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Dual role of agricultural plastic in China's food security and green transition: policy progress and prospects

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KEYWORDS

Agricultural plastic, sustainable management, food security, green transition, policy recommendations

HIGHLIGHTS

- The dual role of agricultural plastics requires their sustainable management in the context of food security and agricultural green transition.
- The current path to sustainable agricultural plastics management can be summarized as source reduction of agricultural plastics and effective recycling of agricultural plastic waste.
- China's agricultural plastics policy has gradually shifted from increasing agricultural production to a parallel focus with environmental protection, and moving towards a systematic and multifaceted approach.
- China's agricultural plastics management policy has made progress, but its impacts remain below expected targets.
- Promoting unified national management alongside regional programs, advancing technological innovation and adoption, and integrating environmental regulations with market mechanisms are essential for sustainable agricultural plastics management.

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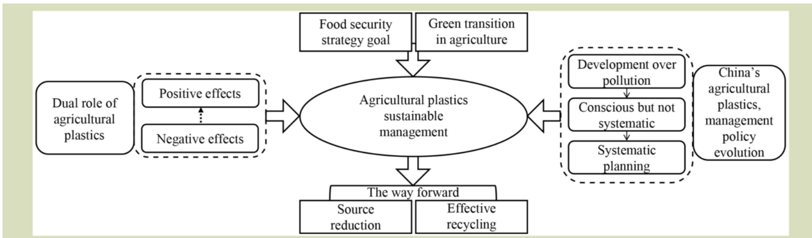
GRAPHICAL ABSTRACT



ABSTRACT

In the context of food security and the greening of agriculture, the sustainable management of agricultural plastics is critical. Although essential to agricultural production, agricultural plastics pose significant environmental risks, particularly in the waste management phase, requiring urgent intervention. Source reduction and effective recycling are key solutions. Based on a systematic review of policy documents, this study analyzed the evolution of China's agricultural plastics management policies. This policy framework has progressed through three stages. The first stage focused on increasing production and promoting technology, leading to widespread adoption of agricultural plastics but weak environmental regulation. In the second stage, policies began balancing production growth with environmental protection, with stronger environmental regulations and regional successes, but nationwide systematic management remains inadequate. The third stage emphasizes agricultural sustainability, promoting life-cycle management and regionally differentiated management. Although recycling rates have improved significantly, a long-term sustainable management mechanism is still lacking, and there are many challenges to source reduction and effective recycling. Based on this analysis and incorporating international experience, a set of key strategies is proposed for sustainable management, including establishing a

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unified national framework with region-specific programs, advancing technological innovation and adoption, and integrating environmental regulations with market mechanisms.

1 Introduction

Food security and the green transformation of agriculture are central to modern sustainable agricultural development, requiring a delicate balance between enhancing productivity and preserving ecosystems. In this context, agricultural plastics (which in this paper refers to plastics used in the agricultural production process and does not currently include plastics used in food packaging, such as fresh produce, storage and transportation) create a problematic paradox, as the same materials that have revolutionized agricultural production and supported global food supply now pose significant environmental challenges[1].

In 2021, agriculture and horticulture accounted for about 4% of global plastic production (~10 Mt·yr^{-1}), and the demand for plastic film is expected to grow by 50% by 2030[2]. Agricultural plastics are widely used in mulch films, greenhouse covers, silage films, irrigation systems, nets, ropes and packaging[3,4]. Specifically, agricultural plastics can help to control pests, adapt to harsh climates, reduce overuse of agrochemicals, increase crop yields, conserve resources and protect the environment[5–7]. At the same time, agricultural plastics are also widely used for packaging fertilizers, pesticides and feed containers, contributing to the efficient use of other agricultural production materials[8]. The multifunctionality of agricultural plastics and their economic viability have made them an important support for modern intensive farming practices.

Despite their many benefits, agricultural plastics generate residues, including macroplastics, microplastics and nanoplastics, that can, through damage, improper disposal and degradation, pose significant threats to soil, water and ecosystems, and consequently food security and human health[9–11]. Research is increasingly highlighting the risks of agricultural plastic residues, particularly terrestrial microplastics as a critical environmental concern[12]. Over time, agricultural plastic residues and additives degrade soil functions, infiltrate biological communities, and migrate into water sources and ecosystems, causing cascading pollution[13–16]. Poor management or improper disposal of these plastics undermines their benefits and threatens food security, human health and socioeconomic development[17]. These challenges underscore the urgent need for sustainable management practices for agricultural plastics.

The dual role of plastics presents a critical global challenge: achieving the short-term benefits of agricultural plastics without compromising their long-term sustainability. Sustainable agricultural plastics management focuses on addressing pollution by adhering to the 3Rs (reduce, reuse and recycle) principle, primarily through source reduction of agricultural plastics and effective recycling of agricultural plastic waste[18–20]. These strategies are complementary, collectively advancing agricultural plastic management from source control through to pollution mitigation. However, reducing or substituting agricultural plastics at the source is constrained by regional resource endowments, technological limitations and market promotion challenges[21,22]. Similarly, recycling faces low efficiency throughout collection and reuse processes, hindered by the physical properties of plastics and insufficient incentives in recycling systems[20].

China is the world's largest consumer of agricultural plastics, using over 64% of global plastic film[23]. China's agricultural film consumption reached 1.34 Mt in 2022, effectively covering an area of 17.5 Mha. Agricultural plastics have substantially enhanced crop productivity contributing to national food security. Simultaneously, China emphasizes the integrated development of food security, ecological civilization, and the establishment of ecologically sustainable rural areas[24]. Through a series of policies aimed at promoting the scientific use of agricultural plastics and mitigating residual film pollution, China has made initial progress. However, challenges remain in reducing and recycling agricultural plastics. Globally, the use of agricultural plastics is increasing rapidly as countries, particularly in the developing world, strive to meet the nutritional needs of their growing populations, the use of agricultural plastics is rapidly increasing. This rapid growth necessitates finding a balance between enhancing agricultural productivity and protecting the environment, while also addressing the contradictions that arise from their dual role[25].

Existing research has obtained rich results in the impact of agricultural plastics[20], mainly focused on the single effect of agricultural plastics, such as environmental pollution or agricultural efficiency, but have not systematically analyzed their dual role from a multidimensional technical, socioeconomic and environmental perspective. In addition, research has also focused on the development of related technological innovations[26], management pathways for residual film contamination and farmer practices[27]. However, comprehensive assessments of agricultural plastics management systems remain insufficient. In particular, there is a lack of comprehensive analysis of agricultural plastics management policies in key developing countries, such as China, as well as a systematic evaluation of their policy evolution. This review systematically identifies the dual roles of agricultural plastics, critically evaluates China's agricultural plastics management policies and analyzes policy measures and their effectiveness at different stages. By identifying key challenges and incorporating international experiences, this study examines future policy directions to establish a scientifically sound management system that ensures food security and supports agricultural green transformation. In addition, this study provides insights for the scientific development of agricultural plastics in other developing countries, facilitating the synergy between economic and environmental benefits.

2 Dual role of agricultural plastics

2.1 Role 1: multidimensional positive effects

Plastics have become an indispensable and central element in modern agriculture[17], due to their low cost, lightweight nature, ease of use, flexibility and multifunctional properties[28]. In agricultural production systems, the efficiency of production can be significantly enhanced through the use of agricultural plastics, which provide crucial support in combating climate change, ensuring food security and optimizing resource utilization. This results in substantial technical, socioeconomic and environmental benefits[6]. Without agricultural plastics, about 60% of global plant and animal production would be at risk[29].

At the technological level, agricultural plastics improve agricultural efficiency through two primary channels: production support and packaging protection. In terms of production support, common plastics such as greenhouse film, mulch film and woven netting significantly improve the growing environment for crops by creating suitable microclimatic conditions that increase yields[4,7]. Greenhouse film extends the growing season for cash crops, including fruits and vegetables, by regulating conditions such as temperature and humidity[4]. In addition, mulch film serves multiple functions, including water conservation, temperature elevation, moisture retention, fertilizer retention, grass suppression, and disease and insect control[30,31], which are essential in crop production, especially in arid and semiarid regions, such as Gansu[23]. Woven netting is widely used to protect crops from hail, strong winds, rain and pests, and to provide shade during hot seasons[4,8]. In terms of packaging protection, agricultural plastics are widely used for packaging fertilizers, pesticides and other products, as well as for bundling and transporting feed and agricultural goods, which significantly increases the efficiency of agricultural plastics agrologistics and the convenience of production[8].

The socioeconomic and environmental benefits of agricultural plastics, which stem from their technological advantages, are equally significant. At the socioeconomic level, the use of agricultural plastics has significantly increased crop yields. For example, mulch film can increase crop yields by no more than 180% in Gansu, and its widespread use nationwide is equivalent to an increase of 3.9 Mha of arable land[23]. In addition, agricultural plastics, such as greenhouse films and mulches, optimize the growing environment, allowing farmers to adjust their cropping cycles more flexibly by planting and harvesting earlier or during the off-season, thereby increasing their market competitiveness and generating higher incomes[20]. From an environmental perspective, agricultural plastics not only enhance microbial diversity, which is essential for soil nutrient cycling and ecosystem stability[32], but they also contribute to water conservation and reduce the reliance on chemical inputs, such as fertilizers and pesticides. For example, polymer coatings enhance nitrogen efficiency by regulating the rate of nutrient release from nitrogen fertilizers, aligning it more closely with the crop growth-cycle, an essential strategy for minimizing emissions in line with dual-carbon goals[33], irrigation pipes significantly improve water use efficiency by delivering water precisely to crop roots[34], and mulches are highly effective in pest management, reducing reliance on agrochemicals by suppressing weed and insect infestations[35]. Also, plastic mulching reduces NH_3 emissions[36] and enhances soil CH_4 uptake, especially during maize growth[37].

2.2 Role 2: multidimensional negative effects

Despite these positive aspects, there are also undesirable effects of agricultural plastics[38,39]. Agricultural plastics have negative environmental impacts during their use. For example, mulching significantly enhances soil organic matter decomposition and increases emissions of major greenhouse gases (CH_4, N_2O and CO_2)[37,40]. However, the greenhouse gas intensity tends to decrease over time, as the yield increases from mulching can offset its negative impact on emissions[41].

However, it is worth noting that the long-term use and irrational disposal of agricultural plastics generate large amounts of waste, which is a major source of environmental, technological and socioeconomic negative effects that threaten ecosystem health and sustainable food production.

Agricultural plastic waste poses a significant threat to soil health and overall ecological integrity[42]. In recent years, studies on the mechanisms of toxic emissions, transport and degradation of agricultural plastics have gradually deepened, revealing their interrelationships with soil properties, nutrient cycling and microbial communities, providing theoretical support for deconstructing the sources of agricultural plastic pollution and developing pollution prevention and control technologies[43,44]. Specifically, plastic residues accumulate in the soil over time, gradually degrading from macroplastics to microplastics[33,43], which have a greater negative impact than macroplastics[45]. These residues are released during aging and degradation processes and pose a direct threat to soil health by adversely affecting its physical, chemical and biological properties[14,20,46], reducing the efficiency of water infiltration and nutrient cycling, and inhibiting root development[47,48]. In addition, agricultural plastics exhibit direct toxicity to soil biomes, disrupting microbial structure and function, which can lead to ecological imbalances[2].

The negative ecological effects of agricultural plastics on soil, water and ecosystems ultimately impact productivity efficiency at the technological level, reduce crop yields, thereby threat food security and safety at the socioeconomic level[44,49,50]. Studies have shown that yields decrease significantly with prolonged residual film time, especially when residual film exceeds 240 $kg \cdot ha^{-1}$[31]. More importantly, chemical additives such as phthalates and bisphenols are often incorporated into agricultural plastics during production to enhance their flexibility, durability and the production process itself[10,51]. Although the time scale of chemical release varies widely[2], these additives leach out as plastics age and degrade, posing risks to soil health, plant uptake, and crop yield[7,10,15]. Additionally, plastic additives can enter human food through the soil-plant-food chain or via food contact materials, posing a potential threat to food safety and human health[10,51].

Improper disposal of agricultural plastics, such as on-site burning, landfilling and illegal dumping, not only devastates rural ecosystems and poses potential threats to human habitats, but also leads to secondary pollution that exacerbates the ecological, technological, and socioeconomic risks[52–54].

2.3 The plastic paradox and treatment path

Table 1 provides a comprehensive analysis of the positive and negative effects of agricultural plastics. While their specific impacts vary based on plastic type, geographic conditions and crop species, a general pattern emerges: positive effects dominate during use with negative effects are more pronounced during disposal. During use, agricultural plastics have become crucial for modern agricultural production, contributing positively to technological, socioeconomic and ecological dimensions. However, their environmental impact remains controversial. Although, their effect on greenhouse gas emissions remains inconclusive, it has been established that certain plastics can release chemical additives under specific conditions, potentially affecting soil quality, crop growth and ecosystem stability. However, with proper management, these risks are generally manageable. However, during disposal, residual agricultural plastic wastes are left in the soil, particularly microplastic pollution, which poses a significant challenge to the sustainability of agriculture.

Figure 1 further illustrates the plastic paradox resulting from the dual role of agricultural plastics. Agricultural plastics are essential for agricultural production, but they also pose a potential threat to sustainable development. The negative impacts of agricultural plastics can negate their positive contributions if agricultural plastic waste is not properly managed[5]. To address this paradox, sustainable management strategies emphasize two key approaches for agricultural plastics: source reduction and effective recycling[20,55].

Table 1 Positive and negative effects of agricultural plastics

Dimension		Main conclusion	Research subject	Plastics Stage	Research methodology	Reference
Positive effects of agricultural plastics	Technological dimension	Control temperature, humidity, and other controlled conditions to effectively combat extreme weather and optimize crop growth cycles	Greenhouse, woven netting	Use	Review, report	[1,2]
		It has various functions such as water conservation, temperature increase, moisture preservation, fertilizer preservation, grass suppression, and disease and insect control, and is especially conducive to improving water-use efficiency	Mulch film	Use	Review, experiment (corn in arid and semiarid areas of China)	[3–5]
		Improves agricultural logistics efficiency and production convenience	Packaging plastics	Use	Report, review	[2,6]
	Socioeconomic dimension	Increases crop production	Agricultural plastics	Use	Review, experiment (corn in Gansu, China)	[5–7]
		Adjust the planting cycle to enhance market competitiveness and obtain higher income	Agricultural plastics	Use	Review	[6]
	Environmental dimension	Promotes microbial diversity, facilitating soil nutrient cycling and ecosystem stability	Mulch film	Use	Experiment (in Shaanxi, China)	[8]
		Conserves water resources and reduces pesticide and fertilizer use	Coated fertilizer, Mulch film, irrigation pipe	Use	Experiment (corn in Xinjiang, China; rice in Japan), review	[5,9–11]
		Reduces NH_3 emissions and enhances soil CH_4 absorption	Mulch film	Use	Experiment (corn in Gansu, China)	[7,12]
Multidimensional negative effects	Environmental dimension	Increases greenhouse gas (CH_4, N_2O and CO_2) emissions	Mulch film	Use	Experiment (corn in Korean; corn in arid and semiarid areas of China)	[12–14]
		Degrades soil health by altering soil properties, nutrient cycles, and microbial communities	Agricultural plastic waste	Disposal	Experiment (soil samples from Xinjiang, Liaoning, Sichuan and Shandong provinces in China), review	[15–17]
		Affects soil's physical, chemical, and biological properties, impairs water infiltration and nutrient cycling, hinders root development, disrupts microbial flora, and reduces crop growth	Microplastics	Disposal	Experiment (greenhouse melon in Thailand, wheat in Chinese laboratory, wheat in Dutch laboratory), review	[6,18–20]
	Technological dimension	Lowers production efficiency, reduces sowing quality, and impacts yield	Agricultural plastic waste	Disposal	Review, experiment (cotton from Xinjiang, China)	[5,21,22]
		Chemical additive leaching poses risks to soil health, plant uptake, and crop yield	Chemical additives	Use/ disposal	Review, experiments (laboratory)	[22,23]
	Socioeconomic dimension	Ultimately threatens food security, quality safety, and human health	Agricultural plastic waste and plastic additives	Use/ disposal	Review	[17,24]
Key insight	Agricultural plastics have become crucial for modern agricultural production. However, their negative environmental impacts, particularly those associated with the disposal phase, require urgent attention and effective management strategies					

Source reduction strategies aim to reduce the use of plastics in agriculture and mitigate environmental pressures by reducing consumption, extending product lifetimes and promoting biodegradable materials[8,56]. Effective recycling strategies aim to achieve a circular economy through the recovery and reuse of agricultural plastic waste[3].

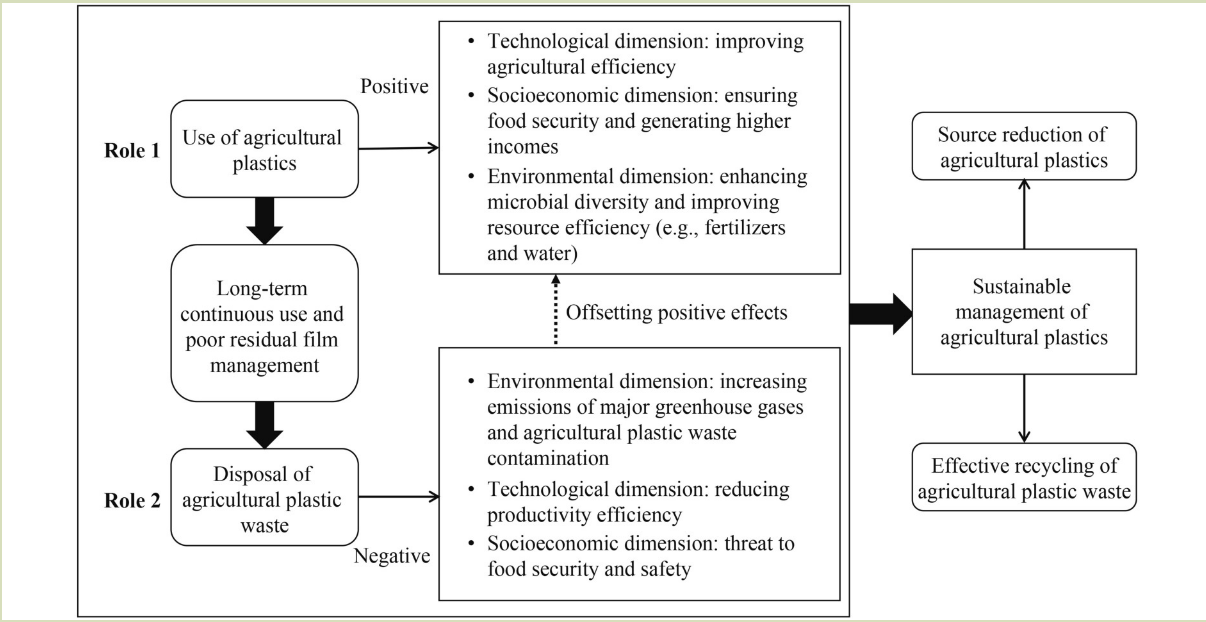

Fig. 1 Dual role of agriculture plastics.

3 Evolution of agricultural plastics management policies in China

As the world's largest user of agricultural plastics, China has gradually established a management system based on policy guidance, technological innovation and multi-stakeholder participation in response to the dual role of agricultural plastics. As shown in Fig. 2, the development of China's agricultural plastic management policy can be divided into three main phases (Tables S1–S3).

3.1 Phase 1: development over pollution (1982–1997)

In the initial phase of China's agricultural plastic management policy, the primary goal was to enhance agricultural productivity, with a policy orientation distinctly emphasizing development over pollution. This phase encompassed two stages: the popularization of agricultural plastics stage (1982–1990) and the emergence of awareness of agricultural plastic waste pollution stage (1990–1997). Key characteristics of this phase included a singular policy focus, rapid diffusion of

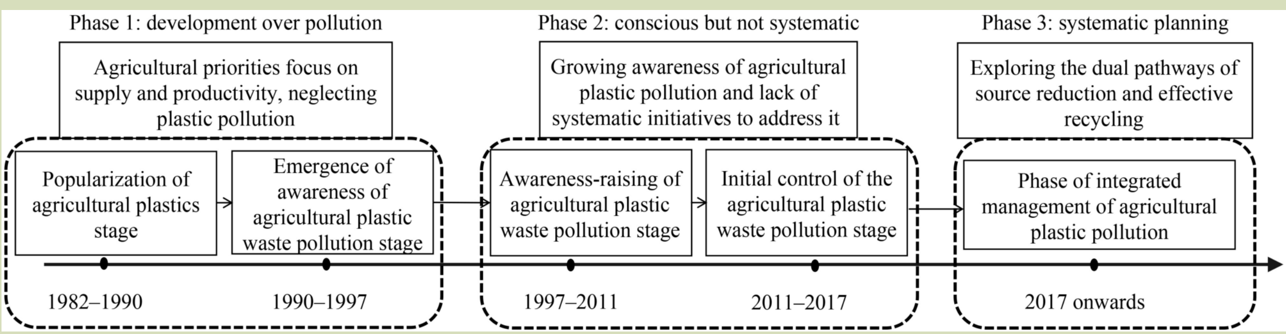

Fig. 2 Evolution and development trend of agricultural plastics management policy in China.

high-efficiency technologies, and a delayed establishment of pollution management systems.

(1) Popularization of agricultural plastics stage (1982–1990)

In the early 1980s, during China's critical transition period of reform and opening up, the nation was under great pressure to increase agricultural production. To ensure food security and promote agricultural modernization, the government prioritized agricultural plastic technology as a key tool for increasing production capacity. The core policy objective was to promote the production and application of plastic films through technical initiatives and financial support[57–59]. In 1982, the *Sixth Five-Year Plan for National Economic and Social Development (1981–1985)* explicitly emphasized increasing agricultural film production, actively promoting new agricultural technologies and systematically implementing plastic film technology[57]. This strategy established plastic as an essential agricultural input. For example, the application of mulch was expanded from arid and semiarid regions in the north to mountainous and colder regions in the south, and its use was expanded from cash crops to staple crops[31]. In addition, the *Decision of the State Council on the Implementation of Specialized Management of Chemical Fertilizers, Pesticides and Agricultural Films in 1988* classified agricultural film as an important production material along with fertilizers and pesticides, which ensured stable market supply and mitigated price fluctuations, thus ensuring farmer access to these inputs[59]. Since the 1980s, China's use of mulch and the area covered by it have expanded rapidly, with an average annual growth rate of about 8%[9].

(2) Emergence of awareness of agricultural plastic waste pollution stage (1990–1997)

In the 1990s, the increasing use of plastic film led to the gradual emergence of residual film pollution in agricultural fields, particularly in the arid and semiarid regions of north-western China, where its adverse effects on soil structure and crop growth became increasingly evident. In response, national policy documents began to address agricultural plastic pollution and incorporate it into environmental management frameworks[60]. In 1990, the *State Council Decision on Further Strengthening Environmental Protection* explicitly included plastic film pollution in the scope of agricultural environmental management, which required the agricultural sector to strengthen environmental protection and control pollution caused by fertilizers, pesticides and agricultural films[60]. Despite this progress, the overall policy orientation continued to focus on promoting technology and increasing productivity[61]. For example, the *Ten-Year Plan for National Economic and Social Development and the Outline of the Eighth Five-Year Plan of the People's Republic of China (1991)* and the *Agricultural Law of the People's Republic of China (1993)* emphasized increasing the supply of agricultural inputs such as mineral fertilizers, pesticides and plastic films, and prioritized the promotion of agricultural mechanization to ensure the continued use of agricultural films in agricultural production[61,62]. Although policies intended to control of environmental problems, including residual film pollution, have been introduced[63,64], agricultural plastic management policies have continued to rely on a technology-driven approach[65,66].

The policy trajectory during this phase exhibited a characteristic pattern of economic priority and environmental lag. As agricultural modernization proceeded rapidly, short-term economic gains took precedence over environmental costs. Policymakers prioritized yield improvement and emphasized the benefits of agricultural plastics, while insufficiently addressing their ecological and environmental externalities. This imbalance resulted in a relatively underdeveloped institutional framework for managing plastic waste pollution.

3.2 Phase 2: conscious but not systematic (1997–2017)

Between 1997 and 2017, China's efforts to address agricultural plastic pollution transitioned from raising awareness to implementing practical measures, reflecting a policy trajectory marked by awareness but lack of a systematic response. This period can be divided into two stages: the awareness-raising of agricultural plastic waste pollution stage (1997–2011) and the initial control of the agricultural plastic waste pollution stage (2011–2017). During this time, the policy focus shifted from a singular emphasis on enhancing agricultural production to a dual emphasis that sought to balance agricultural productivity with environmental protection. However, the establishment of a comprehensive governance framework remained in its infancy and systematic initiatives were lacking.

(1) Awareness-raising of agricultural plastic waste pollution stage (1997–2011)

From 1997 to 2011, China's awareness of agricultural plastic pollution management increased significantly, with policy objectives gradually incorporating environmental protection[67–76]. In 1997, the *Opinions of the State Environmental Protection Administration on Strengthening Environmental Protection Work*, emphasized the need for integrated pollution prevention and control demonstrations targeting mineral fertilizers, pesticides and agricultural films in key regions[67]. In 1999, the *Circular of the State Development Planning Commission and the Ministry of Science and Technology* on the *Issuance of the Guide to the Priority Areas of High-Tech Industrialization for Current Development*, identified biodegradable agricultural film masterbatches and new materials for agricultural use as priority areas for development[69]. By 2002, both the *Law of the People's Republic of China on Promoting Clean Production* and *Agriculture Law of the People's Republic of China (2002 Revision)* explicitly required agricultural producers to use agricultural materials, including films, in a scientific manner to prevent environmental pollution[71,72]. In 2007, the National Development and Reform Commission and other departments issued the *Circular on Strengthening the Management of Agricultural Film Production and Operation* to further regulate the production and use of agricultural films[75]. The *Circular Economy Promotion Law of the People's Republic of China (2008)* further emphasized the importance of resource utilization of agricultural plastic waste[76]. Despite increased emphasis in policy documents on the environmental impacts of agricultural plastics, specific management measures remained fragmented, with ineffective incentives and unclear implementation pathways. According to the *Bulletin of the First National Census of Pollution Sources*, residual film on mulched farmland nationwide totaled 121 kt by 2007[77].

(2) Initial control of the agricultural plastic waste pollution stage (2011–2017)

In 2011, the *Opinions of the State Council on Strengthening Major Environmental Protection Work* reaffirmed the necessity of scientifically managing agricultural film to mitigate its environmental impact[78]. At the same time, the Ministry of Agriculture emphasized the promotion of standardization of film thickness and established a mechanism for recycling used films, laying the policy foundation for systematic management measures[79]. Between 2012 and 2015, National Development and Reform Commission, Ministry of Finance and former Ministry of Agriculture demonstration projects on cleaner agricultural production for four consecutive years, were investing more than 900 million yuan[80]. This initiative promoted film recycling in 229 counties and municipalities in Gansu, Xinjiang and Inner Mongolia, achieving remarkable regional results. In 2014, National Conference on Agricultural Work set a target to achieve an agricultural film recycling rate of over 80% by 2020, signaling a shift toward more defined policy objectives in agricultural plastic pollution management[81]. The *Circular of the Ministry of Agriculture, National Development and Reform Commission and the Ministry of Science and Technology on the Issuance of the National Plan for Sustainable Agricultural Development (2015–2030)* further proposed promoting the research and use of biodegradable films, accelerating the mechanized recycling of used films, and achieving comprehensive agricultural film waste recycling by 2030[82]. In 2016, the *Notice of the State Council on Issuing Soil Pollution Prevention and Control Action Plan* emphasized revising agricultural film standards, studying biodegradable film standards, and advancing the standardized treatment and resource utilization of film pollution[83]. Practical efforts during this period primarily targeted the north-western region, where agricultural film usage is intensive and pollution is severe. However, despite some regional progress, comprehensive management at the national level remains inadequate.

The second phase (1997–2017) marked a transition from awareness to action in addressing agricultural plastic pollution in China, with a significant increase in governance awareness during this period. Compared to the previous phase, policy objectives evolved to balance increased agricultural production with environmental protection. The policy direction shifted from recognizing background issues to actively governing visible problems.

3.3 Phase 3: systematic planning (2017 onwards)

Since 2017, China's agricultural plastic pollution management has entered the systematic planning phase, which is characterized by comprehensive and structured governance. At this stage, agricultural plastic management is integrated into the green agricultural development strategy, focusing on the dual pathways of source reduction and effective recycling. The ultimate goal is to establish a complete lifecycle management system for agricultural plastics that reflects the direction of future development.

In 2017, the *Circular of Ministry of Agriculture on the Issuance* *of the Action Program on Agricultural Film Recycling* proposed specific measures to promote pollution prevention and control through the thickening of mulch film, mechanized recycling and resource utilization, with a focus on arid and semiarid regions in north-western China[84]. In the same year, the *Polyethylene Blown Mulch Film for Agricultural Uses (GB 13735-2017)* raised the film thickness standard to 10 μm, aiming to reduce the film breakage rate and improve the efficiency of mechanized recycling[85]. Subsequently, the *Soil Pollution Prevention and Control Law of the People's Republic of China (2018)* and the *Opinions on Accelerating the Prevention and Control of Pollution from Farmland Films (2019)* further clarified the overall requirements, institutional measures, key tasks and policy guarantees for addressing agricultural plastic pollution[86,87]. According to the *Bulletin of the Second National Census of Pollution Sources* released in 2020, the amount of agricultural film used in 2017 was 1.42 Mt, with a cumulative residue of 1.18 Mt[88]. These data highlight the contradiction between the growing problem of residual film pollution and the slow implementation of related policies. In the same year, measures for the administration of agricultural film were introduced and the *Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Wastes* was revised[89,90]. Then, the *Circular on the Pilot Work of Scientific Use and Recycling of Film (2022)* and the *Circular on Further Strengthening the Supervision and Enforcement of Agricultural Films (2023)* were issued, which emphasized a source-to-end whole-chain management model with the top-level design concept of systematic management driven by the dual goals of source reduction and effective recycling[91,92].

At the beginning of this phase, policy implementation was relatively slow, leading to a continuous accumulation of residual film. The central government defined governance objectives through top-level design, while local governments adopted differentiated approaches based on regional characteristics, aiming to build a relatively comprehensive governance system. However, implementation relied primarily on project-based initiatives or direct subsidies to achieve short-term recycling rate targets. Efforts to promote alternative agricultural plastic technologies and waste recycling focused on short-term outcomes and failed to address the root causes of the problem. As a result, establishing a sustainable management mechanism for agricultural plastics has proven challenging.

3.4 Characteristics the phases of China's agricultural plastics management policy development and key progress

Table 2 presents a comparative analysis of the three phases in the development of China's agricultural plastics management policy. In the first phase, driven by the urgent need to boost agricultural production, policies primarily focused on technological promotion and production control, highlighting the role of agricultural plastics in enhancing food output. During this period, the adoption of agricultural plastics in China expanded significantly. However, weak environmental regulations led to the accumulation of plastic pollution. In the second phase, with the widespread use of agricultural plastics, support mechanisms for standard mulch have been significantly reduced or discontinued[93]. However, agricultural plastic pollution has become increasingly severe, prompting a policy shift toward a dual focus on increasing production and environmental protection. Residual film pollution control was incorporated into relevant laws and regulations, and policymakers gradually strengthened incentive-based, mandatory and guiding policy instruments to promote the development of biodegradable agricultural plastics and the recycling of residual films. These efforts yielded regional and incremental progress. For example, in 2017, Gansu Province used 170 kt of mulch film, achieving a recycling rate of 80%[94]. However, systematic nationwide management remained inadequate, with the recovery rate of agricultural film in the current season falling below two-thirds[95]. In the third phase, green agricultural development has become central to ecological civilization construction, with the core policy objective being the establishment of a sustainable whole life-cycle management system for agricultural plastics. In response to the implementation of the residual film pollution management program, local governments have adopted region-specific management strategies and have continued to enhance the synergy of regulatory, incentive-based and guidance-oriented policy measures to promote comprehensive governance. These measures have yielded positive results in most regions. For example, in 2024, Yanqing District in Beijing conducted a pilot demonstration of 100 ha of fully biodegradable mulch film, implemented dual-use technology for 367 ha, and reduced mulch film usage by 35.8 t, achieving cost savings, pollution reduction and improved production efficiency[96]. Additionally, in regions with recycling pilot projects, such as Gansu Province and Xinjiang Uygur Autonomous Region, regulations and action plans have been implemented to improve regional governance, and a social

Table 2 Stage characteristics and comparative analysis of the development of China's agricultural plastics management policy

Phase	Policy background	Policy objective	Policy instrument	Management model	Main progress	Major issue
The first phase (1982–1997)	In the early years of China's reform and opening up, increasing pressure to boost agricultural production and urgent demands for food security led to the widespread adoption of agricultural plastics as a key tool for increasing productivity. In later years, concerns about pollution from agricultural plastics emerged, but policy efforts continued to focus on technological advancement and production growth	To promote the popularization of agricultural plastic technology, improve the efficiency of agricultural production, ensure the supply of agricultural materials and guarantee food security	Incentive and guidance policies for technology promotion and production control were the main focus, and residual film pollution control was incorporated into relevant laws and regulations in the medium term. However, environmental regulations were relatively weak and policy instruments were not sufficiently synergistic	Government-led	The significant increase in the prevalence of agricultural plastics in China has significantly increased crop productivity and played an important role in ensuring national food security	The logic of prioritizing production increases has short-term tangible production benefits and long-term sustainability pitfalls
The second phase (1997–2017)	Agricultural plastics have become the important means of increasing food production, but the surge in the use of agricultural film has led to the manifestation of "white pollution." Residual film pollution control has become one of the key areas of agricultural surface pollution and even environmental governance	Shift from "giving priority to increasing production" to "giving equal importance to increasing production and protecting the environment" and examine the path of pollution managemen	Based on technology promotion, research and development of biodegradable agricultural plastics and residual film recycling have been promoted by incorporating residual film pollution control into relevant laws and regulations and gradually strengthening incentive, mandatory and guidance policy instruments	Localized, government-led pilot	Environmental laws and regulations have improved, and the treatment of residual film contamination has achieved regional results	Nationwide systematic management remains inadequate
The third phase (2017 onwards)	The green development of agriculture is vital for ecological civilization. Agricultural pollution is worsening, and the contradiction between the lagging political practice and the urgency of the demand for treatment is intensifying	Toward a sustainable total life-cycle management system for agricultural plastics	The systematic mix of mandatory, incentive and guidance policy instruments has been strengthened	A management system based on "policy guidance, technological innovation, multi-subject participation"	Residual film management programs have been introduced with greater clarity and relevance, and most regions have achieved residual film management results	Policies rely on subsidies and prioritize short-term results, lacking long-term mechanisms for sustainable agricultural plastics management

atmosphere and value proposition for recycling agricultural plastic waste has gradually developed[97,98]. With policy support, Xinjiang achieved a 90% recycling rate for used agricultural film in 2021[99], while Gansu Province reached 85% in 2023[100]. These efforts, supported by environmental regulations and social norms, have significantly raised awareness among market participants regarding residual film pollution management, leading to standardized recycling practices[101,102]. However, the current management of agricultural plastics remains subsidy-driven, focuses on short-term objectives and lacks a long-term mechanism for sustainable management.

4 Challenges of China's agricultural plastics management

4.1 Main challenges

China's efforts to manage agricultural plastics have provided valuable lessons, but challenges remain in achieving expected results in policy implementation and system development for source reduction and effective recycling.

(1) Barriers to advancing source reduction

Agricultural plastics are essential in modern farming due to their versatility, affordability and efficiency, making large-scale reduction impractical. However, existing policies overlook the changing contributions of mulch across regions and crops. For example, the output elasticity of mulch for maize declines from 2013 to 2023, indicating diminishing marginal returns due to overuse at current levels of technical efficiency (Fig. S1). However, there is still a lack of accurate measurement of the area-specific contribution of mulch and corresponding policies to optimize its use. This gap significantly hinders the achievement of source reduction goals. Also, the development of commonly-used agricultural plastics with a focus on improved chemical, mechanical and other properties remains insufficient[7]. Particularly for products such as mulch films, achieving an optimal balance between functionality and cost-effectiveness further complicates efforts to extend their service life.

Currently, China's main source reduction effort is the promotion of biodegradable agricultural plastics, which faces multiple technical, social, economic and institutional barriers[47,103]. Technically, the impact of biodegradable plastics on crop growth, ecology and other factors remains inconclusive, and their viability as environmentally-friendly alternatives to currently-used agricultural plastics is still under evaluation[104,105]. Studies indicate that biodegradable plastics can generate more microplastic pollution and higher CO_2 emissions[106]. Their degradation is influenced by soil management practices[21], and some products fail to align with crop growth cycles, undermining both agricultural productivity and pollution control efforts. At the social level, farmers have limited knowledge of biodegradable agricultural plastics with their high cost further discouraging voluntary adoption. Instead, farmers prefer standard polyethylene films, which are cost-effective and visibly enhance yields. Consequently, the ecological benefits of biodegradable plastics are delayed and externalized, leading farmers to prioritize risk avoidance in the absence of direct economic incentives. This results in an implementation deadlock in which the government promotes but farmers hesitate. At the economic level, degradable agricultural plastics lack a stable market promotion mechanism due to high production costs, which reduce their competitiveness[22]. Additionally, supply chain inefficiencies and technical limitations hinder market acceptance, discouraging enterprise investment in research and development and restricting their widespread adoption. At the institutional level, incomplete standards and quality testing systems hinder market supervision, impeding the standardized production and promotion of degradable agricultural plastics. Additionally, their adoption relies heavily on regional government subsidies, limiting widespread application. While subsidies support short-term pilot programs, financial dependence is unsustainable, and regional fiscal disparities exacerbate imbalances in technology promotion.

(2) Barriers to advancing effective recycling

Effective recycling of agricultural plastics poses challenges in terms of market mechanisms, government regulation, and the behavior of the main actors throughout the chain and within the links themselves. Commonly, farmers use agricultural plastics for short-term economic benefits with limited consideration of long-term environmental impacts[48,107]; they have little incentive to collect agricultural plastic waste[108]. Compared to other agricultural plastics, mulch film has lower structural integrity and higher contamination rates, making it the primary contributor to agricultural plastic waste pollution[109]. Additionally, inadequate mechanization, water scarcity, an aging agricultural workforce and low farmer incomes further hinder their ability to retrieve, clear and transport used mulch.

Second, in the processing chain, the limited economic benefits of recycled plastic products, due to high costs and technological constraints, combined with insufficient recycling networks and underdeveloped technology, reduce their market competitiveness and economic viability, leading to low motivation among recyclers[54]. In particular, mulch film is highly fragmented and contains many contaminants making it costly to collect, recycle and process, further limiting the feasibility of recycling and resource utilization[8]. Used and scrap mulch often accumulates due to the lack of effective processing channels, increasing the risk of secondary pollution.

In addition, the agricultural plastic waste recycling market remains underdeveloped, limiting the effectiveness of market-driven incentives. Recycling efforts primarily depend on government pilot programs, such as the old-for-new project, where financial subsidies encourage participation from farmers and enterprises. For example, in Huairen County, Shanxi Province, cooperatives facilitated film recycling by allowing farmers to exchange used film for new film at a 1:1 ratio during the 2017–2019 pilot period. Concurrently, a residual film processing line was established with enterprise subsidies, significantly increasing recycling rates. However, due to weak market demand, reprocessed products were difficult to sell and failed to offset processing costs. When subsidies ended, enterprises shut down processing plants due to financial losses and most farmers abandoned field collection, instead incorporating film residues into the soil during mechanical tillage, exacerbating pollution. This case highlights that while subsidies effectively promote short-term recycling, their impact is unsustainable. Without fostering a stable market for recycled products, long-term waste management effectiveness remains unattainable.

Despite the introduction of a new national standard for agricultural film in May 2018, many farmers continue to use ultra-thin films (6–8 μm) to reduce costs. These films are not only difficult to recycle, but also exacerbate residual film pollution[110]. The proliferation of ultra-thin films illustrates Gresham's law that "bad money drives out good money", revealing weaknesses in policy enforcement and market supervision.

4.2 Implications for other countries from China's practice

China's agricultural plastics policy evolution offers critical insights for global agricultural plastics management, particularly in developing countries.

This policy framework has progressed through three phases: (1) technology promotion, (2) awareness-raising and initial management, and (3) systematic management. Each phase aligns with evolving socioeconomic priorities, transitioning from production-centric goals to integrated environmental governance. However, alignment between phased objectives requires strengthening. For example, integrating environmental standards (e.g., mandatory thickness requirements for plastic film) during technology adoption phases reduces post-use pollution remediation costs and enhances policy efficacy.

In addition, China uses a hybrid policy toolkit combining regulations, incentives and guidance, supported by a pilot-diffusion mechanism to test regional solutions. This approach is particularly relevant for countries that depend on agricultural plastics.

Nevertheless, persistent challenges remain, including limited adoption of biodegradable plastics and inefficient recycling systems. These issues stem from techno-economic constraints and underdeveloped markets for biodegradable plastics and recycled plastic waste products. Subsidy-driven path dependency further weakens market incentives. To address this, policies should prioritize demand-driven market development for plastic reduction and resource recovery, easing fiscal burdens while strengthening market incentives. Concurrently, governments must lead in standard-setting and market oversight to foster public-private governance mechanisms, enhancing policy sustainability.

4.3 International experience

Other countries have gained some experience in agricultural plastics management, including the following aspects. First, enforce stricter thickness standards for agricultural polyethylene film to reduce fragmentation. Polyethylene film thickness standards in developed countries and regions, such as the EU, Japan and the USA, are significantly higher than 10 μm (China's current film thickness standard). Second, optimize incentives to promote R&D and adoption of biodegradable alternatives. For example, the USA initiated federal biodegradable mulch research programs in the 1980s and later formalized material certification standards. Third, refine market mechanisms by establishing extended producer responsibility systems and benefit-sharing linkages across supply chains. The Japanese model illustrates this approach: under its Waste Management and Public Cleansing Law, the Agricultural Film Recycling Promotion Association (established in 1999) coordinates stakeholders, government, agricultural cooperatives, manufacturers, farmers and recyclers to operationalize a closed-loop agricultural film recycling system[111]. These actions collectively incentivize scalable, market-driven solutions while reducing fiscal reliance.

5 Conclusions and outlook

5.1 Conclusions

In the context of food security and green agricultural transformation, agricultural plastics have two key roles. They significantly increase both agricultural productivity and food security, with technological, socioeconomic and environmental benefits. However, the accumulation of plastic residues, especially microplastics, is increasingly leading to negative environmental, technological and socioeconomic impacts. Source reduction and effective recycling are essential pathways to achieve sustainable management of agricultural plastics, but many challenges remain in practice. As the world's largest agricultural plastics user, China's agricultural plastics management policy has gone through three phases: (1) development over pollution (1982–1997), (2) conscious but not systematic (1997–2017), and (3) systematic planning (2017 onwards). The policy objectives have gradually shifted from a single focus of increasing agricultural production to a parallel focus with environmental protection, and toward a systematic and multifaceted approach. Although some progress has been made, there is still a gap between the two objectives of source reduction and effective recycling in realizing the sustainable development goals, and the long-term mechanism has not yet been fully established. There is an urgent need to review existing policies and propose targeted improvements to promote the sustainable management of agricultural plastics.

5.2 Policy implications

To realize the sustainable management of agricultural plastics, China should promote the combination of unified national management and regional programs, strengthen the innovation and adoption of technology, synergize the development of environmental regulations and market mechanisms, promote the dual drive of source reduction and effective recycling, and build an efficient and scientific management system.

(1) Promotion of the combination of unified national management and regional programs

First, a unified national agricultural plastic management system should be established to improve the top-level design of product standards, and regulate use, recycling and treatment processes, thereby promoting orderly management. In particular, source control of mulch should be strengthened by promoting high-strength films with a thickness of more than 15 μm (at least 10 μm) and eliminating the production and circulation of ultra-thin mulch films. Additionally, differentiated management models should be developed to take into account the unique characteristics of different regions. For source reduction, such as in the case of mulching, the structure of mulching areas could be optimized based on the output elasticity of mulch. Regions could be divided into mandatory, optional and prohibited mulching areas, with tailored programs developed for each category. For effective recycling, agricultural plastic waste disposal methods should be adapted to regional conditions. For example, in high-use areas, such as the cotton-growing areas of Xinjiang, high value-added reuse methods, such as energy generation, could be adopted. In areas such as Huanxian County, Gansu, where residual film quantities are smaller and purification levels are higher, mechanical cutting technologies could be promoted to process used film into raw materials for plastic products. In areas with limited agricultural plastic use, agricultural plastic waste could be included in rural waste management systems as a special category for centralized treatment.

(2) Strengthen the innovation and adoption of technology

Innovation and widespread adoption of green technologies are fundamental to addressing agricultural plastic pollution. The government should provide financial support, launch special scientific and technological projects, and establish R&D incentives to promote cooperation among industry, academia and research institutions. These measures would promote systematic research on technological and equipment innovations, with special emphasis on field recycling machines, waste resource utilization technologies and biodegradable agricultural plastics. For example, when developing field recycling machines for mulch film, designs should take into account regional landscape topography, soil characteristics and other natural conditions, while integrating agricultural machinery research to improve overall production efficiency. Given the extensive use of agricultural film in China, especially in the north-west, where residual film contamination rates are high, efforts should be intensified to advance scientific disposal methods, such as improving residual film resource utilization technologies and overcoming the limitations of current cleaning and pelletizing processes. In addition, the development of high-strength films should be accelerated, along with rigorous research into biodegradable film technologies and products. This research should prioritize controllability, cost-effectiveness, safety validation and environmental impact assessment to provide a sound technical basis for the green transformation of agricultural plastics.

(3) Synergistic development of environmental regulations and market mechanisms

The management of agricultural plastic pollution should leverage the synergy between market mechanisms and government intervention. The government should provide direct incentives, such as policy support and subsidies, to encourage active participation from farmers and enterprises in pollution treatment. Concurrently, education and awareness campaigns should be used to foster ecological rationality among individuals, stimulating their intrinsic motivation to engage in sustainable practices. Additionally, efforts should focus on cultivating the market for agricultural plastic waste resource utilization products. This includes establishing regional resource utilization industrial chains to maximize the role of market mechanisms. By doing so, the risks of secondary pollution from the accumulation of agricultural plastic waste can be minimized and a long-term mechanism for its effective recycling can be developed. Such measures would contribute to the sustainable achievement of government objectives in agricultural plastic management.

5.3 Research outlook

Future research should investigate the potential for long-term sustainable pathways for agricultural plastics management, emphasizing their role in agriculture and the optimization of policy synergies and market mechanisms.

Agricultural plastics should be integrated into the framework of sustainable agriculture, particularly within the broader food system, with a comprehensive assessment of their conflicting positive and negative effects. Research should prioritize the impact of agricultural microplastics on the food system and human health, emphasizing the development of a quantitative assessment system to support scientific decision-making and policy optimization.

The management of agricultural plastics should be integrated into the broader environmental policy system, with a comprehensive examination of synergistic governance mechanisms. Importantly, coordination between reduction and resource utilization pathways must be strengthened. In terms of reduction, emphasis should be placed on the coupling effect between reducing agricultural plastics and decreasing other agricultural inputs, such as fertilizers and pesticides. Comprehensive policies should optimize the synergy between water, fertilizers, pesticides and agricultural plastics to enhance resource-use efficiency in agricultural production. Regarding resource utilization, agricultural plastic waste should be incorporated into the broader agricultural waste management system, facilitating coordinated treatment of various agricultural wastes, including livestock manure, straw and household waste. A systematic management approach should be established through technological integration, policy design and promotion strategies. Additionally, the integration and coordination of reduction and resource utilization pathways should be reinforced, as they are often addressed in isolation, leading to fragmented policy implementation and reduced management effectiveness. A multifaceted policy framework should be developed to examine how fiscal incentives, regulatory improvements and technological innovation can promote their synergistic development.

Future research should also examine strategies to enhance the economic feasibility of agricultural plastic waste recycling through market-oriented policy measures. This includes fostering the development of markets for biodegradable plastics and resource utilization products, implementing the extended producer responsibility system, and establishing a credit system for plastics recycling. These measures would strengthen incentives for farmers, enterprises and other market participants, ultimately promoting the sustainability and efficiency of agricultural plastics governance.

Supplementary materials

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Compliance with ethics guidelines

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