Agri-plastics use and end-of-life management: a technical and legislative state-of-the-art

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Abstract: Sustainable agriculture and food systems are a central point in the European Green Deal to advance the economy and increase the quality of life, reducing their footprint on the climate and environment. Among various sustainable practices to improve agriculture sustainability, alternative materials to plastics and the transition to a circular economy to manage agri-plastics waste are necessary to reduce the contamination of soil, water, and air, avoiding adverse effects on the food quality, flora and fauna. In this context, the regional project STEP, funded by Regione Emilia-Romagna, aims to investigate the use of plastics and its end-of-life management in the regional agricultural supply chain to find more sustainable solutions according to all the pillars of sustainability (environment, economy, and society), through an assessment of the impacts of different agricultural strategies based on the replacement and better management of agri-plastics, maintaining its benefits in terms of increase of yield rate and quality and reduced quantity of water and fertilizers. The first phase of STEP project, described in this paper, is to analyse the current use of conventional plastics in agriculture, its potential replacement with bio-based materials, and the agri-plastics waste management, investigating technical and legislative aspects in the European and Italian contexts, with the specific objective to identify the main barriers to the diffusion of more sustainable solutions for agri-plastics and the main drivers that could boost the creation of an integrated supply chain to reduce plastics impact on the food system. The holistic approach used in conducting this analysis will be the basis for the application of a quantitative methodology to evaluate all the pillars of sustainability of alternative solutions for agri-plastics use and management, overcoming the current literature mainly based on the identification of agronomic aspects derived by the use of plastics (or other materials) in agriculture.

Keywords: agri-plastics; bio-based materials; waste management; circular economy

I. INTRODUCTION

Agriculture is a focal area for the European (EU) Green Deal (COM/2019/640 final), and to contribute to its ambitious targets, a new common agricultural policy (CAP) was adopted in 2021 by the European Commission to be effectively active from 2023. Reaching greener agriculture is one of the ten objectives of the new CAP, intending to mitigate the climate impact of this sector, which accounts the 12% of the EU greenhouse gas (GHG) emissions (in 2016) and is the first sector to suffer the negative environmental impact of an unsustainable economy and society [1,2]. Another fundamental action within the EU Green Deal is transitioning to a circular economy (CE) in several industrial sectors, including the plastics value chain. The new Circular Economy Action Plan (COM/2020/098 final) sets some initiatives for plastics to reduce their waste and increase their recycling and incentivizes the use of biodegradable or compostable plastics for applications where their use is positive for the environment [1,3].

In this context, the project STEP, funded by Regione Emilia-Romagna (PSR 2020), integrates the two priorities, aiming to identify effective strategies for reducing and more sustainable use of plastics in agriculture, and mainly in the fruit supply chain. The phases of the project include: (i) a state-of-the-art about the current solutions for mulching and anti-hail/insects nets, considering their materials and end-of-life management; (ii) the identification of more sustainable solutions in terms of traditional plastics replacement with biodegradable/compostable plastics or improving plastics recovery, recycling and reuse; and (iii) the evaluation and comparison of these solutions according to both a techno-economic feasibility study and an environmental impact assessment. This paper focuses on project's first phase, the review of the current use of plastics in agriculture and its management, considering technical and legislative aspects. This activity will allow analysing the potential barriers to spreading more sustainable alternatives. The state-of-the-art addresses different aspects of the topic, as structured as in Figure 1 (Appendix A), and provides (section II): an overview of the current uses of plastics in agriculture with a focus on mulching and net applications, highlighting its benefits and negative effects; a spectrum of the current legislation about plastics to understand how it is applicable or not to agriculture; two potential alternative solutions for improved management of plastics in agriculture are explained, and in section V their barriers and further opportunities to develop are shown. In section III some results and discussions are derived to approach the second step of the project that is the setting of the techno-economic feasibility study of more sustainable solutions for the plastics use and management in agriculture. Finally, in section IV, some conclusions are drawn.

II. State-of-the-art about plastics in agriculture

A. The use of plastics in agriculture

Agriculture is the sixth biggest end-use market sector for plastics: in 2020 in Europe, agriculture consumed 3.2% of the total EU plastics demand, corresponding to about 1.57 Mtons [4]. Its versatility and ease of processing make plastics a suitable material to respond to different agricultural applications and functions, generating some benefits in terms of improved yield rate and food quality and low consumption of water, fertilizers, and pesticides [5]. Plastics are used for several agricultural products, such as greenhouses and polytunnels, mulch films, nets, irrigation system components, and silage. Another relevant application of plastics is packaging (both for pesticides, fertilizers, and food), but it is not directly used on-site but along the agri-food supply chain [6]. The most diffused polymers in agriculture are polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC), mainly in the form of film (more than 80% of the total weight of plastics used in Europe from crop production), which is characterized by a low weight, a high resistance, and a low price [4,6].

The two applications analysed in the project STEP and this paper are mulch films for their high diffusion (which is the second application of plastics in crop production in Europe, after greenhouses, covering the 26% of the total weight [6]), and anti-hail/insects nets (3.2% of the total weight [6]), for lack of sustainable end-of-life solutions.

Mulch films

Mulching is an agricultural practice able to increase crop productivity through its capacity to control weeds, maintain a proper soil temperature and moisture concerning the different phases of the seeds/plant growth cycle, and ensure good soil conditions (low degradation and high compaction) [7]. Plastics, particularly PE (low density PE – LDPE; and linear LDPE – LLDPE), are the most used mulching material since they are cheaper than other materials and easy to apply on-site, determining lower labour time and costs. In particular, it deals with films, with a thickness from 12 to 80 μm, available in different colours (mostly black, clear, or white) according to various crops, which have a life-cycle on-site of 2-4 months [8].

Despite the advantages of plastics for mulching application, the intensive use of plastic mulch films brought a negative impact on the environment due to the macro- and micro- plastic residues in the soil, which determine a reduction in soil and animals health, growth of next crops, and food quality. Even if mulch films are typically removed from the fields after the harvest season (also determining high costs, on average 185 €/ha [7]), it is not possible to completely collect all the plastic debris [9,10]. It occurs since plastic mulch films must be partially buried in the soil during its installation, and they are damaged by the plants, the use of machinery, and the harvesting, determining their fragmentation [6].

Agricultural nets

Plastics nets are more often used in agriculture, for tree fruit cultivation, to repair crops from different natural factors, such as hail, insects, wind, and excessive sunlight [11]. The material, thickness and mesh size, additives, and colour of the nets influence their mechanical and optical properties, such as their tensile strength, durability, porosity, shading factor, and light transmittance. Consequently, they are selected according to the specific function of the nets. This wide spectrum of choices makes the available commercial nets very different, as shown in Table I. Due to versatility, plastics are a suitable material for nets, and particularly HDPE is the most widespread material for agricultural nets, followed by PP [12,13].

However, the increasing use of plastics nets generates issues related to the end-of-life management of these products. The typical problems related to plastics waste treatment are complicated by the characteristics of the nets at the end of their life. The durability of the nets is related to the stability of their mechanical properties to climate agents, such as UV radiation, which determines their degradation. Consequently, the great variety of initial net properties linked to their different degradation level, depending on the specific climate exposition and application time, establish a highly inhomogeneous plastic waste flow, for which it is not possible to effectively know the actual degraded properties and that result difficult to be recycled without generating a recycled plastics with very low properties [14]. It derives that, even if the agricultural nets allow repairing fruit trees from several natural factors, often highly extreme due to climate change, they determine another type of environmental issue and impact.

TABLE I
CHARACTERISTICS OF THE AVAILABLE COMMERCIAL NETS

Features	Value and units
Dimensions: width; lenght	1-20 m; 25-3000 m
Colour	Black; green; transparent
Thickness; mesh size	0.25-0.32 mm; 0.2-7 mm (up to 4 cm for anti-birds nets)
Weight	15-325 g/m^2

B. Legislation about agricultural plastics

The Extended Producer Responsibility (EPR) is an approach adopted by the European Commission in 2015. It makes the plastic producers responsible for the end-of-life management of plastic waste through a tax on manufacturing, intending to boost producers to design products able to favour their recycling. The EU plastics strategy in a circular economy pushes the innovation and investments in two main directions: (i) increasing the quality of plastics waste flow through its improved collection and sorting, also reached with a proper labeling system; (ii) the reduction of plastic waste through its replacement with biodegradable/compostable materials [15]. However, in the agricultural sector, some further steps are necessary.

The effect of the EPR in agriculture is poured out over the farmers with the risk of compromising the economic viability of certain agricultural practices. Incentives, such as a payback mechanism, could help to effectively implement a proper collection, sorting, and recycling system [5]. On the other hand, regarding the labeling of agricultural plastic waste, the lack of specific legislation does not provide clear and diffused standards, but only practical guidelines are available in certain cases [16].

C. Sustainable solutions for agricultural plastics

More sustainable solutions for plastics in agriculture must address two different aspects of mulch films and nets. In particular, the main problem of mulching is the plastic residues in the soil. This debris has different effects on their sizes and refers to the release of plasticizers and chemicals absorbed in their surface for leaching. Microplastics become part of the soil mixture and reach deeper levels [17,18]. The second issue is the use of plastics in agriculture, more related to nets, consists of implementing more sustainable management of these components at the end of their life. In many countries, the legislation forbids the on-site burning or burial of removed plastics, which farmers must manage as waste. Then it is collected and treated according to specific national systems. For farmers, it means high labour and costs to collect and store plastics in the right conditions to maintain them clean and avoid their dispersion. These costs are summed to the taxes for plastics waste disposal [19]. According to these two aspects, more sustainable solutions include: (A) replacing traditional plastics with biodegradable/compostable plastics; (B) implementing a suitable plastic waste collection scheme. In the following sub-paragraph, the available solutions in these two directions are analysed with their benefits and limits.

Use of biodegradable/compostable plastics

One of the alternatives for the use of plastics in agriculture, above all for mulching, is the application of films made with biodegradable/compostable plastics. At least 20 biodegradable/compostable films for mulching are already available on the market (i.e., Ecovio, Mater-Bi). As mulch films, this type of material determines numerous benefits in terms of a reduced environmental impact of its debris in the soil and a potential release of carbon, which can revert to the soil for its biodegradability [20]. Despite these advantages, the diffusion of biodegradable/compostable plastics is limited for the following aspects: (i) lack of reliable information about their agronomic effects; (ii) uncertainty about the time and conditions of degradation of the crop cycle; (iii) lack of data about the release of nano- and micro-plastics in the soil due to the presence of a small part of non-degradable materials; (iv) high purchase costs in comparison with the traditional plastics [21].

In the last ten years, several studies in the literature have investigated the performance of traditional and biodegradable/compostable plastics on different crops and conditions typical of the specific location (e.g., average temperature and moisture). These studies addressed both crop productivity and mulch film degradation. In the STEP project, other tests for the strawberry mulching have already been conducted and are under development in the Emilia-Romagna Region (Italy) with the same objectives. Table II (Appendix A) shows some studies already available in the literature. The variability of analyzed crops and conditions makes the comparison of the literature results difficult. However, it is possible to summarize four main conclusions about the comparison between traditional and biodegradable/compostable plastics: (1) the yield rate is comparable (in some cases greater, in other cases lower, but always with a maximum difference of 10%); (2) the weeds reduction is comparable; (3) the deterioration of biodegradable/compostable films is very variable within the crop cycle (<10 – 90% after 12 months); (4) the biodegradation of all the films can be very low also after 18 months (30%) that makes the mechanical film removal necessary also in case of biodegradable/compostable materials. The last finding is strictly related to the fact that the biodegradation conditions depend not only on the material but also on the additives, microbic soil activities, fauna, climate conditions (temperature, moisture, solar exposition), agricultural practices (e.g., milling and plowing).

Moreover, it is not easy to properly measure biodegradation since both standards and methods have been univocally defined, and often a visual inspection is used [22]. Finally, the transition to biodegradable/compostable plastics does not remove all the issues of traditional polymers. Several biodegradable/compostable mulch films available on the market derive from fossil raw materials (i.e., PBAT, PBS, PCL), and, in general, all the biodegradable/compostable plastics need additives to ensure specific mechanical properties which are not biodegradable, determining nano- and micro-plastics release [6,7].

In this context, the main novelty of the project STEP will be the development of an economic feasibility study that compares different plastics mulch films. In fact, in the literature, economic analyses have not still been conducted. Moreover, an environmental impact will be associated with different solutions, according to the application of the ViVACE tool, which has already been applied to the plastics value chain [23,24].

Agricultural plastic waste collection scheme

The time and costs related to the collection and storage of end-of-life agricultural plastics on-site often drive the farmers to use improper waste treatment that determines the contamination of the environment by plastics residues [6]. It is relevant for agricultural nets, for which solutions such as biodegradable/compostable plastics are not still suitable since the necessary mechanical properties would not be ensured [12]. The implementation of a proper agricultural plastics waste collection scheme could bring several advantages for all the value chain, farmers included, deriving from a greater recovery and recycling of plastics materials. Several EU countries – Italy is not one of these countries – have already implemented a national/local scheme to treat this waste flow effectively. Table III (Appendix A) recaps some available schemes in EU and their main characteristics. However, to favour the sustainability of these schemes through plastics recycling, it is necessary to ensure a clean and well-sorted flow of plastics waste [25].

Ensuring it on-site is not so obvious. It requires dividing the plastics waste according to different typologies/polymers, avoiding exposing the waste to the UV and water, protecting it with a cover, cleaning the waste after the use to eliminate residues of soil, stones, plants, and fruits, and other components, such as fertilizers and pesticides. If these good practices are not implemented, the quality of the plastics waste as a recycling resource is not sufficient.

Currently, the lack of standards and information for farmers does not allow proper sorting of the plastics waste, preventing the possibility of reaching a high recycling rate. Moreover, even if on-site plastics waste could reach a few hundred kilos per year, this amount is still too far from the minimum quantity admitted by recycling plants (>25 tons). Consequently, the numerous tasks required to prepare the waste (i.e., collection, sorting, cleaning) and the low quantity make the process to recycle agricultural plastics waste too expensive in comparison to the price of virgin raw materials [26] (at least during a stable global economic situation).

D. Barriers and opportunities for more sustainable solutions

According to the presented review of the current state-of-the-art of the use of plastics in agriculture, the available sustainable solutions to reduce the environmental impact of this material are not completely ready to be implemented. In this paragraph, the main barriers and the opportunities in these fields are analysed.

Biodegradable/compostable plastics

One of the main limitations in the innovation and development of biodegradable/compostable plastics is the higher costs necessary to manufacture them compared to traditional plastics. Moreover, the production of biodegradable/compostable plastics has some environmental impacts related to the higher energy consumption, the use of soil, and the fossil fuel consumption to produce crops for this application. These aspects limit the diffusion of these materials, which do not have the large production scale of the traditional plastics, with a cycling effect on their price that remains high [27].

An upscaling production of biodegradable/compostable plastics could decrease their costs and price. Moreover, considering the agricultural practices, using these materials could reduce the necessity of certain activities (e.g., mulch film removal), generating further economic advantages. Finally, biodegradable/compostable plastics could derive from crop residues and by-products, without needing additional crop production [6].

The ViVACE tool and economic feasibility study applied in the project STEP will provide quantitative indications about this direction, which has still not been deeply analysed.

Recycling of agricultural plastics

Until plastic waste management remains an additional cost for farmers, involving them as partners in a proper collection and recycling system will not be easy. Consequently, it is necessary to revise the entire supply chain, from the producer to the recycler, to rethink the agricultural plastic products, considering their re-design, manufacturing, and logistics, to take advantage of their treatment at the end of life (collection, sorting and recycling) [23]. It means developing innovation and investments in products and processes to change the vision about waste, which must be considered a resource. Some innovative solutions to be developed could refer to the following aspects: (i) innovative technologies to be implemented on-site to help the farmers clean plastics and remove residues of soil, plants, and chemicals; (ii) innovative equipment to ensure proper storing and collection activities in the farms to reduce their labour time and costs and also the plastic waste damages; (iii) adapted recycling processes to increase the quality of recycled agricultural plastics that necessarily derive from a deeper analysis of the characteristics of plastic waste generated by agricultural applications; (iv) re-design the agricultural products to both facilitate their recycling and reuse as secondary raw material in the same or other applications [28].

In the project STEP, all the elements necessary to implement a suitable plastic waste management system will be evaluated, considering all the actors who participate in this supply chain and identifying the procedures to ensure an improved collection, sorting, and recycling of agricultural plastic waste. These procedures will be compared to the current legislative framework to identify how this system can be applied in Italy, particularly in the Emilia-Romagna Region. Also, for this case, the implementation of the ViVACE tool will provide quantitative data to feed a techno-economic feasibility study and the evaluation of significant Key Performance Indicators to compare the environmental and social impacts of this scheme to the current situation.

III. Results and discussion

Plastics is a suitable material to respond to the technical needs of various agricultural practices, allowing the increase of crop productivity and maintaining low costs. However, the negative plastic impact on the soil and the ecosystem [29] forces the agricultural sector to find more sustainable solutions, which take two main directions: replacing it with biodegradable/compostable plastics [30] and improving its end-of-life management through recycling. Nevertheless, both economically and environmentally, further aspects must be tested and verified to ensure the complete sustainability of these proposed alternative solutions.

In this context, the farmers have a relevant role, but they must be helped in addressing this challenge [31]. In particular, it is necessary to diffuse awareness about these topics, communicating to the farmers the unsustainable conditions of the current situation, making the environmental impacts (also on their activities) understandable, and sharing good practices and their positive effects. Currently, the lack of quantitative information about the improvements generated from the shift to sustainability limits the possibility to take proper decisions about innovation and investments [24]. In doing that, it is also necessary to collect the needs and perceived barriers of the farmers, and avoid imposing legislative limits and taxes, considering them as the only responsible actor in the supply chain. Integrating the supply chain and the implementation of collaborative tasks and procedures is a necessary step to implement [23].

Surely, the legislation could greatly incentivize effective steps to diffusion more sustainable solutions. In particular, standardisation in the design phase, labeling, and incentives for proper sorting of plastic waste could improve the management of plastics in the agricultural sector, reducing its negative impact and maintaining its benefits, such as the low cost and the versatility.

The STEP project will implement a quantitative method for analysing sustainable alternatives for better management of plastics in agriculture. Reliable and robust information about sustainability is fundamental to making the right decision to compare all the possible positive and negative effects of the different available solutions, providing indications to improve the limiting aspects further.

A. *Mulching films*

A techno-economic feasibility study will be implemented to quantitatively compare traditional and biodegradable/compostable mulching films. An agri-environmental agency has already installed two plants for strawberry crop in Italy (Cesena, Emilia-Romagna Region), using the two types of mulching films, to compare the yields and the debris of plastics, in one case after the removal of the film and in the second case after its biodegradation. These data will be used for the techno-economic feasibility study. In particular, the yields, in terms of quantities and size, will be used to evaluate the revenue stream in relation to different cost items, which are procurement costs (mulching film and transports), management costs (installation, maintenance to eliminate weeds and the replacement of damaged film), and removal costs (film removal, transports and disposal). This analysis will require the collection and comparison of numerous data, such as the purchase costs in relation to the thickness and width of the film, the incentives on taxes, the mulching and removal speed, the hourly costs for labour, the use of the specific equipment.

B. *Protective nets*

The ViVACE tool will be set to compare the current management system of the protective nets and more sustainable solutions based on the recycling of the plastics and its reuse for secondary applications. In particular, the nets will be fragmented, melted, and extruded to prepare specimens and test its mechanical and chemical properties with the aim to identify proper secondary applications. In this way, it will be possible to quantify the flows of plastics sent to recycling, energy recovery and landfill and evaluate specific KPIs about plastics end-of-life, understanding the economic benefits of material recovery on the entire supply chain, including the farmer.

IV. Conclusion

Agriculture is one of the main users of plastics, which is not properly managed at the end-of-life, it could generate great damages for the environment (soil, water, further crops, quality of food, and fauna), consequently more sustainable management solutions are necessary. The typical approach in the literature is to investigate the agronomic aspects of different solutions, in terms of yield (quantity and quality of food) at different climatic conditions. Nevertheless, the complete sustainability of alternative solutions is not considered and quantitatively evaluated. Consequently, the quantitative analysis of the STEP project will provide useful models to compare different solutions, in terms of different materials and/or different management systems, to effectively support the decision-making process on agricultural practices.

References

[1] European Commission (2019). The European Green Deal (COM/2019/640/final). Available online at: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-

11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF (accessed on 7th April 2022).

[2] European Commission (2020). CAP SPECIFIC OBJECTIVES…explained – Brief No 4. Available online at: https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/key_policies/documents/cap-specific-objectives-brief-4-agriculture-and-climate-mitigation_en.pdf (accessed on 7th April 2022).

[3] European Commission (2020). Circular Economy Action Plan (COM/2020/98/final). Available online at https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF (accessed on 7th April 2022).

[4] Plastics Europe (2021). Plastics - the Facts 2021. Available online at: https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf (accessed on 7th April 2022).

[5] Pazienza, P. and De Lucia, C. (2020). For a new plastics economy in agriculture: policy reflections on the EU strategy from a local perspective. *Journal of Cleaner Production*, 253, 119844.

[6] Pereira, R.; Hernandez, A.; James, B.; LeMoine, B.; Carranca, C.; Rayns, F.; Cornelis, G.; Eralinna, L.; Czexh, L. and Picuno, P. (2021). The actual uses of plastics in agriculture across EU: an overview and the environmental problems. EIP-AGRI, European Commission, Brussels.

[7] Liu, L.; Zou,G.; Zuo, Q.; Li, S.; Bao, Z.; Jin, T.; Liu, D . and Du,L.(2022). It is still too early to promote biodegradable mulch film on a large scale: A bibliometric analysis. *Environmental Technology & Innovation*, 27, 102487.

[8] Marí, A.I.; Pardo, G.; Cirujeda, A.; Martínez, Y. (2019). Economic Evaluation of Biodegradable Plastic Films and Paper Mulches Used in Open-Air Grown Pepper (Capsicum annum L.) Crop. *Agronomy*, 9, 36.

[9] Li, S.; Ding, F.; Flury, M.; Wang, Z.; Xu, L.; Li, S.; Jones, D.L. and Wang, J. (2022). Macro- and microplastic accumulation in soil after 32 years of plastic film mulching. *Environmental Pollution*, 300, 118945.

[10] Qi, Y.; Yang, X.; Pelaez, A.M.; Lwanga, E.H.; Beriot, N.; Gertsen, H.; Garbeva, P. and Geissen, V. (2018). Macro- and micro- plastics in soil-plant system: Effects of plastic mulch film residues on wheat (Triticum aestivum) growth. *Science of The Total Environment*, 645, 1048-1056.

[11] Manja, K. and Aoun, M. (2019). The use of nets for tree fruit crops and their impact on the production: A review. *Scientila Horticulturae*, 246, 110-122.

[12] Mukherjee, A.; Knoch, S.; Chouinard, G.; Tavares, J.R.; Dumont, M.-J. (2019). Use of bio-based polymers in agricultural exclusion nets: A perspective. *Biosystems Engineering*, 180, 121-145.

[13] Briassoulis, D.; Mistriotis, A.; and Eleftherakis, D. (2007). Mechanical behaviour and properties of agricultural nets – Part 1: Testing methods for agricultural nets. *Polymer Testing*, 26, 822-/32.

[14] Zeenat; Elahi, A., Bukhari, D.A.; Shamim, S.; and Rehman, A. (2021). Plastics degradation by microbes: A sustainable approach. *Journal of King Saud University – Science*, 33(6), 101538.

[15] European Commission (2018). A European Strategy for Plastics in a Circular Economy (COM/2018/028/final). Available online at: https://eur-lex.europa.eu/resource.html?uri=cellar:2df5d1d2-fac7-11e7-b8f5-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed on 7th April 2022).

[16] Briassoulis, D.; Hiskakis, M.; Scarascia, G.; Picuno, P.; Delgado, C. and Dejean, C. (2010). Labeling scheme for agricultural plastic wastes in Europe. *Qual. Assur. Saf. Crop. Foods,* 2, 93–104.

[17] Wang, T.; Yu, C.; Chu, Q. Wang, F.; Lan, T.; and Wang, J. (2020). Adsorption behavior and mechanism of five pesticides on microplastics from agricultural polyethylene films. *Chemosphere*, 244.

[18] Guo, J.J.; Huang, X.P., Xiang, L., Wang, Y.Z., Li, Y.W.; Li, H.; Cai, Q.Y., Mo, C.H. and Wong, M.H. (2020). Source, migration and toxicology of microplastics in soil. *Environ, Int.*, 137, 105263.

[19] Miskolczi, N.; et al. (2009). Fuels by pyrolysis of waste plastics from agricultural and packaging sectors in a pilot scale reactor. *Fuel Processing Technology*, 90(7), 1032-1040.

[20] Razza, F.; Briani, C.; Breton, T. and Marazza D. (2020). Metrics for quantifying the circularity of bioplastics: the case of bio-based and biodegradable mulch films. *Resources, Conservation & Recycling*, 159, 104753.

[21] Serrano-Ruiz, H.; Martin-Closas, L. and Pelacho, A.M. (2020). Biodegradable plastic mulches: impact on the agricultural biotic environment. *Science of the Total Environment*, Ed. Elsevier.

[22] Li, C.; Moore-Kucera, J.; Miles, C.; Leonas, K.; Lee, J.; Corbin, A. and Inglis, D. (2014). Degradation of potentially biodegradable plastic mulch films at three diverse U.S. locations. *Agroecology and Sustainable Food*

[23] *Systems*, 38(8), 861–889.

[24] Bianchini, A. and Rossi, J. (2021). Design, implementation and assessment of a more sustainable model to manage plastic waste at sport events. *Journal of Cleaner Production*, 281, 125345.

[25] Bianchini, A.; Rossi, J. and Pellegrini, M. (2019). Overcoming the main barriers of circular economy implementation through a new visualitzation tool for circular business model. *Sustainability*, 11, 6614.

[26] Iñiguez, M.E.; Conesa, J.A. and Fullana, A. (2018). Recyclability of four types of plastics exposed to UV irradiation in a marine environment. *Waste Management*, 79, 339–345.

[27] James, B.; Trovati, G.; Penalva, C.; Czech, L.; Mendioroz, I. and Milicic, V. (2021). Reducing the plastic footprint of agriculture – Agricultural management, on site practice to reduce plastic use and the contamination in the environment. EIP-AGRI, European Commission, Brussels.

[28] Enyoh, C.E.; Shafea, L.; Verla, A.W.; Verla, E.N.; Qingyue, W.; Chiwdhury, T. and Paredes, M. (2020). Microplastics Exposure Routes and Toxicity Studies to Ecosystems: An Overview. *Environ Anal Health Toxicol*, 35(1), e2020004.

[29] LeMoine, B.; Eralinna, L.; Trovati, G.; Casallo, I.M..; Amate, J.J.; Zlatar, K.; Butlewski, K.; Ojanpera, M. and Picuno, P. (2021). Reducing the plastic footprint of agriculture – Minipaper B: the agri-plastic end-of-life-management. EIP-AGRI, European Commission, Brussels.

[1] [29] Xu, L.; Xu, X.; Li, C.; Li. J.; Sun, M. and Zhang, L. (2022). Is mulch film itself the primary source of meso- and microplastics in the mulching cultivated soil? A preliminary field study with econometric methods. *Environmental Pollution*, 299, 118915.

[31] [30] Wang, K.; Wang, C.; Chen, M.; Misselbrook, T.; Kuzyakov, Y.; Soromotin, A.; Dong, Q.; Feng, H. and Jiang, R. (2022). Effects of plastic film mulch biodegradability on nitrogen in the plant-soil system. *Science of the Total Environment*, 833, 155220. Bergtold, J.S.; Caldas, M.M.; Ramsey, S.M.; Sanderson, M.R.; Granco, G. and Mather, M.E. (2022). The gap between experts, farmers and non-farmers on perceived environmental vulnerability and the influence of values and beliefs. Journal of Environmental Management, 316, 115186.

Appendix A. FIGURES AND TABLES

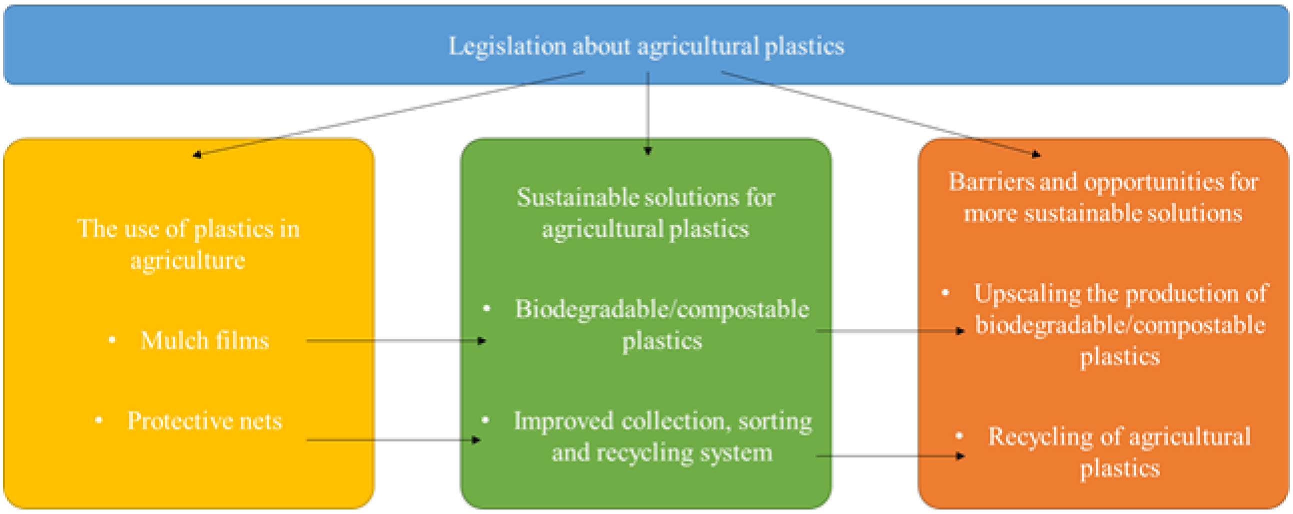

Fig. 1. Framework of the paper to cover the state-of-the-art about agri-plastics.

TABLE II
REFERENCES ABOUT THE AGRONOMIC PERFORMANCE OF MULCH FILMS: TRADITIONAL AND BIODEGRADABLE/COMPOSTABLE PLASTICS

Reference	Crop; location; and conditions (temperature - T, moisture - M)	Investigated mulching materials (traditional plastics – T, biodegradable/compostable plastics – B)
Miles et al. 2012, American Society for Horticultural Science, 47(9), 1270-1277	Tomatoes; Tennessee, Texas, Washington State; T: 15-22°C, M: 59-83%	1 T: PE (control); 3 B: BioTelo Agri, Weed Guard Plus, SB-PLA-10
Morra et al. 2015, XLIV Convengo Nazionale della Società Italiana di Agronomia	Strawberry; Campania (Italy); n/a	1 T: PE (control); 1 B: Mater-Bi
Zang et al. 2020, Horticulturae, 6(3), 47	Strawberry; Washington State; n/a	1 T: PE (control); 4 B: BASF 0.5 and 0.6, Novamont 0.5 and 0.6.
Jia et al. 2020, Journal of Arid Land, 12(5), 819-836	Tomatoes; Urumqi (China); T: 26.8°C	1 T: PE (control); 4 B: BM1, WM1, BM2, WM2.
Braunack et al. 2020, Agronomy, 10(4), 584	Cotton; New South Wales (Australia); n/a	No mulch film (control); 2 B: n/a

TABLE III
EXISTING NATIONAL/LOCAL SCHEMES FOR AGRICULTURAL PLASTICS WASTE TREATMENT

Name of the scheme	Country	Features
ADIVALOR	FR	All the players in the plastic supply chain - 300 organisations (e.g., agricultural cooperatives, farmers retailers, fertilizer/plastic film producers) – pay a contribution to financing the scheme, which collects 66000 tons of plastics (empty cans of pesticides, seed/fertiliser bags, silage films and protective nets).
CICLOAGRO / MAPLA	ES	It aims to finance a model for the management of non-packaging agricultural plastic waste. The first attempt (CICLOAGRO – ended in 2018) did not collect waste.
RIGK	DE	The plastic packaging industry association and the waste disposal partners (27 in total) voluntary collaborate to recovery agricultural films. Farmers who return their plastics waste are incentivised with a bonus for other purchases. In 2016, about 5500 tons of agricultural films were collected.
SvepRetur	SWE	A subcontractor is hired to organise the collection of plastic waste from farmers. The scheme is sustained by a tax for plastics producers (74€/ton), which is bestowed on products and hence on consumers, who can deliver their waste in 340 points. The collection target is 70% of sold plastics.
IFFPG	IE	It is a mandatory scheme set by legislation. It is financed through a fee covered by producers (75%) and farmers (25%). The scheme organises a bookable collection on-site and in 237 centres. In 2016, about 27000 tons of agricultural plastics were recovered and the 74% of the sold plastics were recycled (60% recycled in Ireland).