and it is difficult to unify and include them in this comprehensive evaluation [28,59,65]. As a result, this study comprises a tentative exploration of the comprehensive assessment of indirect effects of MFRs, primarily focused on MPs and PAEs accumulation, without accounting for other potential risks. In the future, more research should be conducted to refine the evaluation system of the cumulative ecological effects of MFRs [9]. Specifically, the effects of different plastic fragments on soil biology and enzyme activity warrant further investigation, as does the exploration of the "plastisphere effects" in agricultural systems [27,39,66].

5. Conclusions

This study analyzed the impact of different strategies on MFR pollution by estimating the accumulation and assessing cumulative ecological effects of MFRs over the next 50 years. Results indicated that the increasing amount of MFRs would be 480 kg hm^{-2} without any recovery of PE film, and it would be 190 kg hm^{-2}, 142 kg hm^{-2}, 95 kg hm^{-2}, and 47 kg hm^{-2} with PE film recovery rates of 80%, 85%, 90%, and 95% over the next 50 years. In contrast, the increase in MFRs would be 39 kg hm^{-2} at most when using PBAT film. The 95% recovery rate of PE film strategy and using PBAT film strategies could work well in reducing MFRs in soil in all historical conditions. Under the strategy of using PE film without recovery, the CEEs would intensify significantly. In comparison, increasing PE recovery rates and using PBAT film could curb these impacts over the next 50 years. Notably, under historical conditions of 75 kg hm^{-2} and 160 kg hm^{-2}, CEEs remained low, while at 220 kg hm^{-2}, CEEs decreased from medium to low levels. Under 300 kg hm^{-2} and 400 kg hm^{-2} conditions, CEEs stabilized at medium levels, avoiding escalation to high levels. Specifically, the CEEs of MFRs could maintain the current status or decrease under the strategy of 95% recovery rate of PE film and using PBAT film, similar to the variation of direct effects. With the increase in accumulated MFRs, the indirect effects of MFRs increase; however, the indirect effects would not decrease with a reduction in MFRs accumulation due to ongoing microplastics' and phthalate esters' release from residual films. In conclusion, a 95% recovery rate of PE film and the use of PBAT films are most effective in mitigating plastic pollution in arid areas. Furthermore, the indirect ecological effects of MFRs cannot be neglected in the future as they pose a potential threat to crops, animals, and human beings. These results could provide a theoretical support for agricultural sustainable development in arid regions.

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Abbreviations

MFRs	mulching film residues;
CEEs	cumulative ecological effects.

References

1. Sun, D.B.; Li, H.G.; Wang, E.L.; He, W.Q.; Hao, W.P.; Yan, C.R.; Li, Y.Z.; Mei, X.R.; Zhang, Y.Q.; Sun, Z.X.; 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]
2. Hu, Q.; Li, X.Y.; Goncalves, J.M.; Shi, H.B.; Tian, T.; Chen, N. Effects of residual plastic-film mulch on field corn growth and productivity. *Sci. Total Environ.* **2020**, *729*, 138901. [CrossRef] [PubMed]
3. Mansoor, Z.; Tchuenbou-Magaia, F.; Kowalczuk, M.; Adamus, G.; Manning, G.; Parati, M.; Radecka, I.; Khan, H. Polymers Use as Mulch Films in Agriculture—A Review of History, Problems and Current Trends. *Polymers* **2022**, *14*, 5062. [CrossRef] [PubMed]
4. Hu, C.; Wang, X.F.; Chen, X.G.; Tang, X.Y.; Zhao, Y.; Yan, C.R. Current situation and control strategies of residual film pollution in Xinjiang. *Trans. CSAE* **2019**, *35*, 223–234. (In Chinese) [CrossRef]
5. Li, S.T.; Ding, F.; Flury, M.; Wang, Z.; Xu, L.; Li, S.Y.; Jones, D.L.; Wang, J.K. Macro- and microplastic accumulation in soil after 32 years of plastic film mulching. *Environ. Pollut.* **2022**, *300*, 118945. [CrossRef]
6. Cao, J.H.; Gao, X.D.; Cheng, Z.; Song, X.L.; Cai, Y.H.; Siddique, K.H.M.; Zhao, X.N.; Li, C.J. The harm of residual plastic film and its accumulation driving factors in northwest China. *Environ. Pollut.* **2023**, *318*, 120910. [CrossRef]
7. Steinmetz, Z.; Wollmann, C.; Schaefer, M.; Buchmann, C.; David, J.; Troeger, J.; Munoz, K.; Fror, O.; Schaumann, G.E. Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation. *Sci. Total Environ.* **2016**, *50*, 690–705. [CrossRef]
8. Koskei, K.; Munyasya, A.N.; Wang, Y.B.; Zhao, Z.Y.; Zhou, R.; Indoshi, S.N.; Wang, W.; Cheruiyot, W.K.; Mburu, D.M.; Nyende, A.B.; et al. Effects of increased plastic film residues on soil properties and crop productivity in agro-ecosystem. *J. Hazard. Mater.* **2021**, *414*, 125521. [CrossRef]
9. Zhang, M.; Liu, J.T.; Fu, T.G.; Gao, H. Review on cumulative ecological effects of mulching film residues in farmland. *Asian J. Ecotoxicol.* **2023**, *18*, 223–237. (In Chinese) [CrossRef]
10. Yan, C.R.; Liu, E.K.; Shu, F.; Liu, Q.; Liu, S.; He, W.Q. Review of agricultural plastic mulching and its residual pollution and prevention measures in China. *J. Agric. Resour. Environ.* **2014**, *31*, 95–102. (In Chinese)
11. Bao, M.Z.; Hong, M.; Zhao, B.Y.N.M.L.; Xing, A.; Ye, H.; Shen, Q.G.; Wang, L.Q. Distribution characteristics and influencing factors concerning residual quantity of agricultural mulch film in Hetao irrigation area, Inner Mongolia. *J. Agric. Resour. Environ.* **2023**, *40*, 45–54. (In Chinese) [CrossRef]
12. Zhang, D.; Liu, H.B.; Hu, W.L.; Qin, X.H.; Ma, X.W.; Yan, C.R.; Wang, H.Y. The status and distribution characteristics of residual mulching film in Xinjiang, China. *J. Integr. Agric.* **2016**, *15*, 2639–2646. [CrossRef]

13. Brodhagen, M.; Goldberger, J.R.; Hayes, D.G.; Inglis, D.A.; Marsh, T.L.; Miles, C. Policy considerations for limiting unintended residual plastic in agricultural soils. *Environ. Sci. Policy* **2017**, *69*, 81–84. [CrossRef]
14. Ren, S.Y.; Wang, K.; Zhang, J.R.; Li, J.J.; Zhang, H.Y.; Qi, R.M.; Xu, W.; Yan, H.R.; Liu, X.J.; Zhang, F.S.; et al. Potential sources and occurrence of macro-plastics and microplastics pollution in farmland soils: A typical case of China. *Crit. Rev. Environ. Sci. Tec.* **2023**, *54*, 533–556. [CrossRef]
15. Qi, Y.L.; Beriot, N.; Gort, G.; Lwanga, E.H.; Gooren, H.; Yang, X.M.; Geissen, V. Impact of plastic mulch film debris on soil physicochemical and hydrological properties. *Environ. Pollut.* **2020**, *266*, 115097. [CrossRef]
16. Wen, Y.; Li, H.Q.; Li, W.H.; Gu, Z.D.; Wang, Z.H. Responses of infiltration and evaporation to amounts and distribution characteristics of the residual plastic films within agricultural soil. *Irrig. Sci.* **2022**, *40*, 309–320. [CrossRef]
17. Li, Z.R.; Ma, J.J.; Sun, X.H.; Guo, X.H.; Zheng, L.J.; Chen, J.P. Plastic pollution in soil and crops: Effects of film residuals on soil water content and tomato physiology. *Agronomy* **2022**, *12*, 1222. [CrossRef]
18. Zhang, D.; Ng, E.L.; Hu, W.L.; Wang, H.Y.; Galaviz, P.; Yang, H.D.; Sun, W.; Li, C.; Ma, X.; Fu, B.; et al. Plastic pollution in croplands threatens long-term food security. *Glob. Chang. Biol.* **2020**, *26*, 3356–3367. [CrossRef]
19. Gao, H.H.; Liu, Q.; Yan, C.R.; Mancl, K.; Gong, D.Z.; He, J.X.; Mei, X.R. Macro-and/or microplastics as an emerging threat effect crop growth and soil health. *Resour. Conserv. Recycl.* **2022**, *186*, 106549. [CrossRef]
20. Khalid, N.; Aqeel, M.; Noman, A.; Rizvi, Z.F. Impact of plastic mulching as a major source of microplastics in agroecosystems. *J. Hazard. Mater.* **2023**, *445*, 130455. [CrossRef]
21. Zhang, Q.Q.; Ma, Z.R.; Cai, Y.Y.; Li, H.R.; Ying, G.G. Agricultural plastic pollution in China: Generation of plastic debris and emission of phthalic acid esters from agricultural films. *Environ. Sci. Technol.* **2021**, *55*, 12459–12470. [CrossRef] [PubMed]
22. Azeem, I.; Adeel, M.; Ahmad, M.A.; Shakoor, N.; Jiangcuo, G.D.; Azeem, K.; Ishfaq, M.; Shakoor, A.; Ayaz, M.; Xu, M.; et al. Uptake and accumulation of nano/microplastics in plants: A critical review. *Nanomaterials* **2021**, *11*, 2935. [CrossRef]
23. Jia, L.; Liu, L.N.; Zhang, Y.J.; Fu, W.X.; Liu, X.; Wang, Q.Q.; Tanveer, M.; Huang, L.P. Microplastic stress in plants: Effects on plant growth and their remediations. *Front. Plant Sci.* **2023**, *14*, 1226484. [CrossRef] [PubMed]
24. Li, L.Z.; Luo, Y.M.; Li, R.J.; Zhou, Q.; Peijnenburg, W.J.G.M.; Yin, N.; Yang, J.; Tu, C.; Zhang, Y.C. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. *Nat. Sustain.* **2020**, *3*, 929–937. [CrossRef]
25. Hu, X.J.; Yu, Q.; Waigi, M.G.; Ling, W.T.; Qin, C.; Wang, J.; Gao, Y.Z. Microplastics-sorbed phenanthrene and its derivatives are highly bioaccessible and may induce human cancer risks. *Environ. Int.* **2022**, *168*, 107459. [CrossRef]
26. Winiarska, E.; Jutel, M.; Zemelka-Wiacek, M. The potential impact of nano- and microplastics on human health: Understanding human health risks. *Environ. Res.* **2024**, *251*, 118535. [CrossRef]
27. Hahladakis, J.N.; Velis, C.A.; Weber, R.; Iacovidou, E.; Purnell, P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J. Hazard. Mater.* **2018**, *344*, 179–199. [CrossRef]
28. Luo, Y.M.; Zhou, Q.; Zhang, H.B.; Pan, X.L.; Tu, C.; Li, L.Z.; Yang, J. Pay attention to research on microplastic pollution in soil for prevention of ecological and food chain risks. *Bull. Chin. Acad. Sci.* **2018**, *33*, 1021–1030. (In Chinese) [CrossRef]
29. Food and Agriculture Organization of the United Nations(FAO). *Assessment of Agricultural Plastics and Their Sustainability: A Call for Action*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2021; pp. 16–28.
30. Ministry of Agriculture and Rural Affairs of the People's Republic of China. Agricultural Film Recycling Action Plan. 2017. Available online: http://www.moa.gov.cn/nybgb/2017/dlq/201712/t20171231_6133712.htm (accessed on 20 June 2017).
31. Jin, A.N.; Yu, F.X.; Wang, Y.L.; Du, T.; He, J. Degradation characteristics of PBAT fully Biodegradable mulch film. *Environ. Sci.* **2024**. (In Chinese) [CrossRef]
32. Xin, X.W.; Chen, C.; Wu, W.Q.; Chen, Q.; Li, C.T. Ecological effects of PLA and PBAT biodegradable microplastics on soil-plant systems. *J. Agro-Environ. Sci.* 2024. Available online: https://link.cnki.net/urlid/12.1347.S.20240621.1643.006 (accessed on 27 September 2024) . (In Chinese).
33. Hadaly, S.R.; Lluis, M.C.; Ana, M.P. Biodegradable plastic mulches: Impact on the agricultural biotic environment. *Sci. Total Environ.* **2021**, *750*, 141228. [CrossRef]
34. Madrid, B.; Wortman, S.; Hayes, D.G.; DeBruyn, J.M.; Miles, C.; Flury, M.; Marsh, T.L.; Galinato, S.P.; Englund, K.; Agehara, S.; et al. End-of-life management options for agricultural mulch films in the United States—A Review. *Front. Sustain. Food Syst.* **2022**, *6*, 921496. [CrossRef]
35. Compilation Committee of the First National Pollution Source Census. *Manual for Mulching Film Residue Coefficient in Handbook of Pollution Production and Discharge Coefficient in Pollution Sources Census*; China Environmental Science Press: Beijing, China, 2011. (In Chinese)
36. *GB 13735-2017*; Polythylene Blown Mulch Film for Agricultural Uses. Standards Press of China: Beijing, China, 2017. Available online: https://std.samr.gov.cn/gb/search/gbDetailed?id=71F772D82020D3A7E05397BE0A0AB82A (accessed on 27 September 2024).
37. *GB/T35795-2017*; Biobased Degradable Materials and Products, Biodegradable Mulching Film for Agricultural Uses. Standards Press of China: Beijing, China, 2017.
38. Sander, M. Biodegradation of polymeric mulch films in agricultural soils: Concepts, knowledge gaps, and future research directions. *Environ. Sci. Technol.* **2019**, *53*, 2304–2315. [CrossRef]
39. Chen, L.; Qiu, T.Y.; Huang, F.Y.; Zeng, Y.; Cui, Y.X.; Chen, J.; White, J.C.; Fang, L.C. Micro/nanoplastics pollution poses a potential threat to soil health. *Glob Chang. Biol.* **2024**, *30*, e17470. [CrossRef]

40. Thompson, R.C.; Courtene-Jones, W.; Boucher, J.; Pahl, S.; Raubenheimer, K.; Koelmans, A.A. Twenty years of microplastics pollution research—What have we learned? *Science* **2024**, *386*, 6720. [CrossRef] [PubMed]
41. Li, C.; Chen, J.Y.; Wang, J.H.; Han, P.; Luan, Y.X.; Ma, X.P.; Lu, A.X. Phthalate esters in soil, plastic film, and vegetable from greenhouse vegetable production bases in Beijing, China: Concentrations, sources, and risk assessment. *Sci. Total Environ.* **2016**, *568*, 1037–1043. [CrossRef] [PubMed]
42. Sun, Q.; Zhang, X.X.; Liu, C.R.; Nier, A.; Ying, S.; Zhang, J.X.; Zhao, Y.J.; Zhang, Y.T.; Wang, Z.H.; Shi, M. The content of PAEs in field soils caused by the residual film has a periodical peak. *Sci. Total Environ.* **2023**, *864*, 161078. [CrossRef]
43. Sun, H.Y.; Wei, X.F.; Liu, W.; Li, D.J.; Jia, F.C.; Chen, Z.R.; Sun, X.M. Baseline segmentation evaluation for ecological risk accumulation effect of soil heavy metals based on optimization by GIS overlay model and land use unit. *Acta Geol. Sin.* **2022**, *96*, 1488–1502. [CrossRef]
44. Chen, Y.L.; Liu, X.N.; Leng, Y.F.; Wang, J. Defense responses in earthworms *(Eisenia fetida)* exposed to low-density polyethylene microplastics in soils. *Ecotoxicol. Environ. Saf.* **2020**, *187*, 109788. [CrossRef]
45. New York State Department of Environmental Conservation of USA. *TAGM 4046 Determination of Soil Cleanup Objectives and Cleanup Levels*; New York State Department of Environmental Conservation of USA: New York, NY, USA, 1994.
46. Zhang, J.J.; Li, X.Y.; Peng, Z.Y.; Guo, Y.; Ding, Z.J.; Leng, X. The distribution of soil water, temperature, nitrogen and salinity under biofilm mulching in Hetao sunflower field. *Ecol. Environ. Sci.* **2018**, *27*, 1067–1075. (In Chinese) [CrossRef]
47. Ren, S.Y.; Kong, S.F.; Ni, H.G. Contribution of mulch film to microplastics in agricultural soil and surface water in China. *Environ. Pollut.* **2021**, *291*, 118227. [CrossRef]
48. Ren, S.Y.; Sun, Q.; Ni, H.G.; Wang, J.F. A minimalist approach to quantify emission factor of microplastic by mechanical abrasion. *Chemosphere* **2020**, *245*, 125630. [CrossRef]
49. Ding, W.L.; Liu, Q.; Liu, Q.Y.; Yan, C.R. Characteristics and safety of phthalates (PAEs) for plastic mulch films in China. *J. Agro-Environ. Sci.* **2021**, *40*, 1008–1016. (In Chinese) [CrossRef]
50. Tian, Y. Functional polyolefin agriculture films in China. *China Plast.* **2004**, *18*, 1–8. (In Chinese)
51. Yang, X.J.; Zhou, G.H.; Wang, W.S.; Wang, Z.L. Analysis and research of plasticizer in three typical agricultural films. *China Plast. Ind.* **2020**, *48*, 117–120+138. (In Chinese) [CrossRef]
52. Dong, H.G.; Wang, D.; Wang, Y.T.; Tong, J.; Liu, T. Spatial and temporal distribution characteristics of mulch residues in cotton field in Shihezi, Xinjiang. *J. Arid. Land Resour. Environ.* **2013**, *27*, 182–186. (In Chinese)
53. He, H.J.; Wang, Z.H.; Zheng, X.R.; Zhang, J.Z.; Li, W.H. Distribution of size and quantity of film residuals in cotton fields under film-mulched drip irrigation in oasis region. *J. Irrig. Drain.* **2019**, *38*, 63–69. (In Chinese)
54. 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]
55. Zhou, J.; Jia, R.; Brown, R.W.; Yang, Y.D.; Zeng, Z.H.; Jones, D.L.; Zang, H.D. The long-term uncertainty of biodegradable mulch film residues and associated microplastics pollution on plant-soil health. *J. Hazard. Mater.* **2023**, *442*, 130055. [CrossRef]
56. Conti, G.O.; Ferrante, M.; Banni, M.; Favara, C.; Nicolosi, I.; Cristaldi, A.; Fiore, M.; Zuccarello, P. Micro- and nano-plastics in edible fruit and vegetables. The first diet risks assessment for the general population. *Environ. Res.* **2020**, *187*, 109677. [CrossRef]
57. Yates, J.; Deeney, M.; Rolker, H.B.; White, H.; Kalamatianou, S.; Kadiyala, S. A systematic scoping review of environmental, food security and health impacts of food system plastics. *Nat. Food* **2021**, *2*, 80–87. [CrossRef]
58. Lwanga, E.H.; Vega, J.M.; Quej, V.K.; Chi, J.D.; del Cid, L.S.; Chi, C.; Segura, G.E.; Gertsen, H.; Salanki, T.; van der Ploeg, M.; et al. Field evidence for transfer of plastic debris along a terrestrial food chain. *Sci. Rep.* **2017**, *7*, 2045–2322. [CrossRef]
59. Wu, C.C.; Ma, Y.J.; Wang, D.; Shan, Y.P.; Song, X.P.; Hu, H.Y.; Ren, X.L.; Ma, X.Y.; Luo, J.Y.; Cui, J.J.; et al. Microbiology combined with metabonomics revealing the response of soil microorganisms and their metabolic functions exposed to phthalic acid esters. *Ecotoxicol. Environ. Saf.* **2022**, *233*, 113338. [CrossRef] [PubMed]
60. Wang, J.; Luo, Y.M.; Teng, Y.; Ma, W.T.; Christie, P.; Li, Z.G. Soil contamination by phthalate esters in Chinese intensive vegetable production systems with different modes of use of plastic film. *Environ. Pollut.* **2013**, *180*, 265–273. [CrossRef] [PubMed]
61. Mumtaz, T.; Khan, M.R.; Hassan, M.A. Study of environmental biodegradation of LDPE films in soil using optical and scanning electron microscopy. *Micron* **2010**, *41*, 430–438. [CrossRef]
62. Qin, M.; Chen, C.Y.; Song, B.; Shen, M.C.; Cao, W.C.; Yang, H.L.; Zeng, G.Z.; Gong, J. A review of biodegradable plastics to biodegradable microplastics: Another ecological threat to soil environments? *J. Clean. Prod.* **2021**, *312*, 127816. [CrossRef]
63. Liu, L.Y.; Zou, G.Y.; Zuo, Q.; Li, C.Z.; Gu, J.L.; Kang, L.Y.; Ma, M.T.; Liang, K.Y.; Liu, D.S.; Du, L.F. Soil bacterial community and metabolism showed a more sensitive response to PBAT biodegradable mulch residues than that of LDPE mulch residues. *J. Hazard. Mater.* **2022**, *438*, 129507. [CrossRef]
64. Hu, X.J.; Gu, H.D.; Wang, Y.B.; Liu, J.J.; Yu, Z.H.; Li, Y.S.; Jin, J.; Liu, X.B.; Dai, Q.W.; Wang, G.H. Succession of soil bacterial communities and network patterns in response to conventional and biodegradable microplastics: A microcosmic study in Mollisol. *J. Hazard. Mater.* **2022**, *436*, 129218. [CrossRef]

65. Chang, J.N.; Fang, W.; Liang, J.S.; Zhang, P.Y.; Zhang, G.M.; Zhang, H.B.; Zhang, Y.J.; Wang, Q.Y. A critical review on interaction of microplastics with organic contaminants in soil and their ecological risks on soil organisms. *Chemosphere* **2022**, *306*, 135573. [CrossRef]
66. Bhagat, J.; Nishimura, N.; Shimada, Y. Toxicological interactions of microplastics/Nanoplastics and environmental contaminants: Current knowledge and future perspectives. *J. Hazard. Mater.* **2021**, *405*, 123913. [CrossRef]