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REVIEW

Sustainable plasticulture in Chinese agriculture: a review of challenges and routes to achieving long-term food and ecosecurity

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KEYWORDS

Circular plastics economy, crop production, food security, plastic pollution, sustainable plasticulture

HIGHLIGHTS

- Macro-, micro- and nanoplastic pollution in agricultural soils threaten long-term crop production and environmental health in China.
- Resolving the existing issues with plasticulture in China requires holistic solutions that target plastic production, use and waste management.
- Mechanisms for change must focus on education, incentivization and the development of infrastructure to positively reinforce the procurement, management and disposal of agriplastics.
- The sustainable intensification of plasticulture in Chinese agricultural production systems is key to achieving long-term food and eco-security in China.

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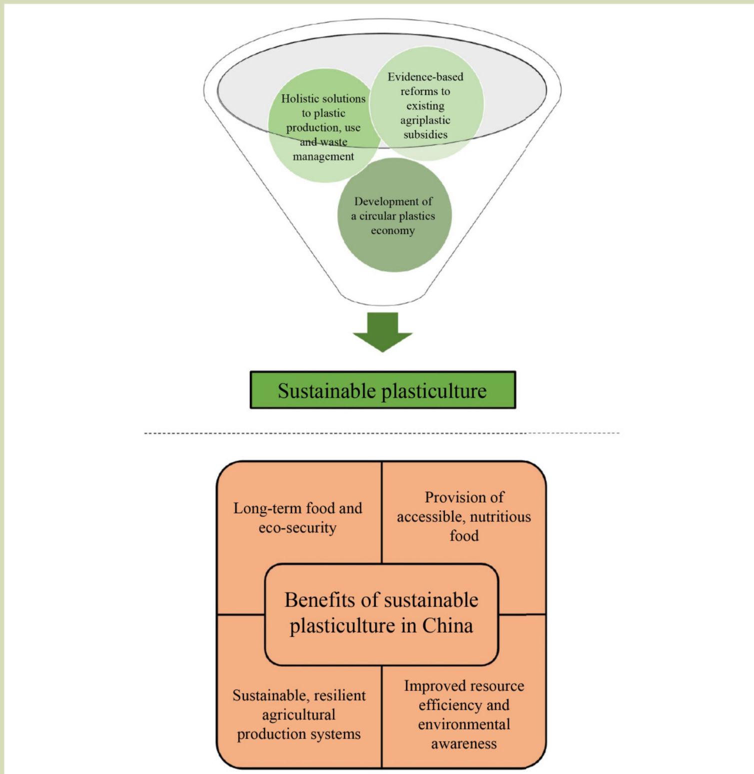
GRAPHICAL ABSTRACT



ABSTRACT

Plastic pollution is global concern, affecting most aspects of global food production systems. Plasticulture, a practice used in agriculture to improve crop quality and quantity, among other factors, is a significant source of plastic pollution. This review examines the extent of plasticulture in China, the implications of the practice across decades of use and the legislative instruments used to resolve those issues. It briefly assesses the effectiveness of these policies and proposes possible future innovations to promote increases in long-term food and eco-security, where sustainable plasticulture is a key agent for change. While plasticulture has increased agricultural productivity in growth-limiting conditions, plastic pollution in agricultural soils has become acute in China. Consequently, plastic pollution is having deleterious effects on soil health and in turn, crop productivity in China. Plastic pollution in agriculture is a multifaceted issue and so proposed solutions should be informed by this complexity. Current measures do not reflect a holistic approach to solving this socioecological challenge and adopt a top-down approach, with little or no supportive mechanisms. Future recommendations need to consider the particular set of conditions that influence the production, use and end-of-life management of agriplastics, specific to the environmental, economic and social conditions in each location.

1 Plasticulture: a brief history

Plasticulture, the use of plastic applications in agriculture, has revolutionized agricultural production systems worldwide. Plastics are highly valued in agriculture due to the spectral and material properties, flexibility, low cost and non-toxicity of the material[1,2], although the latter attribute is now widely contested[3,4]. The use of plastics has been crucial to efforts to extend the production of fruit, vegetables and other food crops into periods of the year in which growth conditions are suboptimal[5].

Plastic applications are commonly used, but not exclusive so, in crop production. Greenhouses, polytunnels, irrigation equipment, netting, mulch and silage films are common applications used in global crop production systems. These applications are used for the primary function of increasing the quantity and quality of fresh produce for the consumption by both humans and livestock[6]. Other functions of plasticulture are integral to reduce the overuse of natural resources and agrochemical loads while providing protection against pests, disease and adverse weather conditions[7]. The use of plastics outside of crop production is equally important. The role of plastics in improving the transportation conditions, protection and storage of fresh produce has been fundamental to reduce food waste and increase the supply of good quality food to those who need it[8]. In many regions, the development of plasticulture has come at a critical time when countries are struggling to meet the nutritional and dietary needs of growing populations. Plasticulture is a useful technique to future-proof production systems against increasingly common events such as temperature extremes, droughts, geopolitical instability and supply chain disruption[8,9].

Plasticulture is a global practice, largely concentrated in Asia. By volume, China is the largest producer and user of agricultural plastics, consuming over 7.2 Mt of agriplastics per year[8]. Plastic use is common in many agricultural systems employed in China. Although it is well established that plasticulture has driven an increase in agricultural productivity and food security in China, it is now widely accepted that decades of widespread, and in some cases unavoidable plastic use, have led to unintended environmental effects in both the aquatic and terrestrial environments[4,8,10–12]. Although most plastic residues in aquatic systems originate from the terrestrial sources, little is known about the source, presence, fate and impacts of plastic residues in the terrestrial environment[13].

Emerging research suggests that the accumulation of plastic film residue is negatively impacting crop productivity and soil physiochemistry, jeopardizing the sustainability of future crop production in China[3,14] and in many other parts of the world[15]. Progress toward resolving this issue is being made. Standards for biodegradable mulch film have been developed, prohibiting the production, sale and use of thin mulch film (< 0.01 mm). Regulations have been introduced which encourage the use of high quality, thicker plastic films that can be reused and recycled, as summarized in Table 1.

It is increasingly difficult to detach plastic use from agriculture without compromising agricultural productivity. Current food production systems are so reliant on plastic that production systems without plastic in particular parts of the world could potentially show increased susceptibility to climate extremes at particular times of the year and further contribute to global greenhouse gas emissions[6,15]. Instead of recommending the abandonment of plasticulture, we explore the viability of a future food system that promotes food and eco-security, where the sustainable use of plastic is a key component of the food production process.

Here, we explore the condition of the current agricultural

Table 1 Main policies, strategies and legislative instruments to address plastic pollution in China

Mechanism	Description
Law of the People's Republic of China on Promoting Clean Production, 2002	Agricultural producers are encouraged to use agricultural films in a scientific way to improve agricultural productivity, while preventing agricultural environmental pollution
Circular Economy Promotion Law of the People's Republic of China, 2009	This law was established to raise resources utilization rate, protect and improve the environment and sustain development
Soil Pollution Prevention and Control Action Plan, 2016	This action plan strategized improvement of the recycling of abandoned agricultural film, revise standards for agricultural film thickness and test the viability of degradable alternatives to reduce plastic pollution in soil
Biodegradable Mulching Film for Agricultural Uses (GB/T35795-2017), 2017	Following the promotion of biodegradable mulch films, this standard was created to evaluate the performance, safety and characteristics of biodegradable alternatives. The standard specifies the requirements for production, use and the management of biodegradable mulch films
Soil Pollution Prevention and Control Action Plan, 2018	This is a development on the previous action plan to make 95% of polluted arable land safe for use by 2030. By 2020, more than 80% of all agricultural plastic waste should be recycled. Farmers responsible for plastic pollution in soil must bear the costs of investigating, remediating and managing soil contamination
National Mulch Film Standard, 2018	This standard requires the thickness of agricultural mulch film to be no less than 0.01 mm, to reduce soil pollution and improve collection rates
Soil Pollution Prevention and Control Action Plan, 2019	Updated regulations that require the use of thicker, better quality mulch film that remains structurally intact once used. The action plan bans the production, sale and use of mulch film with a thickness less than 0.01 mm. Mulch film should be reused, collected and recycled where possible. Incentives are to be provided to encourage the use of biodegradable mulch
Notice on making solid progress in the treatment of plastic pollution, 2020	This notice requires that each province should provide a detailed and feasible plan to improve the recycling of waste agricultural film. Provinces should investigate and punish those producing or using agricultural film with a thickness less than 0.01 mm
China's National Green Agriculture Development Plan, 2021 (14th Five Year Plan)	The plan aims to strengthen the control of plastic pollution from plastic agricultural films. An increase in the collection rate of agricultural plastic film to 85% by 2025 is expected. This plan includes the development of pilot projects for agricultural pollution control as well as the supervision and provision of guidance to better manage and control agricultural pollution

system and discuss the legacy of current and past plasticulture practices in China. With knowledge of the positives and negatives associated with plasticulture, we recommend techniques to help farmers manage agriplastic waste and remediate plastic pollution, on farm and in the wider environment without compromising food production. We propose adaptations to an established plastic-intensive production system compatible with Agricultural Green Development (AGD) techniques to form a more inclusive and sustainable method of future food production in China, reducing the environmental effects of plastic use in agriculture from production to disposal[16–19].

2 Plasticulture: a key contributor to the rise of agricultural productivity in China

There is little doubt that the food production system in China has benefitted enormously from the introduction of plasticulture over the past 40 years. Faced with feeding a growing population from a diminishing area of agriculturally productive land due to widespread development of housing and industry, water scarcity, soil erosion and desertification[20,21], plasticulture has become a widely used technique to deliver high crop productivity per unit area of cropping. Semiarid and arid regions represent 37% of the total area of China, where two-thirds of the local population is in poverty[21]. An example of which is southern Xinjiang, characterised by limited water resources, a high poverty rate and slow economic development[22]. The use of plastic mulch in China is thought to increase crop yield by 25%–42% in the immediate season, largely as a response to increase in soil temperature and moisture (+ 8% and + 17%, respectively)[14]. In China, the development of plasticulture has equipped farmers with a relatively inexpensive means to improve yields, particularly under water-scarce conditions[11].

Nationwide, the use of plastic mulch has translated to a 45.5% increase in crop yield across 51 crop species[23]. Ridge-furrow mulched systems, where ridges are covered by plastic mulch and the furrows are left bare or laid with straw, have delivered an 84% increase in crop yield[23]. This increase is of international and domestic importance. As the world's largest producer of potatoes, the use of plastic applications, primarily mulch films, has led to an increase in potato yield exceeding 24% between 1989 and 2017[24]. Similar rates of increase in crop yield have been observed across a range of grain and cash crops due to the application of plastic mulch films[10,11]. In 2012, the use of plastic film in grain production (maize, rice and wheat) resulted in a 30 Mt increase in production volume[23].

Plastic mulch films are typically laid over the soil before planting or shortly after to induce localized soil warming, conserve moisture, provide weed control and accelerate the germination of crops (Fig. 1). To monitor the crop and apply field amendments these films are briefly removed and relaid until the crop has matured. At this stage, mulch films are either removed, plowed into the soil, or left to degrade as the crop grows through. Although it is well established that the use of plastic applications has been successful in improving crop quantity and quality in China, the effectiveness of plastic applications is highly dependent on the environmental, social and economic conditions in the region[15]. In arid regions, greenhouses can provide protection from scorching, heavy rainfall events and dust storms (Fig. 2). However, these structures are not as effective at retaining heat and buffering the diurnal temperature variation compared to more complex structures and are therefore not suitable to grow frost-sensitive crops or for use in colder regions. Novel polymers in more complex systems modify the incoming solar radiation to manipulate the micronutrient content of the crop and improve taste, quality and aesthetics[5], but can also create a favorable environment for fungal development[15].

Fig. 1 Plastic mulch film used for maize cultivation in north-western China. The mulch film is left to degrade into the soil once the maize crop grows through the film and matures.

Fig. 2 Steel-framed, multilayered polyvinyl chloride covered greenhouses used for the production of fruit and vegetables in spring and autumn. The plastic film is buried in the ground to secure the structure.

The success of plasticulture in Chinese agriculture has driven an increase in the volume of agriplastics and the area of arable land covered by plastic. From 1981 to 2010, the area of arable land covered by plastic in China rose from 4.2 kha to 28 Mha of which 19.8 Mha were covered by plastic mulch films[7,10,25]. The area of arable land covered by plastic mulch films has significantly increased in China, growth rates of 30% a year have been observed, eclipsing the 5.7% global annual growth rate[1]. In 2012, the area of land covered by plastic mulch films accounted for 13% of cropland in China[23]. In 2015, the total amount of agricultural film used in China was above 2.6 Mt, of which the amount of plastic mulch film was 1.45 Mt. At this time, national agricultural film recycling rate was less than 66%[26]. Models suggest that the use of plastic mulch films in China will increase to 2.28 Mt by 2025, covering 23.4 Mha[4]. The cost of plastic film per mu (~0.07 ha) varies depending on the coverage and thickness of the plastic film. For example, if a plastic film with a thickness of 0.008 mm is used to implement half-film coverage (at least 50% soil cover), the average amount of plastic film applied is 4.8 kg·mu^{-1} with an investment cost of 70 yuan, whereas the use of a plastic film with a thickness of 0.012 mm that is used for full-film coverage (complete soil cover), has an average weight of 8.4 kg·mu^{-1} and an investment cost of 120 yuan[27].

Crop growth in China is widely limited by water stress and plastic mulch helps to minimize water loss from the soil thereby increasing water availability to the crop. In conjunction with a ridge-furrow system, plastic mulch can increase water use efficiency, that is, crop yield produced per unit of water used by the crop, by 106%[23]. Generally, the greatest economic benefit of using plastic applications in China, particularly mulch film, is due to improved water use efficiency[1]. Farmers anticipated a saving of up to 25% of their total water budget when plastic mulch film was applied to fields[28]. Not surprisingly, the effect of plastic mulch on water use efficiency and a corresponding economic saving are more pronounced in regions where annual precipitation is lower[23]. The use of plastic applications does not necessarily translate to higher returns for the farmer. In some cases, the acquisition and removal of the plastic applications can be costly, negating the savings from reduced resource consumption (e.g., water, fungicides, and herbicides)[1]. To reduce the cost of agricultural production, state administered prices for mulch film, compensation for increases in price of mulch film and subsidies for residual film recycling have been provided[29]. Many of these support mechanisms were not statewide and have now ceased or are significantly reduced, which is similar to the heavy subsidy and overuse of fertilizers, pesticides and water, all of which are now recognized to compromise long-term agricultural productivity in China[17,18].

The incompatibility of some crops with plastic mulch film has triggered a shift in cultivation patterns across semiarid and arid regions in China, particularly Gansu, Inner Mongolia, Ningxia and Xinjiang regions. Traditionally, families in this region practice subsistence agriculture to meet their own nutritional needs, primarily wheat cultivation. Due to acute water scarcity in many regions, a government-mandated irrigation quota further restricts the water use of individual farmers[28]. A combination of both has led to a shift from more water-intensive grain production to the cultivation of cash crops suitable for the use of mulch, such as cotton, maize and potatoes. Plastic mulch film is often placed on the soil before planting to warm the soil and create a favorable environment for growth. Crops are then planted through punctures in the mulch film which then germinate, grow through the film, and mature, leaving plastic residues in the soil as the structural integrity of the mulch film is often compromised[10,14].

Semiarid and arid regions such as northern China, rely on the use of plastic applications more than humid regions in southern China. The use of plastic greenhouses has increased since the 1970s, covering an area over 3.3 Mha, accounting for over 90% of plastic greenhouses worldwide[30]. Plastic greenhouse use is concentrated in semiarid provinces, such as Henan, Hubei, Shaanxi and Shandong, and are critical to maintaining and increasing productivity in regions with diminishing availability of arable land. In this context, where desertification is increasingly prevalent, plastic greenhouses provide a vital role in soil retention, optimizing fertilizer application and provide protection against dust storm events[30]. Plastic greenhouses are relatively inexpensive, easily-erected and require little management, making an ideal method of cultivation for smallholder farmers[31]. The use of both plastic greenhouses and plastic mulch film has been integral to alleviating the degree of poverty in many semiarid and arid regions of China. The income of farmers in Sanyuanzhu, Shouguang County, increased by 68% annually, coinciding with an increase in the use of plastic greenhouses[30]. Plastic mulch films are often designed to last for a single growing season and then plowed or left to disintegrate in the field, whereas plastic greenhouses are generally replaced every 3 years and are easier to recover and recycle post-use. If these applications are well-managed in use and as a waste material, the almost immediate benefits of this practice should, in theory, continue to have an effect. However, the continuation of traditional practices in parallel with the unsustainable use and inappropriate waste management of plastic applications has impeded and, in some cases, is beginning to reverse decades of agricultural progress (Table 2).

3 Issues with plasticulture: production, use and waste management

Plastics, throughout their lifespan, represent a relatively unknown environmental, ecotoxicological and human health hazard. The majority of plastics in use are produced from fossil-fuel feedstocks, which inherently contributes to the rising levels of greenhouse gas emissions[33]. Although agriplastics represent only 2%–3.5% of annual global plastic production, the degradation and contamination of these applications in the environment raise significant waste management and pollution concerns[19,34]. Globally, 16%–50% of all agricultural plastic waste (APW) is not managed[8], although it has been suggested that these rates are higher in China[35]. Given that 80% of all marine plastics are thought to originate from terrestrial sources[36], mismanaged APW can be a significant source of pollution to the marine environment.

By design, many of the plastic applications used in Chinese agriculture do not exceed the duration of the crop cycle or are reused irresponsibly when the structural integrity of the application is clearly compromised[14]. As the thickness of plastic mulch film used within China is typically thin (0.01 mm), relative to that used in Europe and the USA (0.015–0.20 mm), mulch films can degrade shortly after use and it is therefore more difficult, time-consuming and costly to recover this material from the field[10]. Contamination of

Table 2 Average annual growth rate of agricultural production and plastic use in China

Average annual growth rate (%)	1952–1977	1978–1985	1986–1995	1996–2005	2006–2016
Gross value of agriculture	2.48	6.29	4.22	4.35	4.55
Grain	2.91	3.35	2.16	0.51	2.24
Cotton	5.07	12.21	2.75	2.81	−0.03
Oil seeds	2.13	18.00	4.12	3.36	1.74
Sugar crops	9.34	14.87	2.84	3.27	2.79
Vegetables				8.32	3.23
Fruits	3.88	6.97	14.13	17.96	5.27
Livestock	5.26	10.77	9.38	7.44	3.43
Aquatic products	13.10	9.44	14.82	7.58	5.03
Mechanization		8.61	5.64	6.60	3.41
Irrigated land		−0.30	1.14	1.11	1.83
Fertilizers		10.69	7.32	2.88	2.10
Pesticides			9.26	3.04	2.04
Plastic greenhouse area				65.0	13.3
Plastic mulch film area			44.26	12.4	8.33

Note: Data extracted from Chang et al.[30] and Yu & Wu[32].

mulch films limits the amount that can be recycled with up to half the weight of such recovered films consisting of soil debris and inorganic amendments, and such material is often rejected by the operators of recycling facilities. Considering that most films are used in areas of water scarcity, cleaning the plastic application is unlikely to be a viable option. As a result, a significant portion of these films is left on the field and are often incorporated into the soil. Additionally, the inadequate provision of waste-management facilities and a lack of knowledge on how to appropriately handle end-of-life agriplastics, both in China and worldwide has contributed to the pollution of agricultural soils, water courses and beyond[37,38].

The issue of plastic pollution is particularly acute where plastic mulch film is used. It is well established that this application is the primary source of plastic residues in agricultural soils within China[39]. Although plastics used in greenhouse cultivation can be easily recovered and reused, due to the lack of contamination, films used in this way are still a source of environmental concern. Once the plastic has served its use in the field (a single season for mulch but perhaps two or three seasons for greenhouse film), these films are often buried, burned or discarded on farm, releasing toxic byproducts, posing a threat to air and soil quality[40]. The reasons behind these decisions are well-known and are relevant to agriplastics and other agricultural waste products, that is, a lack of experience and environmental awareness, and often technical guidance available to farmers is minimal. Combined with a lack of economic compensation and the lack of infrastructure to collect, sort and transport plastic applications, farmers have limited options to appropriately handle APW[38]. In recent years, the use of mulch film in the Gansu, Hebei, Shandong and Xinjiang regions has increased. By 2010, 6.96 Mha of arable land in Gansu was covered by mulch film as part of a double-ridge-furrow system, amounting to 100 kt, 80% of which became agricultural plastic waste within a year[41]. The thickness of domestic agricultural mulch film is only 0.006–0.008 mm, much thinner than the 0.02 mm standard in the USA and some European countries[10]. Thinner film is cheaper to produce but has a lower tensile strength and therefore loses its structural integrity more quickly, readily degrades and is harder to recover. As the recovery of waste agricultural film is labor-intensive and the mechanized recovery of waste is poor, the mechanized recovery rate can be less than 15% in some areas[41]. Although efforts have been made to regulate the thickness of plastic films used in agriculture and enforce the collection and recycling of plastic applications globally, there is little evidence to suggest that the accumulation of plastic residues in agricultural soils worldwide is being reduced.

Once plastic residues are incorporated into the soil, any further degradation is slow as the residue is no longer exposed to the conditions that trigger photodegradation. In such contexts, plastic residues could potentially remain for decades until mechanically, chemically or biologically degraded[1]. Due to a combination of inadequate waste management and the slow degradation rate of plastics in the environment, plastic residues have begun to accumulate in the terrestrial environment, particularly agricultural soils[3,4,8,10,11,42]. The load of plastics in agricultural soils is compounded by other inputs such as plastic-coated fertilizers, farmyard manure, agricultural machinery, slurry and atmospheric deposition from dust storms. The fragmentation of plastic residues, from macroplastics to microplastics, can be accelerated where the soil is subject to high intensity machine tillage[43].

It is well established that the concentration of plastic residues (macro-, micro- and nanoplastics) in agricultural soils across China are of great concern. Due to the lack of standardized analytic procedures, reporting the concentrations of plastic residues in agricultural soils yields a range of results. Meta-analyses have reported that the concentration of plastic residues in agricultural soils across > 700 sites averaged 34 $kg \cdot ha^{-1}$, in some cases exceeding 380 $kg \cdot ha^{-1}$ [7,14]. From 25% to 33% of plastic mulch film applied each year can remain in the field[44]. This, accompanied with a slow degradation rate, has led to the progressive accumulation of plastic residues in the soil, averaging 51.9 $kg \cdot ha^{-1}$ in cases where plastic mulch film has been used for 20 years or more[14]. Due to the longstanding use of plastic mulch film, the residue load in north-western China and on the North China Plain is the highest recorded in China. Microplastics, defined as plastic particles < 5 mm, have been reported to range between 320 and 42,960 particles kg^{-1} in farmland soils across China[45–47]. Although macroplastic pollution in China is thought to be acute in comparison to other agricultural environments, published quantities of microplastics in similar environments are comparable. For example, 3500 particles$\cdot kg^{-1}$ was detected in Chile, 500–7659 particles kg^{-1} in Valencia and 71,000–145,000 particles kg^{-1} in Danish agricultural soils[48].

4 The impact of agriplastic pollution on soil, plant and human health

Quantifying the impact of plastic residues (macro-, micro- and nanoplastics) on environmental, ecological and human health is complex. Due to the difficulty in point-source tracing, it is hard to discern whether an observed impact is the direct result of agriplastic pollution. During the production of agriplastics, a host of additives and plasticizers are integrated into the polymer, depending on the material characteristics required for use. As these chemicals are often loosely bound to the polymer, and can be released into the environment shortly after use and accumulate in the soil[4]. Consequently, it is difficult to separate the effects of the plastic residue and that of the additives that are integrated into the polymer.

The proposed effects of plastic pollution on crop production are multifaceted. The microbial, physical, chemical and structural properties of soil have been observed to change as a function of varying degrees of contamination. In highly-contaminated soils, macroplastics can compromise soil structure. Here, nutrient and water transport is limited, negatively affecting the water holding capacity of the soil, which can lead to soil anoxia[4,10], one of the most damaging of soil conditions for all crop plants. Anoxia will negatively impact seedling emergence and the establishment of a root network. This has been shown to reduce the yield of the cotton crop by 4%–19%[7,10]. Based on a meta-regression, plant height has been shown to decrease at a rate of 2%, root weight by 5% and crop yield by 3% as plastic residues in soil increase by 100 $kg \cdot ha^{-1}$[14]. Laboratory-based experiments suggest that the impacts of these changes increase markedly as macroplastic load increases[14]. Micro- and nanoplastics can accumulate in plant tissue through submicrometer openings in roots[49]. In such contexts, particles and additives have a negative effect on plant physiology. The diffusion of additives, notably diisobutyl phthalate, into mesophyll cells disrupts chlorophyll formation[7,50]. Other studies have observed that germination, height, biomass and root length in cereal and cash crops are negatively impacted by the presence of macroplastics and microplastics[51].

Under both plastic mulch films and greenhouses, soil health and fertility are threatened. Although, plastic covers protect soil from water erosion and weathering, farmers often manage these systems in a similar way to open-field grain crops, often leading to the overuse of fertilizer[10,30,31]. The accumulation of residual salts, particularly NO_3^-, has led to soil salinization and acidification in many of these systems[31]. Compared to open-field systems NO_3^-, K^+ and Ca^{2+} concentrations were 265%, 224% and 139% higher[31]. Under these conditions, the soil microbial community is reshaped, inhibiting crop growth, production, and quality[52]. In areas which practice flood irrigation or receive isolated heavy rainfall events, the leaching of these residual salts can pollute surface and groundwater systems[53]. The impact of plastic pollution on soil chemistry and nutrient cycling is poorly understood. Evidence has suggested that plastic residues in soil can affect carbon and nitrogen cycles and the consequent release/sequestration of greenhouse gas emissions[51,54]. Meta-analyses have shown that soil available phosphorus and soil organic matter are negatively impacted by plastic residues, decreasing at a rate of 5% and 0.8%, respectively, as residue concentrations increase by 100 $kg \cdot ha^{-1}$[14]. In some cases, the use of plastic greenhouses has led to an increase in plant-available N, P and K, although, the underlying mechanisms for these changes are unknown[30]. A consensus has not been reached on whether plastic residues in agricultural soils have a direct net positive or negative impact on nutrient cycling.

The presence of microplastics in soils is known to negatively impact the reproduction, survival and weight of soil organisms[51,55]. Earthworms serve a vital role in maintaining soil health and quality. When exposed to microplastics, earthworms have higher mortality and lower growth rate, which is thought to be the result of changes in the gut microbiota[56]. With less available energy due to microplastic ingestion, earthworm activity and density are lower, resulting in less soil mixing and reduced soil fertility and nutrient availability[57]. Changes in the structure and activity of the soil microbial community, and likewise the micro-, meso- and macrofauna, can influence the decomposition of soil organic matter and carbon sequestration, both positively and negatively[58]. In some cases, the presence of microplastics is thought to increase root biomass, soil enzyme activity and the bioavailability of Zn[51,59]. The understanding of the mechanisms responsible for these positive impacts is poor. Effects of plastic pollution are dependent on the concentration, chemical properties, shape, and exposure time to the plastic residue, all of which are magnified in higher trophic levels[60]. Therefore, it is difficult to establish critical limits of plastic residue contamination at which impacts, both positive or negative, are observed.

Leaching of additives and plasticizers from plastic residues and the sorption of toxicants, heavy metals and agrochemical inputs poses a threat to aquatic and terrestrial food webs and ultimately human health[3,43]. The use of phthalates as plasticizers, particularly polychlorinated biphenyl, can have deleterious effects on the soil microbial community, directly affecting the endocrine system[61]. The uptake of phthalates in crops has been widely reported, for example, diethylhexyl phthalate (DEHP) has been observed to be taken up by the roots of vegetable and grain crops and translocated to stems and leaves[62]. In 2017, mulch and greenhouse films in China contributed to the release of 42.2 and 24.5 t DEHP, respectively[12]. The severity of this bioaccumulation raises human health concerns, particularly for children. It is thought that human exposure to DEHP is 4–17 times higher from vegetables grown under plastic greenhouses in China, than the EU[63]. Due to the size of smaller residues (micro- and nanoplastics), the bioaccumulation of particles in food, among other things, can expose humans to plastic loads exceeding 100,000 particles per day[49,64]. Microplastics and nanoplastics, due to their size, are able to pass through cell membranes and accumulate within human tissue[65]. An disconcerting amount of evidence has identified the presence of microplastics in human faces, gut tissue, and placenta[66,67]. It is difficult to determine whether these particles have any direct impact on human health. Proposed effects are similar to those caused by nanomaterials and particulate air pollution, including inflammatory and oxidative stress, cytotoxicity, autoimmune response and DNA damage[65,67].

The extent of effects from plastic pollution in agricultural soils, and the accompanying mechanisms, remains largely unknown. However, the known effects already threaten the long-term food security of communities dependent on many agricultural systems, due to potentially irreversible soil degradation and impacts on human health[68]. Considering that plastic pollution is more acute in north-western China, a region that suffers from water scarcity, desertification and a range of other climate change impacts, the impacts of all these pressures can disproportionally affect those in the region who largely depend on production from their own smallholdings.

5 Current solutions to plasticulture

In 1997, China’s Ministry of Ecology and Environment began to focus on the prevention and control for plastic pollution from the agricultural use of mulch films. In response to an increasingly acute problem, a management framework to address plastic pollution was established as part of the Soil Pollution Prevention and Control Action Plan, 2016. Later iterations in 2018 and 2019 aimed to increase the recycling rate of agriplastics to more than 80% by 2020 and introduce regular soil testing to encourage a shift to less harmful practices, a key mechanism for reducing plastic pollution[69,70].

As a consequence of their nature, plastic films are clearly contributing to a growing plastic pollution crisis. The use of thicker film reduces the time and labor required to retrieve plastic film from the field after use and encourages reuse, if structurally intact. In 2018, only 21% of plastic mulch film in use met the previous national standard of 0.008 mm and 66% of all plastic film was not recovered after use. Therefore, in September 2018, the Chinese Government proposed that mulch film for agriculture should be a minimum thickness of 0.010 mm, thought to reduce the amount of residual mulch film by 60%[70]. This, among other mandatory national standards to improve the production, sale, use, recycling and reuse of agricultural film, were introduced as part of a measure to protect and improve the agricultural environment in China[71] (Table 1).

Much of the production and use of plastic film is decentralized and spread across a vast area of China and it is difficult to regulate and enforce legislative changes with the limited resources available to the state[72]. In such contexts, the local market supervision, agriculture and rural affairs department are responsible for the investigation and enforcement of breaches to the national standards of agricultural film production and use. In 2022, the government of Hebei Province proposed that 3 million mu (~210,000 ha) of thicker mulch film with a higher tensile strength and 500,000 mu (~35,000 ha) of fully biodegradable mulch should be procured and applied to cropland[73]. By 2025, it is expected that the mulch film recovery rate in Hebei will exceed 85%, and the residual amount of mulch film in farmland will achieve zero growth. Farmers growing crops that are extensively covered by mulch film (cotton, maize and vegetables) will be encouraged to use thicker, reinforced mulch films with a minimum thickness of 0.015 mm to improve the recyclability and recovery rate of agriplastics.

Forming a scientific rationale and standardized guidance for the promotion and use of plastic mulch film alongside clear rights and responsibilities for recycling agriplastics with appropriate governance will be effective at controlling plastic pollution and integrating sustainable plasticulture at a provincial level. These unprecedented approaches to reducing plastic production, use and pollution at a national and provincial level targets a wider range of plastic products at a higher administrative and legal level, promoting research into the development of alternative products over the next 5 years[72]. While other countries have introduced legislative mechanisms with limited range or scope to control agriplastic pollution on a nationwide to individual scale, China's nationwide, provincial and community approach has the potential to create a circular plastics economy and better control domestic and international plastics pollution.

Active research is focused on developing biodegradable, environmentally benign plastic film. Although these films offer a promising alternative to currently-used agriplastics produced from fossil-fuel feedstocks, the short- and long-term effects of these materials are relatively unknown[74]. Following an urgent need to reduce residual mulch pollution in croplands in China, the promotion and application of biodegradable mulch film is a necessary development. In Hebei, the use of biodegradable mulch films which meet the national standard GB/T35795-2017 will be trialed on garlic, peanuts and potatoes to test the feasibility of widespread promotion on suitable crops[73]. Biodegradable mulch films are typically made from polysaccharides (such as starch), cellulose, chitin or polyesters (such as polylactic acid) and polybutylene adipate terephthalate. Most variations of biodegradable films are optimized to undergo photodegradation or microbial degradation and are often prefabricated. Novel biodegradable mulch films can be sprayed onto the soil surface for easier application, faster degradation and this material is less labor-intensive to recover[75]. In theory, once the biodegradable plastic film has fulfilled its purpose, it should undergo complete degradation into biomass, carbon dioxide and water. However, biodegradation takes place in the soil under suboptimal conditions in comparison to optimal, well-defined laboratory conditions[1]. It is not known whether the use of biodegradable mulch films contributes to microplastic and nanoplastic pollution in agricultural soils.

The nationwide implementation of biodegradable plastic film is limited by the high cost of the material and the lack of a commercially feasible production systems[7,76]. Currently-used plastic mulch film can cost 10,000 yuan·t^{-1}, whereas biodegradable film could cost between 25,000 and 30,000 yuan·t^{-1}[44]. Consequently, there is a call from industry for the government to subsidize the research and development, and to encourage the use of biodegradable mulch film by farmers and enterprises in the plastics industry. Equipped with the knowledge that biodegradable films, in theory, will ensure sustainable agricultural development, farmers are keen to use these in replacement of currently-used mulch films where economically viable[29]. As the majority of farmers in China are smallholders operating on small-profit margins, many continue to use the prohibited, thinner film, due to its low cost and the better perceived quality[14].

Without widespread financial and behavioral measures to support existing policies and legislative instruments, an urgent transformative change in the agriplastics industry has not been achieved and seems unlikely in the foreseeable future. These policies and regulations target singular aspects of the life cycle of plastics. The FAO has recommended that new laws should regulate all aspects of plasticulture, the production, use and end-of-life management to practice sustainable agriculture[8].

6 A role for sustainable plasticulture in AGD

The impact of plasticulture can jeopardize soil health, crop quality, food security and sustainability of agricultural systems in the long term[1]. In recognition of these impacts, there has been a call to significantly restrict or ban the use of plastics in agriculture. China, much like other countries, has become reliant on plasticulture to feed a growing population with accessible, nutritious and sustainable food. Meeting these demands is a growing concern in China given that water scarcity and desertification is projected to increase[20]. The prevalence of diabetes and obesity is rising, each affecting over 10% of the population[77]. Given that the Chinese administration has prioritized the improvement of the capacity to grow, handle and store fresh produce, and to reduce food waste, it is therefore expected that plastic use in agriculture will continue to increase[77]. It is not a question of whether plastic use should increase or decrease within the Chinese agricultural system, but rather, how can it be better managed.

To better manage plasticulture through production, use and waste management the Chinese agricultural system requires evidence-based solutions. Policies, regulations and subsidies must be both precautionary and practical, requiring collaboration between scientists and policy, to support farmers to enhance ecosystem services, produce sufficient amounts of fresh produce and reduce the detrimental impacts of plastic use[30,77]. Given the diversity of environmental conditions, agricultural practices and social, cultural and economic landscape across China, solutions must be tailored to the province, local government and village to be most effective.

Waste-management infrastructure must be further developed. The historic exportation of highly-contaminated and non-recyclable APW from the EU and USA to China has been problematic. To reduce the environmental concerns of largely unregulated and often illegal APW, China introduced the National Sword policy in January 2018 to better manage and regulate waste imports. The legacy of this relationship still exists as many of agriplastic recycling facilities in China are designed to process agricultural plastic waste imports and not domestically-produced agriplastics. A nationwide assessment of plasticulture must precede the widespread implementation of waste-management infrastructure. Identifying where inappropriate plastic use, waste generation and pollution is most acute will be integral to the strategic distribution of such infrastructure. The process of recovering, sorting and recycling agriplastic waste must not place a financial burden on the farmer or be excessively time consuming. The design and implementation of accessible, simple waste facilities with sufficient economic compensation is key to increasing rates of reuse and recycling[8,29,78].

To remediate plastic pollution from past, current and future use, subsidizing the provision of recovery machinery for both individual farmers and rural communities might be effective in reducing plastic pollution and improving recycling rates[14]. The integration of recovery equipment into plowing machinery would improve the separation of plastic residues from complex root systems and increase the efficiency and volume of recovered agricultural plastic waste[79]. Plastic recovery machinery must be able to operate effectively on complex terrain and with the wide variety of crops currently grown in China. Where recovery machines cannot be purchased by individual farmers due to financial constraints, these machines could be purchased at the village level as a collective. In the absence of dedicated recovery machines, the manual removal and recycling of plastic residues could be coordinated at the village level, conducted at the end of the growing season.

The recycling practices of farmers in China are largely influenced by informal institutions, more so than formal institutions such as government[80]. The role of village regulations has an important role in dictating farmer behavior[71,81]. The regulation of plastic film thickness, use and waste management could be an effective mechanism to promote sustainable plasticulture. Where formal institutions lack the capacity to effectively enforce the plastic film standards, rewards and penalties implemented at a village-scale could generate positive change regarding the purchase, use and end-of-life management of agriplastics[71,82]. To encourage sustainable plasticulture, comprehensive policy should be introduced to suit the environmental, economic and social conditions in each area.

A lack of environmental awareness, experience in agriplastic waste management and technical guidance are key barriers to sustainable plasticulture[69]. Education, engagement, and guidance are important mechanisms in driving change. Equipped with the knowledge of how to prepare agriplastics for recycling with minimal contamination, the recovery and recycling rates of agriplastics by individual farmers might greatly increase. Reducing the contamination of agriplastics at source decreases the loss of soil and nutrients from the topsoil and alleviates the financial burden on farmers and recycling facilities to remove impurities from the waste plastic before it is processed. The Chinese government should encourage farmers to use codes of best practice, whereby any plastic used should have no impact on the immediate and wider environment[78]. Targeted campaigns should seek to increase environmental awareness of farmers in areas that are non-compliant to existing regulations or experiencing severe levels of plastic pollution. Campaigns should actively engage young farmers, equipping the next generation of farmers with the expertise and knowledge to better manage agriplastics in use[69].

Evidence suggests that farmers who have expressed environmental conscientiousness, recognize that plastic film has negative implications for soil health and were less likely to use mulch film[69]. Instead of abandoning plastic use, farmers can work to a set of criteria that has benefits for long-term food and eco-security. Providing guidance on how to handle agriplastics sustainably could have corresponding benefits for the sustainable use of fertilizer, pesticide and water. In parallel, providing farmers with more stable property rights could empower individuals to consider the long-term implications of how they use and manage plastics, instead of being driven by the short-term, economic benefits of the material[69]. Giving farmers greater stewardship over their land encourages investment into improving soil health, quality and environmental awareness over the continuation of unsustainable practices[77,83].

All of these solutions require investment and funding to be effective. Enforcing the extended producer responsibility principle on agriplastics producers would assist farmers in procuring agriplastics and managing their agricultural plastic waste, through education, appropriate financial support and provision of waste-management facilities. In such contexts, the responsibility of end-of-life plastics is shared between the producers, distributors and users proved to be effective in parts of Europe[78]. In parallel, investment is required from centralized and decentralized sources, a nationwide to local government approach, reflective of the environmental conditions, agricultural practices and the social, cultural and economic landscape.

Agriculture in China is experiencing a set of multifaceted pressures which threaten to compromise food and eco-security targets. A solution to these issues could rely on the sustainable intensification of agriculture through new ADG programs launched the Chinese government and supporting universities[16,84]. Plasticulture, as a form of intensive agriculture, has been proven to produce more food, using less land and fewer inputs. As discussed, plasticulture can result in a wide range of negative consequences. There is scope to adapt current production systems and introduce mechanisms to mitigate the existing issues with this practice. The solutions we present here rely on a multifaceted, holistic, collaborative approach to remediate the existing issues with plastic pollution and waste management. The removal and recovery of plastic residues from the soil must take priority. Without immediate action, plastic pollution is likely to compromise a range of ecosystem services and long-term agricultural productivity. From an individual farm to a regional scale, mechanisms for change must be complementary, focusing on education, incentivization and infrastructure. Some of the environmental concerns associated with plasticulture could be addressed in the short-term by widespread dissemination and adoption of codes of best practice[78]. A long-term vision of sustainable plasticulture is desirable. Chinese policymakers must urgently consider how plasticulture is likely to shape the future of agricultural systems and consequently the food security and safety of the nation, both positively and negatively.

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Compliance with ethics guidelines

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