

From plasticulture to pollution: addressing disposal and recycling challenges in Egyptian farming systems

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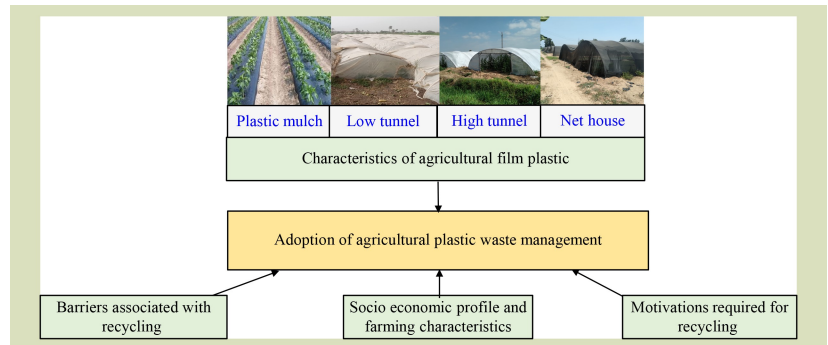
KEYWORDS

Barriers, disposal, environmental sustainability, farmers, motivations, plastic mulch, plastic waste management

HIGHLIGHTS

- Egyptian farmers use plastic film primarily for vegetable production in winter.
- Recycling plastic mulch poses greater challenges than recycling plastic covers, primarily due to fragmentation.
- Economic barriers, such as high recycling costs, impede recycling of agricultural plastics by farmers.
- Financial incentives and improved plastic quality have a crucial role in motivating farmers to engage in recycling.
- Larger farm sizes and family involvement enhance recycling behavior among Egyptian farmers.

GRAPHICAL ABSTRACT



ABSTRACT

The global use of agricultural plastic film has severely impacted the ecosphere due to their non-biodegradability, unsafe disposal and limited recyclability. This study aimed to investigate how farmers use agricultural plastic film, including plastic mulch and plastic covers and manage their disposal. The study was conducted in three governorates of Egypt: Dakhalia, Giza and Minya. Data were collected through stratified proportional random sampling based on farm size, surveying 300 farmers managing four plasticulture systems: plastic mulch in open fields, net houses, low tunnels and high tunnels. The data were collected through face-to-face interviews using a structured questionnaire. The study findings reveal that plastic mulch residuals are often burnt in the open or plowed back into soil matrix, whereas plastic film covers are typically collected for recycling. Also, farmers identified the lack of recycling facilities and the absence of fixed disposal locations as the main obstacles for proper plastic waste management. The regression analysis findings also showed the main factors positively affecting the plastic mulch recycling behavior of farmers, including farm size, farm ownership, family member participation in

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agriculture, and years of experience with plasticulture systems. The findings provide valuable insights for policymakers to develop collaborative management strategies for plastic disposal and recycling, aiming to reduce the environmental risks of microplastics in terrestrial ecosystems.

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1 Introduction

Farmers use plastic extensively in agriculture, leading to the term “plasticulture”^[1]. According to the *Plastics Europe report, Plastics—the Facts 2022*, agricultural, farming and gardening activities generated 4% of the 391 Mt of plastic globally^[2]. Although this share is small compared to other industries, the widespread availability and low cost of plastic products have transformed agriculture from a traditionally low-waste sector into one facing significant waste management challenges^[3].

The importance of plastic use in agriculture is unequivocal, as it contributes to improved crop protection, water conservation, food safety and quality, and ultimately reduces the environmental footprint of the agricultural sector^[4,5]. Agricultural plastics have become essential for supporting sustainable practices, such as implementing effective pest management programs, minimizing pesticide applications and reducing the use of fertilizers and agrochemicals^[6]. Plasticulture is used in several areas, including mulching, low tunnels, high tunnels, net houses, silage, irrigation, storage and transportation^[7,8]. Despite these benefits, considerable drawbacks arising from the continuously generated plastic wastes^[9]. Also, the proper collection and disposal of these polymers remain questionable^[10]. This fact is emphasized in the Food and Agricultural Organisation report^[7], *Assessment of Agricultural Plastics and Their Sustainability*, which notes that the fate of a substantial portion of the 12.5 Mt of plastic waste produced annually and dispersed in the environment remains unspecified.

Low-value, single-use materials make up a substantial proportion of agricultural plastics and farmers often contaminate them heavily, making collection, recycling and reuse challenging. As a result, most recyclers reject these materials^[11]. High costs of transportation, landfilling and recycling often drive farmers to unlawfully bury, dump or burn plastic waste on-site, which releases dangerous compounds into the air, soil and water, harming the environment and human health^[12,13]. Additionally, when farmers repeatedly

dispose of plastics improperly, they contribute to the generation of microplastics (particles smaller than 5 mm) that spread through surface runoff into subsurface soil layers. This accumulation degrades soil health and threatens the food chain^[14,15]. Therefore, farmers and policymakers must manage the mass production of plastic waste sustainably to minimize its adverse effects on terrestrial and aquatic ecosystems.

The application of the 3R waste hierarchy, reduce, reuse and recycle, is essential to manage agricultural plastics sustainably^[16]. Farmers can reduce plastic waste by adopting alternative materials, such as biodegradable mulch film, and by optimizing plastic use efficiency in greenhouse systems and irrigation^[17]. Reusing plastic products, like irrigation pipes, containers and silage covers, can extend their lifespan and minimize waste generation. Recycling, the final step, involves collecting used plastic mulch, film and drip tape for processing into new products^[18]. Establishing accessible recycling facilities and incentivizing farmers to participate in recycling programs can address economic and logistical barriers. Integrating these practices can help transition agriculture from a linear to a circular plastic economy, reducing environmental impacts and enhancing resource efficiency^[19].

In Egypt, recycled plastic production reached 1.5 Mt in 2022/2023, with public and private investments in plastic waste recycling valued between 1 billion and 2 billion EGP during the same year. Additionally, about 1800 workers were employed in the plastic waste recycling sector^[20]. However, the fragmented nature of agricultural plastic market in Egypt, which is characterized by numerous actors, limits the potential for systematic data collection on recycling and disposal practices across different plastic waste categories. Additionally, the insufficient collaboration between the Ministry of Agriculture and the Ministry of Environment does not maintain comprehensive statistics or reports on agricultural plastic waste, resulting in sporadic and often unreliable information from alternative sources. Egypt has implemented several policies and initiatives to manage agricultural plastic waste,

emphasizing sustainable development and circular economy principles. The Waste Management Law No. 202 of 2020 and its subsequent executive regulations set the framework for waste collection, recycling and disposal, including agricultural plastics^[21]. National campaigns, such as those targeting single-use plastics, aim to reduce environmental pollution by promoting alternatives and raising public awareness^[22]. Additionally, international collaborations with organizations like UNIDO and the Government of Japan support sustainable practices in the plastics value chain^[23]. Local initiatives, such as Baramoda recycling programs, further contribute to managing agricultural waste by converting it into valuable products^[24]. These combined efforts highlight Egyptian commitment to reducing plastic pollution and enhancing waste management practices.

To manage agricultural plastic waste sustainably, innovators must link their efforts to social processes. Farmers, who act as recipients of agricultural plastics, victims of their waste and beneficiaries of recycling initiatives, are crucial in addressing this issue^[25,26]. Researchers must examine farmer knowledge, attitudes and behaviors regarding plastic waste management to develop effective interventions^[27]. King et al.^[27] highlighted that as farm incomes rise, so does the concern about plastic pollution, leading them to invest more in environmental solutions. However, the success of these initiatives relies on farmer knowledge, positive attitudes and willingness to engage in waste management schemes. Despite its importance, few empirical studies have explored farmer perspectives on managing agricultural plastic waste, especially in Egypt. To fill this gap, this study proposes a conceptual framework to analyze current disposal and recycling practices in Egypt. A deeper understanding of this issue could help design awareness campaigns and policy interventions that encourage pro-environmental behaviors among farmers. Accordingly, this study aimed to examine the behavior Egyptian farmers in plastic waste management. The objectives of the study were to: (1) analyze the types and characteristics of plastic film used, (2) identify farmer adoption of plastic waste management methods, (3) explore the barriers faced by farmers in managing plastic waste and the motivations needed to address these challenges, and (4) determine the factors influencing farmer behavior toward plastic recycling.

2 Conceptual framework

The study proposed a conceptual framework to analyze plastic

waste management at the farm level (Fig. 1). The framework briefly explains four key components examined in the study: farmer socioeconomic profile and farming characteristics, adoption of farm waste management methods, barriers to plastic recycling and motivations needed to encourage farmers to recycle agricultural plastics. Additionally, the personal attributes of farmers were used as explanatory variables to evaluate their effect on the plastic mulch recycling behavior.

The literature on agricultural plastic waste management has considered recycling behavior as a sustainable farming practice or a form of pro-environmental behavior. Numerous studies acknowledge the importance of farmer socioeconomic characteristics in affecting various environmental aspects of plastic waste management. These include behavior related to intention, adoption or participation in pro-environmental schemes^[25,28–31]; attitudes and preferences^[27,32–35], and perception, knowledge or awareness of plastic waste management practices^[35–37].

Improper disposal methods for agricultural plastic waste by farmers have drawn considerable attention in the literature due to the non-biodegradable nature of plastics, which pose important risks to aquatic and terrestrial ecosystems, human health and the aesthetic quality of landscapes and water bodies^[38,39]. In response, governments have prioritized the development of legislation, the implementation of continuous monitoring programs and the proposal of incentive schemes to encourage pro-environmental behaviors among farmers while showcasing their environmental commitment to consumers and markets^[40]. Farmers currently use various disposal methods for agricultural plastic waste, including burning, burying, piling, landfilling and recycling^[4,12,27,41]. Examining the current level of on-farm disposal practices is essential to evaluate how well these methods comply with legislative requirements for safety, health and environmental protection. Also, quantifying the percentage and volume of plastic waste that is disposed of correctly and identifying practices that should be avoided critical steps^[42,43]. These efforts are fundamental to designing or updating a comprehensive waste minimization plan that emphasizes avoiding, reducing, reusing and recycling plastic waste wherever possible.

Recognizing barriers is important in predicting recycling behavior. Analyzing farmer perceptions of these barriers helps identify the point at which a particular obstacle becomes too important, thereby aiding the development of targeted

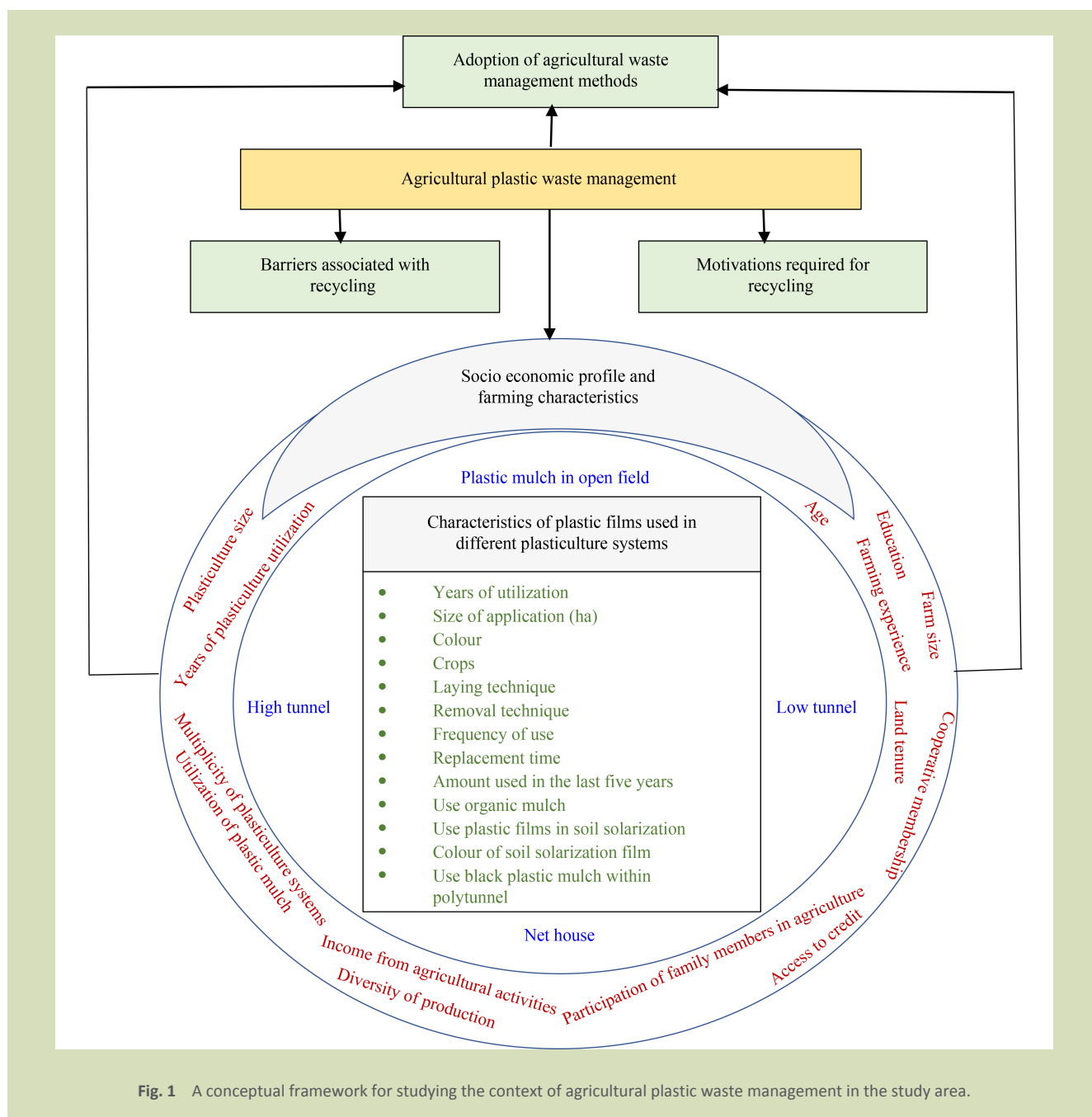


Fig. 1 A conceptual framework for studying the context of agricultural plastic waste management in the study area.

intervention plans^[9,44]. Such analyses can also differentiate between farmers who are concerned or unconcerned about environmental issues, clarifying their readiness to participate in recycling initiatives^[45]. Studies have highlighted several barriers that prevent farmers from effectively recycling agricultural plastic waste. Of these, inequitable enforcement of legislation has been identified as a critical barrier to agricultural plastic waste management^[25,44]. Cognitive barriers, such as

limited advocacy for circular economy and sustainability concepts^[46], insufficient information about proper methods to reduce plastic waste^[4,29,47] and low awareness of relevant legislation^[40], are also critical. Service quality and management challenges are particularly impactful, including inadequate waste collection services^[12,31,44,47], insufficient capacity of recycling services to handle large volumes of plastic waste^[31,46,47], long distances to recycling facilities^[29,31,47] and

gaps in management structures between the farming community and the plastics industry^[31,34]. Financial barriers, such as the rising costs of plastic waste collection^[25,29,44], unwillingness to pay for recycling and the failure to provide economic compensation for recycling efforts^[25], further complicate this issue. Finally, cognitive barriers in terms of personal beliefs and a lack of knowledge about recycling practices have also been noted as factors limiting effective recycling behaviors among farmers^[29,47]. Addressing these barriers is essential to improving agricultural plastic waste management and promoting recycling initiatives.

Motivations are the specific circumstances that drive stakeholders to collaboratively address a particular issue or set of issues^[48]. Overcoming barriers to agricultural plastic waste management depends on the type and extent of incentives offered by governments, industry or through partnership mechanisms involving farmers, their representatives, agricultural cooperatives or non-profit organizations^[49,50]. The literature emphasizes the profound effect of motivation on pro-environmental behavior, particularly the source of that motivation, highlighting two key aspects. The first is the distinction between intrinsic and extrinsic motivations^[51]. Intrinsic motivation refers to engaging in an activity because it is inherently enjoyable or interesting, while extrinsic motivation involves performing an activity to achieve a specific external outcome^[52]. The second is that studies exploring motivations for pro-environmental practices often employ the protection motivation theory (PMT) framework^[53–56]. PMT identifies six elements that affect protective motivation decisions. Response efficacy: the belief that the protective behavior^[57] will effectively prevent or mitigate a threat. Self-efficacy: the perceived ability to perform the protective behavior. Severity: the negative outcome or damage caused by the threat. Susceptibility: the degree to which an individual feels vulnerable to the consequences of the threat. Response cost: the financial and non-financial costs associated with engaging in protective behavior. Rewards of non-protective behavior: the perceived benefits, both financial and non-financial, of not engaging in protective behavior. Studies have highlighted several key strategies for addressing barriers to agricultural plastic waste recycling. Meng et al.^[31] and Muise et al.^[12] emphasized the importance of developing co-management partnerships between farmers and stakeholders in the plastics industry to enhance collaboration. Xu et al.^[34] argued the need for improving the quantity and quality of waste management services to boost recycling rates. Additionally, organizing capacity-building programs and

awareness campaigns focused on waste handling and recycling has been suggested as an effective approach^[4,42,44]. Huang and Elahi^[32] and Xu et al.^[34] also highlighted the critical need for economic incentives, recommending the design of subsidy-based incentive policies to encourage recycling. Also, the proximity of recycling services to farming communities^[34,58] and the provision of additional waste pickup services by recycling providers^[41] were identified as important motivators for farmers to participate in recycling initiatives.

3 Methodology

3.1 Description of study area

This study was conducted in three Egyptian Governorates: Giza (Central Region), Dakhalia (North-eastern Region) and Minya (Upper Region). The study area was purposively selected based on the number of farmers using agricultural plastic systems during the 2022/2023 agricultural season and the diversity of plasticulture systems adopted^[59]. Giza Governorate, situated in the Central Region (29.762° N, 30.462° E), spans a land area of 13,184 km² with a total arable area of about 100 kha^[60]. Between 2015 and 2023, the average annual temperature was 22.1 °C, and the average monthly rainfall was 20 mm^[61]. Key agricultural produce in this governorate includes faba beans, maize, onions, peanuts, sesame, vegetables and wheat^[59]. Dakhalia Governorate, located in the North-eastern Region (31.140° N, 31.220° E), has agricultural fields accounting for 37% of its total land area^[60]. The climate is characterized by hot and humid conditions, with an average annual temperature of 20 °C and monthly rainfall of 57 mm^[62]. The primary crops grown in Dakhalia include citrus fruits, Egyptian clover, grapes, maize, onions, rice, sugar beet, vegetables and wheat^[59]. Minya Governorate, located in the Upper Region (28.077° N, 30.093° E), covers a total land area of 32,279 km², with about 205,000 ha designated for agriculture^[60]. The average annual temperature is 15.72 °C, and the average monthly rainfall is 3.08 mm^[63]. Predominant crops in Minya include bananas, cotton, grapes, maize, soybeans, sugarcane, vegetables, watermelons and wheat^[59].

3.2 Sampling and data collection

A two-stage random sampling method was used to select farmers for the study, ensuring the sample accurately represented the three governorates. One district from each

governorate, known for extensive use of plasticulture systems in agriculture, was identified. Minya, Bilkas and Monshae't El Kanater Districts were selected from Minya, Dakhalia, and Giza Governorates, respectively. Within each district, three villages were randomly selected with guidance from agricultural extension officers. The selected sites were Beni Ahmed, Tahnasha and Der Attia in Minya; Al Gehad, Abo Madi and 15 May in Bilkas; and Abu Ghalib, Berkash and Beni Salama in Monshae't El Kanater. The study population consists of all farmers in these nine villages who used four agricultural plastic systems (plastic mulch in open fields, low tunnels, high tunnels and net houses) during the 2022/2023 agricultural season, totaling 2883 farmers. Data collection used stratified proportional random sampling based on farm size. Farmers were categorized into four groups: large (> 10 ha), medium (> 4–10 ha), semi-medium (> 2–4 ha), and small (2 ha or less). The number of farmers in each category was determined for every community. The survey sample consisted of 351 respondents, calculated using the Yamane sample size method^[64], with data collected from 39 farmers per village. Data were collected between April and July 2023 using a structured questionnaire administered through face-to-face interviews. Of the sampled farmers, 300 agreed to participate and completed the interview, resulting in a response rate of 85.5%.

3.3 Instrument and variable measurement

The questionnaire consists of four sections. Section 1 included the demographic profile and farming characteristics of the farmers, including variables such as age, education, farm size, farming experience, cooperative membership, access to credit, income from agricultural activities, plasticulture size, years of plasticulture use, multiplicity of plasticulture systems, diversity of production and use of plastic mulch in the previous year. Section 2 collected data about the different plasticulture systems. It discusses aspects such as years of use, farm size, color, crops, laying technique, removal technique, frequency of use, replacement time, amount used over the past 5 years, use of organic mulch, use of plastic film for soil solarization, the color of soil solarization film, and the use of black plastic mulch under polytunnels. Section 3 examined waste management methods for plastic mulch and plastic film covers. Based on the literature^[4,12,27,41], 12 disposal methods were identified: burying on the farm, burying elsewhere, burning on the farm, burning elsewhere, piling on the farm, piling

elsewhere, roadside collection for landfill, transport to landfill, storage for future reuse, repurposing, recycling on the farm and sending to a recycling unit. Farmers were asked to determine their use of each method on a dichotomous scale (1 = yes, 0 = no) and estimate the proportion (%) of plastic disposed of for each method they used. Section 4 assessed barriers and motivations related to plastic film disposal and recycling using a Likert scale (1 = not important to 5 = extremely important) to measure the importance of each factor. To establish face validity, the questionnaire underwent a pilot study with 10 farmers from the study region. This process identified potential deficiencies and assessed the clarity and comprehensibility of the questions. Feedback was thoroughly analyzed and integrated into the final questionnaire to improve reliability and validity. Researchers used straightforward language, illustrations, and real-world situations to encourage accurate responses from farmers. These actions helped farmers feel more understood and inspired them to provide candid feedback. Before data collection, the purpose and objectives of the study were explained to participants and oral consent was obtained. The research received ethical approval from the University of Reading (Ref# APD 1911D).

3.4 Data analysis

Data analysis was performed using Stata (v.16.1, StataCorp LLC, College Station, TX, USA). Summary statistics, frequency distributions, percentages, mean and standard deviation were used to describe the data. Additionally, the relative importance index (RII) was performed to measure the importance of each barrier or motivation related to the disposal and recycling of plastic film. RII is calculated as^[65]:

$$RII = \frac{\sum_{i=1}^5 w_i n_i}{AN} = \frac{5n_1 + 4n_2 + 3n_3 + 2n_4 + 1n_5}{5N} \quad (1)$$

where, n_i is the frequency of the responses ($i = 1-5$ on a Likert scale), w_i is the constant that shows the weighting of each response (1 = not important to 5 = extremely important), A is the maximum value in the Likert scale (5), and N is the total number of the responses. The RII value ranges from 0 to 1, with 0 not inclusive. A greater RII value signifies increased significance of the criteria. The importance levels were categorized into three levels: low, $0 < RII \leq 0.4$; medium, $0.4 < RII \leq 0.7$; and high, $0.7 < RII \leq 1.0$.

The binary logistic regression model was used to analyze the factors affecting the plastic mulch recycling behavior of

farmers. A significance level of $P < 0.05$ was set for determining statistical significance. This model was used to predict the dependent variable (recycling adoption) based on one or more explanatory variables, as outlined in [Table 1](#).

4 Results

4.1 Socioeconomic and farming profile of the respondents

Descriptive statistics for the socioeconomic profile and farming characteristics are presented in [Table 1](#). The average age of the sampled farmers was 47.0 years, with an average farming experience of 24.9 years. Over half of the respondents (58%) had at least a secondary school education, and 54% reported family members participating in agricultural activities. Most of the farmers (73.3%) owned their farms, with an average farm size of 5.29 ha. Agricultural activities were the primary source

of income for 85.3% of respondents. Additionally, the majority of farmers (72.7%) were members of agricultural cooperatives, while only 26.7% had access to credit for agricultural purposes. For plasticulture usage, the findings revealed that plasticulture covered an estimated 75.4% of the total farm size, with an average of 16.5 years of experience in plasticulture farming. Only 21.3% of farmers had adopted multiple plasticulture systems, and 37.3% practiced crop diversity within their plasticulture systems. Lastly, 53% of farmers reported using plastic mulch in their agricultural practices.

The types of plasticulture systems used by the respondents are illustrated in [Fig. 2](#), showing that many respondents adopted more than one system within the same season. Low tunnels were the most used system, adopted by 73.3% of the farmers. Adoption rates for other plasticulture systems were much lower, ranging from a maximum of 7% for combined low and high tunnels to a minimum of 0.3% for plastic mulch and net houses.

Table 1 Socioeconomic and farming profile of the respondents

Variable	Description and measurement	Mean	SD	%
Continuous variable				
Age	Farmer age (years)	46.98	11.42	–
Farming experience	Years of farming experience	24.89	11.92	–
Farm size	Size of the farm (ha)	5.29	5.93	–
Plasticulture size	Percentage of plasticulture size to total farm size	75.37	29.67	–
Years of plasticulture use	Average years of farming experience in managing plasticulture systems	16.45	9.34	–
Income from agricultural activities	Percentage of farm income to total income	85.34	23.91	–
Dummy variable				
Education	Education status of a farmer (1 = if the farmer had at least secondary education; 0 = otherwise)	–	–	58
Land tenure	Ownership of farm (yes = 1; otherwise = 0)	–	–	73.7
Participation of family members in agriculture	Family member participation in agricultural activities (yes = 1; otherwise = 0)	–	–	54
Cooperative membership	Membership of agricultural cooperative (yes = 1; otherwise = 0)	–	–	71.7
Access to credit	Access to institutional sources of credit (yes = 1; otherwise = 0)	–	–	26.7
Multiplicity of plasticulture systems	Number of plasticulture systems adopted by the farmers in the last year (1 = if the farmer had adopted more than one; 0 = otherwise)	–	–	21.3
Diversity of production	Number of crops cultivated per season in the plasticulture systems (1 = if the farmer had grown more than two; 0 otherwise)	–	–	37.3
Use of plastic mulch in last year	Applying plastic mulch either as a standalone method or in conjunction with other plasticulture methods (1 = if yes; 0 = otherwise)	–	–	53

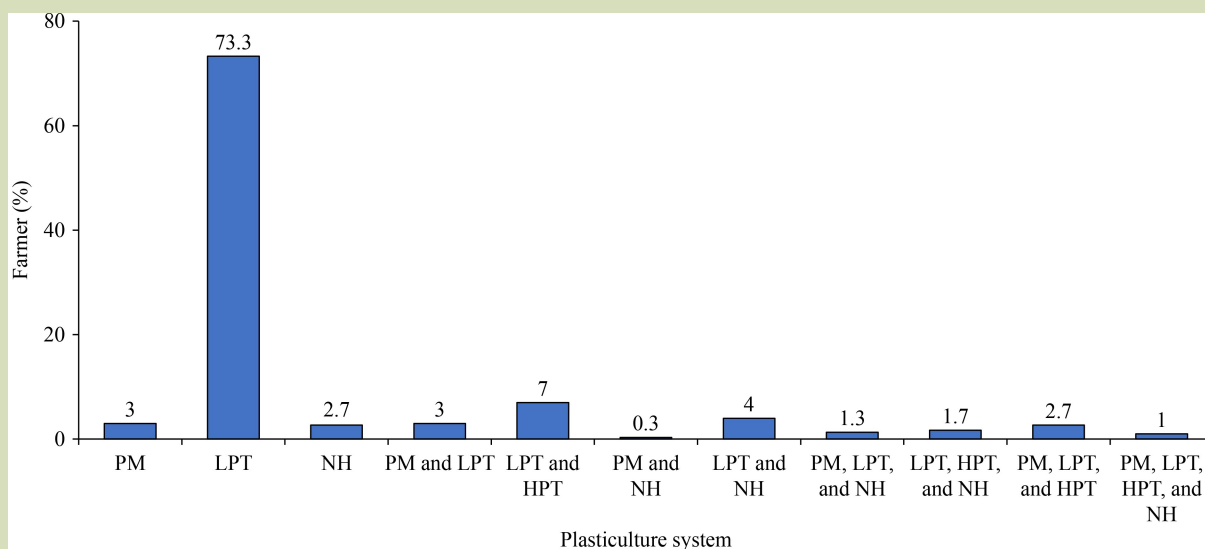


Fig. 2 Farmer adoption of plasticulture systems (PM, plastic mulch; LPT, low polytunnels; HPT, high polytunnels; and NH, net houses) in the study area.

4.2 Characteristics of plastic film used in different plasticulture systems

Variables related to plastic film use in plasticulture systems (mulch in open fields, low tunnels, high tunnels and net houses) are summarized in Table 2. In terms of years of use, the highest percentage of farmers using plastic mulch in open fields reported less than 11 years of experience. For low tunnels and high tunnels, most farmers had 11–20 years of experience, while 42.4% of net house users had more than 20 years of experience with this system. The majority of farmers across all plasticulture systems were in the farm size category of < 6 ha. Farmers using plastic mulch in open fields and net houses exclusively used black plastic film, whereas those using low and high tunnels used white plastic covers. The results showed a wide variety of crops, specifically vegetables, cultivated in low tunnels, high tunnels and net houses. In open fields with plastic mulch, cantaloupe, chili pepper, cucumber and watermelon were the primary crops grown. Farmers predominantly relied on manual techniques for laying and removing plastic film in all plasticulture systems.

For the frequency of use of plasticulture systems, the findings revealed that all farmers who adopted plastic mulch in open fields, low tunnels and net houses used plastic film annually, with usage rates of 100%, 66.8%, and 81.8%, respectively. In the

same context, a clear majority of high tunnel farmers (80.6%) used plastic film seasonally. Farmers using plastic mulch replaced it seasonally, while 55.8% of low tunnel farmers and the majority of high tunnel farmers (83.3%) replaced cover film every two years. Most net house farmers (87.9%) replaced film seasonally. In terms of the amount of plastic film used, most farmers across all plasticulture systems reported that the quantity of plastic film remained unchanged over the last five years. Additionally, the majority of farmers in all systems stated that they used organic mulch during the preparatory stages of farming, with chicken manure being the most commonly used organic mulch. Variations were observed in the use of plastic film for soil solarization, with adoption levels ranging from a maximum of 60% among farmers using plastic mulch in open fields to a minimum of 15.9% among low tunnel farmers. Among those using soil solarization, black, transparent and silver plastic film were reported. Lastly, plastic mulch use within polytunnels was noted, with adoption rates of 43.8% among low tunnel farmers and 72.2% among high tunnel farmers.

4.3 Disposal of plastic film

The findings on farmer adoption levels of disposal methods for plastic mulch and plastic covers, along with the proportion of

quantity disposed by each method, are shown in Figs. 3 and 4. For plastic mulch (Fig. 3), farmers reported using multiple disposal methods. The most frequently adopted methods were plowing into soil (32.1%), burning outside the farm (32.1%),

burning on the farm (26.4%) and sending to recycling units (18.2%). The proportion of plastic mulch disposed of by plowing on the farm and burning elsewhere was 74.3% each, followed by roadside collection for landfill at 61%. For plastic

Table 2 Characteristics of plastic film used by farmers in different plasticulture systems

Plastic film variable	Category	Mulch in open field (n = 35)		Low tunnel (n = 283)		High tunnel (n = 36)		Net house (n = 33)	
		F.	%	F.	%	F.	%	F.	%
Years of use	< 11 years	17	48.6	99	34.9	10	27.7	12	36.4
	11–20 years	9	25.7	124	43.8	18	50	7	21.2
	> 20 years	9	25.7	60	21.2	8	22.2	14	42.4
Farm size	< 6 ha	22	62.9	188	66.4	21	60	14	42.4
	6–10 ha	7	20	80	28.3	5	2.1	13	39.4
	> 10 ha	6	17.1	15	5.3	10	27.8	6	18.2
Color	Black	35	100	–	–	–	–	33	100
	White	–	–	283	100	36	100	–	–
Crops*	Cantaloupe	11	31.4	79	27.9*	4	11.1	3	9.1
	Watermelon	29	82.8	77	27.2	–	–	–	–
	Chili pepper	4	11.4	11	3.9	6	16.7	1	3
	Cucumber	2	5.7	82	28.9	25	69.4	11	33.3
	Tomatoes	–	–	32	11.3	18	50	7	21.2
	Eggplant	–	–	41	14.5	14	38.9	2	6.1
	Pepper	–	–	27	9.5	12	33.3	5	15.2
	Kidney beans	–	–	9	3.2	3	8.3	1	3
	Zucchini	–	–	3	1.1	5	13.9	2	6.1
	Jute mallow	–	–	98	34.6	–	–	–	–
	Okra	–	–	3	1.1	–	–	–	–
	Cabbage	–	–	2	0.7	–	–	–	–
	Banana (seedlings)	–	–	2	0.7	–	–	23	69.7
	Grapes (seedlings)	–	–	12	4.2	–	–	–	–
Laying technique	Manual	32	91.4	283	100	36	100	33	100
	Mechanical	3	8.6	–	–	–	–	–	–
Removal technique	Manual	31	88.6	283	100	36	100	33	100
	Mechanical	4	11.4	–	–	–	–	–	–
Frequency of use	Seasonally	–	–	36	12.7	29	80.6	–	–
	Annually	35	100	189	66.8	7	19.4	27	81.8
	Every two years	–	–	58	20.5	–	–	6	18.2
Replacement time	Seasonally	35	100	116	4.1	–	–	29	87.9
	Every two years	–	–	158	55.8	30	83.3	4	12.1
	Every three years	–	–	10	3.5	6	16.7	–	–

		(Continued)							
Plastic film variable	Category	Mulch in open field (n = 35)		Low tunnel (n = 283)		High tunnel (n = 36)		Net house (n = 33)	
		F.	%	F.	%	F.	%	F.	%
Amount used over the past 5 years	Decreased	–	–	11	3.9	3	8.3	–	–
	Same	30	83.3	236	83.4	27	75	25	75.8
	Increased	4	16.7	36	12.7	6	16.7	8	24.2
Use organic mulch	Yes	35	100	259	91.5	36	100	30	90.9
	No	–	–	24	8.5	–	–	3	9.1
Use plastic film for soil solarization	Yes	21	60	45	15.9	11	30.6	12	36.4
	No	14	40	238	84.1	25	69.4	21	63.6
Color of soil solarization film**	Black	11	31.4	31	68.9	8	72.7	–	–
	Transparent	14	40	6	13.3	3	26.3	12	100
	Silver	10	28.6	8	17.8	–	–	–	–
Use black plastic mulch within polytunnel	Yes	–	–	124	43.8	26	72.2	5	15.2
	No	–	–	159	56.2	10	27.8	28	84.8

Note: F., frequency. * More than one answer was allowed, so percentages of the categories do not sum up to 100%. ** The percentages are calculated according to the number of farmers who use plastic mulch in soil solarization.

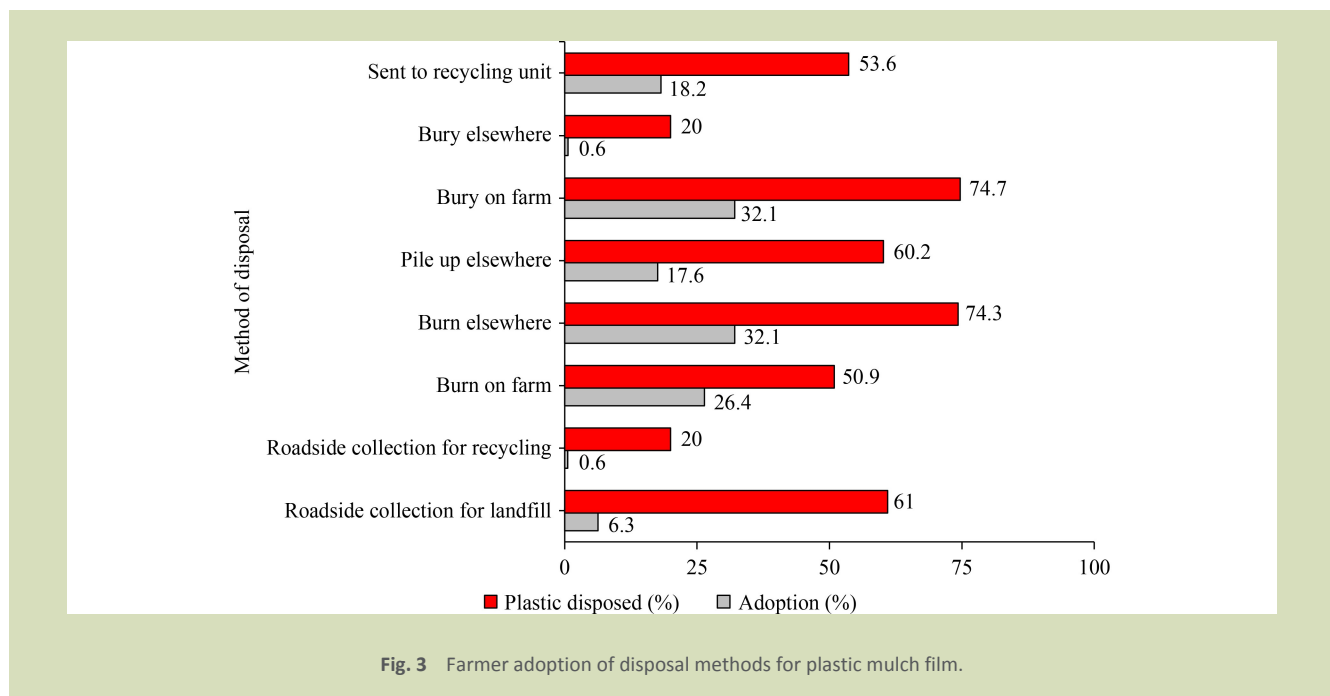


Fig. 3 Farmer adoption of disposal methods for plastic mulch film.

covers (Fig. 4), an overwhelming proportion of farmers (95.8%) sent plastic covers to recycle units, disposing of 88.8% of the total plastic covers through this method. Additionally, 39.9% of farmers reported storing plastic covers for future use,

with stored covers representing 20.3% of the total plastic waste. Additionally, 28.3% of farmers reported disposal of plastic cover by burying them elsewhere, accounting for only 15.6% of the total plastic disposed of using this method.

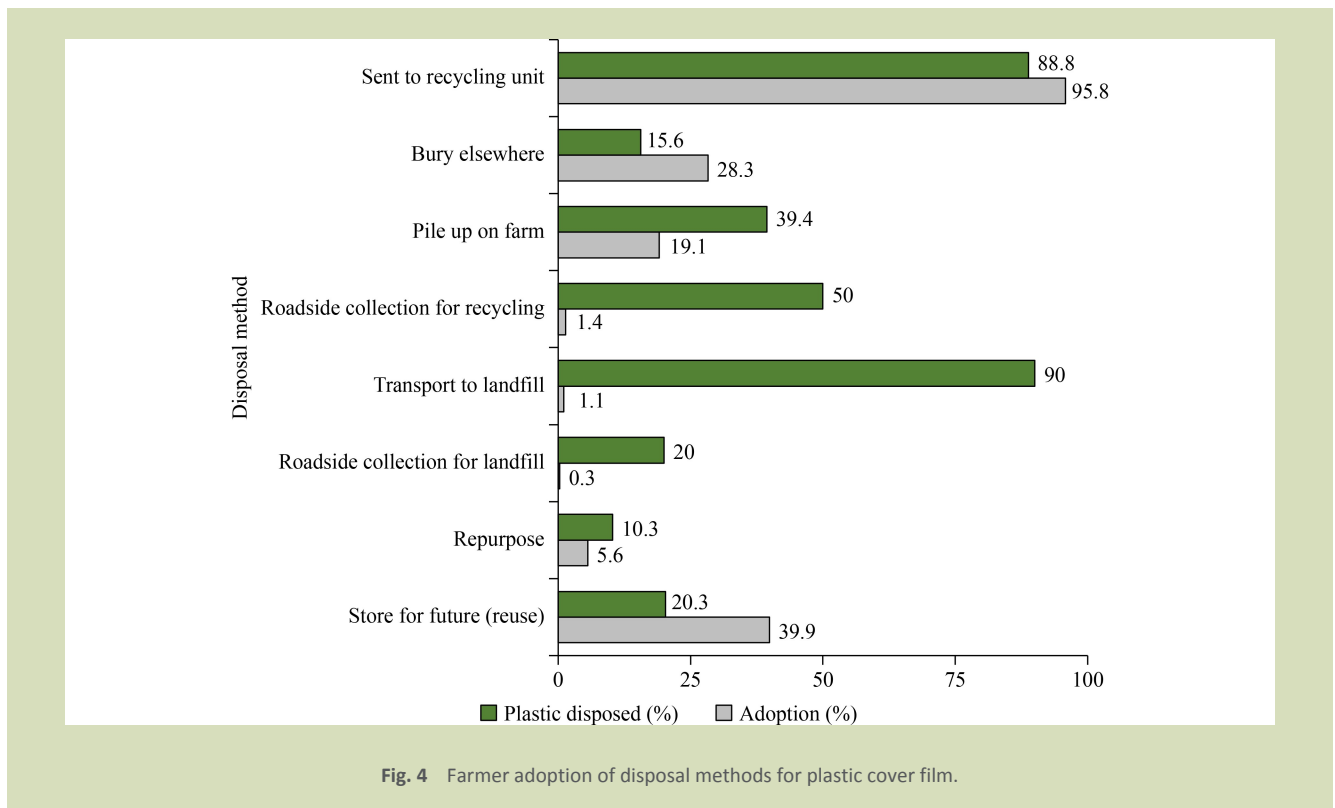


Fig. 4 Farmer adoption of disposal methods for plastic cover film.

4.4 Barriers to the disposal and recycling of plastic film

The findings of the RII analysis on the barriers to the disposal and recycling of plastic film show that all examined barriers were considered moderately important by farmers, as shown in Table 3. Of these, the barrier “disposal charges are high” was ranked as the most significant, with an RII of 0.65. In contrast, the least important barrier was identified as “there is no fixed place to dispose,” with an RII of 0.52.

4.5 Motivations for the disposal and recycling of plastic film

For the eight motivations assessed (Table 4), the importance levels ranged from moderate to high across all statements. The most relevant motivations, ranked by importance, were providing financial incentives for recycling plastic film (RII = 0.74), improving the quality of plastic film (RII = 0.73), and providing cleaning and assembly requirements (RII = 0.72).

Table 3 Barriers faced by the farmers in removing and disposal of plastic film

Variable	RII	Rank
Unavailability of recycling facilities	0.56	5
High cost of recycling	0.54	6
There is no fixed place of disposal	0.52	7
Disposal charges are high	0.65	1
Difficulty in getting labor for collecting and consolidating	0.63	2
We must give bribes for disposing	0.59	4
Collecting and consolidating are problematic as the plastic mulch falls apart	0.61	3

Table 4 Motivations that could be provided to farmers to encourage them to recycle plastic film

Variable	RII	Importance	Rank
On-farm pickup service of plastic mulch	0.6	Medium	7
Knowledge/information/education on recycling	0.65	Medium	4
Financial disincentives (fees for not recycling, penalties)	0.53	Medium	8
Convenient/accessible location for disposal and collection	0.62	Medium	6
More collection /recycling facilities	0.63	Medium	5
Improving the quality of plastic film	0.73	High	2
Providing cleaning and assembly requirements	0.72	High	3
Financial incentives for recycling plastic film	0.74	High	1

4.6 Factors influencing farmer behavior in recycling

Personal attributes and farming characteristics were hypothesized to examine the factors affecting disposal and recycling of plastic mulch, as shown in Table 5. The chi-square value of 84.3 shows that the likelihood ratio statistics are highly significant ($P < 0.01$), showing strong explanatory power for the adoption model. The Nagelkerke R^2 value shows that the explanatory variables account for about 29% of the variation in recycling behavior of farmers. The results indicated that 4 of 12 variables positively affected the likelihood of disposal and recycling of plastic film at the 0.05 and 0.01 significance levels. Farm size emerged as a significant factor, with a 1-ha increase in farm size associated with a 36% increase in the likelihood of

recycling plastic mulch. Similarly, the involvement of two additional family members in farming activities increased the odds of recycling behavior by 22%. Farm ownership was also an important factor, with farmers who owned their land being 2.11 times more likely to practice recycling. Additionally, a one-year increase in plasticulture use was linked to 11% increase in the likelihood of recycling. Finally, an increase of one plasticulture system managed by the farmer corresponded to a 19% increase in the likelihood of recycling behavior.

5 Discussion

This study aimed to provide a comprehensive understanding of

Table 5 Factors influencing the recycling behavior of the respondents

Explanatory variable	Odds	S.E.	Wald	P-value
Age	1.54	0.99	2.32	0.14
Farming experience	1.11	1.09	1.08	0.28
Farm size	1.36	1.68	2.98	0.02*
Participation of family members in agriculture	2.22	1.48	8.66	0.001**
Land tenure	1.27	0.84	3.05	0.02*
Years of plasticulture use	2.11	0.95	2.26	0.03*
Income from agricultural activities	1.29	1.4	1.45	0.16
Education	-1.85	1.66	1.89	0.09
Cooperative membership	1.35	1.44	1.57	0.18
Access to credit	-1.25	0.89	1.31	0.22
Diversity of production	-1.73	1.68	2.42	0.08
Multiplicity of plasticulture systems	1.19	0.91	1.43	0.28

Note: 2log-likelihood = 209.6; Chi-square = 84.3; P-value (chi-square) = 0.00; Nagelkerke R^2 = 0.29. ** $P < 0.01$, * $P < 0.05$.

how farmers dispose of agricultural plastic waste and the factors affecting their practices. It examined four main areas: the characteristics of agricultural plastic film used, the extent of plastic waste disposal, the barriers considerably impacting recycling behavior and the motivations required to accelerate recycling rates. To achieve this, the study systematically examined four plasticulture systems across three governorates in Egypt. The findings contribute to supporting the objectives of Egypt's Sustainable Strategic Plan 2030 in the field of plastic waste management. This plan emphasizes four key aspects: promoting plastic recycling, raising awareness about the risks of plastic pollution, improving infrastructure for integrated solid waste management, and regulating employment conditions within the waste management system^[20]. These results provide actionable insights to align agricultural waste management practices with the national sustainability goals.

The examination of plastic mulch use in the study area showed that Egyptian farmers in the three governorates predominantly use it to produce vegetables in winter. This practice aligns with the benefits of plastic mulch in cooler months, such as raising soil temperature and reducing soil moisture loss during crop growth. For off-season production, other plasticulture systems are used year-round, with low tunnels being the most commonly used system. This preference can be explained by the high cost of establishing greenhouses, which leads farmers to use low-cost alternatives that still offer plant protection benefits, similar to high tunnel systems. The study highlighted that greenhouse production in the region does not rely on modern soilless culture systems. Also, in the absence of alternative materials, many farmers reported using polyethylene plastic, as Egypt currently lacks comprehensive legislation regulating biobased, biodegradable or compostable plastics. Although these materials could help addressing plastic pollution, they have problems, including inconsistent certifications and limited feasibility. New policy frameworks should cover the economic and practical feasibility of adopting biobased, biodegradable and compostable plastics in agriculture^[66]. The findings also reveal the widespread use of agricultural plastics, both in terms of annual usage frequency and the amount used over the past 5 years. Discussions with farmers during data collection provided further insights: farmers prioritize the role of plastic mulch in weed control, a high-value benefit. Additionally, they acknowledged other advantages of plasticulture, including enhanced production, off-season crop availability, quality preservation, climate change adaptation and water conservation.

Pro-environmental behavior regarding plastic cover disposal was observed among farmers, with most either using roadside collection for recycling or sending plastic covers to a recycling unit. In contrast, plastic mulch disposal methods varied, with plowing back into soil and burning on farms being the most common practices. This discrepancy highlights the important barriers facing farmers in recycling plastic mulch, which poses a considerable threat to environmental sustainability. Other contributing factor is the use of low-thickness plastic mulch, which often tears during removal, preventing full collection. Li et al.^[67], in their study on thickness choices among Chinese farmers, found that the use of substandard mulch materials not only hindered recycling but also contributed to plastic film pollution. Similarly, the study area relies on manual techniques for removing plastic mulch, which is labor-intensive and costly. As Madrid et al.^[41] reported, manual removal is often incomplete, leaving behind fragments of polyethylene mulch and drip tape in the soil, which are challenging and time-consuming to retrieve^[68]. Although some farmers recognize the environmental consequences of improper disposal, practical and cost-effective disposal methods are essential to encourage sustainable practices^[27]. Promoting responsible plastic use through awareness campaigns is critical to reducing the adverse effects of plastic pollution on the environment and human health. Collaboration among stakeholders including governmental organizations, plastics industry companies, research/academic institutions, non-government organizations and end users is necessarily needed to enforce strict regulations on plastic production, use and disposal^[41]. Consistent with prior studies, disposal as landfill, burying on farms and burning remain the most frequent disposal methods for plastic mulch among farmers^[68,69].

These results clarify the importance of developing plastic mulch recycling policy. Currently, there is no specific policy in Egypt addressing the recycling of plastic mulch, which leaves a significant gap in managing the negative environmental impacts associated with its disposal. The absence of regulations mandating appropriate collection, recycling or the use of biodegradable alternatives exacerbates the problem, allowing harmful practices to persist unchecked^[70]. Therefore, analysis of international success models is beneficial to offer valuable insights for enhancing waste management practices in Egypt. In this regard, the government in South Korea has implemented a comprehensive strategy to manage agricultural plastic mulch waste, focusing on reinforcing producer responsibility and establishing a value chain for proper disposal. This approach includes the promotion of

biodegradable mulching vinyl to minimize environmental pollution, a deposit system to recover agricultural waste vinyl and awareness programs to prevent illegal disposal^[71]. In France, the organization A.D.I.VALOR, established in 2001, uses a voluntary, nationwide approach to agricultural waste recycling, emphasizing shared responsibility among producers, distributors and farmers. The system funds its recycling and processing activities through an eco-contribution fee paid by producers, who may also use A.D.I.VALOR logos to enhance product appeal. Farmers sort, clean, and deliver agricultural waste, including mulch film, to over 7,000 designated collection points operated by registered cooperatives and distributors. In 2020, A.D.I.VALOR collected over 79 kt of agricultural plastic waste, achieving a collection rate of 78% and a recycling rate of 74%. Specifically for mulch film, the collection rate reached 85%, with 99% of the collected waste being recycled, demonstrating the effectiveness of this structured and collaborative model^[72].

Economic barriers, including the high costs of recycling and manpower expenses for removing plastic mulch, were identified as primary factors hindering farmers in the study area from engaging in recycling activities. This finding aligns with previous findings^[25,29,44]. Likewise, institutional barriers, such as the lack of recycling facilities, were also highlighted by farmers, consistent with earlier research^[12,31,44,47]. These challenges stress the urgent need to develop recycling incentive schemes to encourage farmers to adopt recycling and reuse practices. Also, characteristics of plastic film, such as quality, structural integrity, color, duration of use and covering methods, considerably affect the cost and difficulty of collecting film residues, thereby affecting farmer recycling behavior^[73]. Addressing these issues requires the implementation of targeted initiatives and the development of advanced technical processes to improve the collection, cleaning and recycling of plastic film^[41]. The results for barriers faced by farmers in recycling reveal the importance of policy-driven solutions, such as government-supported waste collection services and subsidies for biodegradable alternatives, to enhance farmer recycling behavior by reducing economic and logistical barriers, as indicated by the results on the high relative importance of financial incentives. However, the study also reveals that most farmers are unaware of or do not participate in existing government-led recycling programs, highlighting a gap in awareness and access to information. Additionally, informal recycling networks and community-driven efforts, such as local collectors and small-scale recyclers,

are crucial for managing agricultural plastic waste, particularly in areas lacking formal waste management infrastructure. Strengthening collaborations between these informal networks and governmental programs could bridge the existing gaps, fostering a more integrated and effective approach to plastic waste management^[70]. Addressing these aspects would provide a more comprehensive understanding of the potential for policy adjustments to influence farmer recycling practices.

The results show that farmers considered financial incentives as an important motivator for recycling, suggesting that the net income generated from recycling contributes to fostering sustainable behavior. This aligns with some studies conducted in China, which reported that incentive-based policies and subsidies had a positive and significant impact on farmer plastic mulch recycling behavior^[32,74–76]. However, relying merely on government subsidies to sustain agricultural plastic waste management is challenging. Designing co-funding programs that include public contributions presents a promising strategy to address funding gaps^[26]. Economic incentives play a crucial role in encouraging farmers to participate in recycling programs, as they can offset the high costs of recycling and provide a tangible financial benefit. The results reveal that financial incentives ranked highest among the motivations for recycling, suggesting that subsidies or price support for recycled plastics could significantly boost participation. However, stricter regulations on plastic use could enhance compliance by establishing clear disposal requirements and penalties for non-compliance, thereby discouraging harmful practices like open burning and on-farm burial. Integrating both incentives and regulations into policy frameworks could address the economic and institutional barriers identified in the study, ultimately promoting sustainable waste management practices among farmers. This approach would not only improve compliance but also align farmer behavior with national environmental goals, enhancing the practical relevance of this study for policymakers.

The findings also highlighted the importance of improving the quality of agricultural plastics as a key motivator for reducing plastic waste and increasing recycling rates. Developing research and development processes to design polymers that are more suitable for recycling and reuse is critical^[77]. Filipe et al.^[6] recommend incorporating research and development activities into an integrated approach to recycling and valorizing agricultural plastics. This approach should include raising awareness, implementing adjusted policies (incentives,

benefits or fines), fostering supply-chain collaboration and addressing the socioeconomic context to create a comprehensive and sustainable solution for agricultural plastic waste management.

Based on the study findings, it would be safe to say that farm size was an important socioeconomic factor affecting farmer recycling behavior. Larger farms are more likely to engage in recycling, possibly because they produce adequate quantities of plastic waste to meet the minimum weight requirements set by recycling facilities. In contrast, smaller farms, producing less plastic waste, may face challenges in meeting these thresholds. This aligns with findings by King et al.^[27]. Another personal attribute associated with the recycling behavior was family member participation in farming activities. Larger family participation reduces labor costs associated with plastic removal, incentivizing farmers to collect plastic waste and potentially secure higher income from recycling. Experience in plasticulture farming also emerged as an essential determinant. Experienced farmers are more likely to observe the benefits of recommended practices compared to traditional methods and may have established connections with brokers in the plastic value chain, facilitating waste collection for recycling. Type of farm ownership was another important factor. Farmers who own their land showed a greater propensity for recycling, possibly due to their concern for the long-term health of their farms. They may consider the adverse effects of microplastic contamination on soil quality and crop productivity, which fosters a favorable attitude toward recycling and motivates them to adopt pro-environmental practices. Consequently, these results highlight the need to investigate how socioeconomic and other experiential factors can be leveraged as a foundation for promoting positive plastic waste management behaviors among farmers.

There are some limitations to be acknowledged when interpreting the results, however. The generalizability of the study findings to different regions in Egypt or to a global context was limited, because the research was conducted on three governorates only. This underscores the need for future studies in different economic, cultural, and geographical settings. Second, the study relied on a Likert scale methodology to examine the importance of barriers and motivations. While this approach provided valuable insights, it reflects farmer perceptions, which may introduce response bias into the findings. Third, although efforts were made to ensure sample inclusivity by categorizing farms based on their size, other

critical factors, such as variations in the types of plastic used and differences in cropping systems, warrant further exploration. These limitations can be addressed in future studies and contribute to a better understanding of the management of agricultural plastic waste while enabling the implementation of more specific and effective interventions.

6 Conclusions

This study provides a new perspective by examining the specific factors influencing Egyptian farmer behavior in the disposal and recycling of agricultural plastics, highlighting the role of financial incentives, socioeconomic characteristics and the absence of targeted policies, which have been insufficiently considered in previous research. The empirical investigation conducted in this study has yielded five conclusions. First, the primary application of agricultural plastic film in the study area is for vegetable production in winter. Second, recycling plastic mulch poses more challenges than recycling plastic covers. Third, economic barriers, including high recycling costs and labor-intensive removal processes, are major factors associated with low recycling rates. Fourth, recycling is strongly motivated by financial incentives, subsidies, and improvements in the quality of plastic film. Fifth, the plastic mulch recycling behavior is considerably affected by farm size, family involvement in farming activities, farmer experience in plasticulture and farm ownership.

Four practical implications can be drawn from the current investigation. First, awareness campaigns delivered through personal meetings, mass media, and social media tools can effectively convey extension messages to farmers about proper disposal methods. Second, analyzing the barriers and motivations highlighted in this study is essential for designing interventions that promote recycling and reduce plastic pollution. Third, research and develop efforts should focus on cleaning used plastic mulch using recycling machines and improving biodegradable mulch film to provide more sustainable options. Fourth, co-partnerships between governments, cooperatives, farmers and plastic industry stakeholders should be established to develop incentive-based policies that accelerate recycling rates at the farm level. Future research that combining behavioral data with soil contamination insights (e.g., measuring plastic fragment density or microplastic accumulation) could create a more systematic and influential study, connecting farmer actions to real-world environmental consequences. Additionally,

examining farmer recycling behavior by investigating other dimensions, such as the adoption of varying levels of plastic

quality, the role of social capital, and compatibility with export specifications, could further enrich this field of study.

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Compliance with ethics guidelines

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