Scientific review paper

INNOVATIVE MATERIAL AND IMPROVED TECHNICAL DESIGN FOR A SUSTAINABLE EXPLOITATION OF AGRICULTURAL PLASTIC FILM

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Abstract. *The use of plastic material in agriculture has been growing during the last decades thanks to the benefits that it provides in agricultural production. Mainly in protected cultivation plastics play an important role, by performing a passive effect – by protecting the crops from negative weather conditions – and, at the same time, an active effect – by realizing a more favorable environment for the cultivation. On the other hand, the durability of plastic films is strictly related to the modes of use, and in particular to the meteorological and environmental conditions, as well as to the consequences of stresses they are subjected to upon mounting and during their operational life. The possibilities for an improvement in the technical design of the agricultural plastic film, in terms of mechanical strength, radiometric properties and better aptitude of the material for a further recycling are connected with a more close link between its chemical formulation and the engineering performance of the material. The present paper shows, on the basis of an analysis about the main technical achievements in terms of improvement of the engineering properties of agricultural plastic film, a general review about innovative material and new techniques for mechanical recycling of agricultural plastic film.*

Key words: *Agricultural plastic film, technical characteristics, innovative material, radiometric properties, mechanical recycling.*

1. INTRODUCTION

The growing use of plastics in agriculture has enabled farmers to increase their crop production. Today's use of plastics in agriculture results in increased yields, earlier harvests, less reliance on herbicides and pesticides, better protection of food products and more efficient water conservation [15, 42]. According to most recent estimation, the annual consumption in the World of plastic material in the agricultural sector is approximately 5 Millions tons (about 2% of the total plastic production), and it seems to be steadily growing [36, 56]. Protection from hail, wind, snow, or strong rainfall in fruit-farming and ornamentals, together with the realization of a confined airspace with better microclimatic conditions, is the most common case. Plastic films are widely diffused for covering greenhouse, low and medium tunnel, and for soil mulching, while shading nets for greenhouses, or nets for a modification of the microenvironment, are employed as well. Films or nets for the protection against virus-vector insects and birds are also used as standalone covers or in connection with structures for the growing of arboreal cultivation [45].

Agriculture is the most important sector for the application of plastic material as a building component. Within civil and industrial constructions, where other building materials (*i.e.*, bricks, concrete, steel, wood, *etc.*) are more widespread, the use of this material is limited to complementary applications, as window or door frame, as well as flooring, insulating or facing covers. Employed as a covering material in protected cultivation plastic plays a central role, by performing a passive effect – protecting the crops from negative weather conditions – and, at the same time, an active effect, realizing a more favorable environment for the cultivation.

The increasing use of plastic films in protected cultivation calls for further on-depth studies on their durability even in order to contribute to reduce the impact that plastic films in agriculture have on environmental sustainability. The use of plastics in agriculture generates, in fact, serious environmental problems, as those connected with the management of large amounts of post-consume material, mainly in areas characterized by a fragile environment and a marked tourist vocation [10, 15, 44, 45]. With the aim to explore new possibilities of use of plastic material in the agricultural sector, characterized by a lower environmental impact, new materials are currently developed. The main actual technically interesting solutions are those connected with new plastic material characterized by very limited thickness or by longer useful life, with degradable material (mainly bio-based), or through the improvement of recycling techniques, able to transform the post-consume plastic material into a new secondary product [19, 26, 41, 47, 48, 52, 55, 57, 58]. This paper presents, on the basis of an analysis about the main technical achievements on the improvement of the engineering properties of agricultural plastic film, a general review about actual innovative material and new techniques of mechanical recycling of agricultural plastic film.

2. TECHNICAL PROPERTIES OF AGRICULTURAL PLASTIC MATERIAL

The use of plastic materials in protected cultivation is usually limited by an insufficient knowledge of their durability in relation to the typical climatic and environmental conditions of the exposure zone. Recent developments in materials science and technology led to the adoption of a wide range of innovations in the production of new covering materials for greenhouses. Economic and environmental reasons are more and more pushing the industrial producers towards the definition of more thin plastic films, or to the formulation of new materials, that could degrade after their exploitation period [11, 12, 18, 21, 37, 49].

The main technical properties influence the working performance of the plastic material, making it more or less suitable for an agricultural application. These characteristics, moreover, are generally determined by laboratory tests, that are conducted on new material, but a constant exposure to the atmosphere could quickly change some of them. The effect of external factors on the ageing of plastic material could determine a worsening of the mechanical strength, mainly the elasticity modulus and the percentage elongation at break, as well as an influence on the chemical-physical characteristics of the material, with a lowering of the vitreous transition temperature, and finally a general worsening of the spectro-radiometrical characteristics, with a reduction of the transmissivity in the Photosynthetically Active Radiation (PAR) wavelength or strong variation in the Long Infrared wavelength [29, 30, 33, 34, 35].

Under the framework of a general definition of the engineering characteristics that plastic material should perform, the following categories could be pointed out [42]:

*) Physical and chemical properties;
*) Mechanical properties;
*) Spectro-radiometrical properties;
*) Recycling properties;
*) Ageing factors.

2.1. Physical and chemical properties

The most important physical properties that a plastic material should have for its application in protected cultivation are [53]:

-) density;
-) gas and steam permeability;
-) thermal expansion coefficient;
-) thermal conductivity;
-) chemical neutrality;
-) low- and high-temperature stability;
-) melting point;
-) electrostatic properties;
-) surface adhesion of motes.

2.2. Mechanical properties

The most important mechanical properties that a plastic material should have for its application in protected cultivation are [1, 2, 4, 5, 22, 46, 64]:

-) tensile stress at yield;
-) tensile stress at break;
-) percentage elongation at break;
-) tear resistance;
-) elastic limit;
-) Young modulus;
-) compression and bending properties (for rigid plastic material).

2.3. Spectro-radiometrical properties

The most important spectro-radiometrical properties that a plastic film should have for its application in protected cultivation are [59, 66]:

-) transmissivity and reflectivity in the solar band [0 ÷ 3,000] nm, mainly in the PAR wavelength [400 ÷ 700] nm;

-) transmissivity and reflectivity in the Long Infrared band [7,500 ÷ 12,500] nm;

-) transmissivity and reflectivity during stress condition.

2.4. Recycling properties

The most important recycling properties that a plastic material should have for its application in protected cultivation are [14, 43, 60, 61, 62]:

-) the Melt Flow Index (MFI);

-) sufficient mechanical characteristics of the material as new.

2.5. Ageing factors

The factors playing a role in the ageing of a plastic material used for application in protected cultivation are [3, 6, 23, 31, 39, 40]:

-) solar radiation, mainly the UV component;

-) temperature and relative humidity;

-) contact with the oxygen contained in the air and in the rain water;

-) mechanical effect of wind, rain and snow;

-) contact with air dust and atmospheric pollutants;

-) contact with pesticides;

-) contact with the agricultural soil;

-) contact with supporting structural frames;

-) internal stress connected with the installation phase and the external factors.

Among all of these ageing factors, solar radiation, mainly with its Ultra-Violet (UV) component, plays the main role. Based on this assumption, the global energy arriving in that area by the sun is usually accepted in the international technical and scientific literature as a general parameter expressing the global conditions of the area where the plastic material will be installed. This global energy amount, calculated as the integral of the solar power coming from the sun, is expressed in Langleys (Ly), the unit of energy distribution over an area, where:

$$1 \text{ Ly} = 1 \text{ cal/ cm}^2 = 41840 \text{ Joule/m}^2 \quad (1)$$

3. THE SUSTAINABLE EXPLOITATION OF AGRICULTURAL PLASTIC FILM

The formulation of plastic film is currently based on chemical consideration mainly connected with the composition of the polymer and its additives. The technical aspects about the performance of this material during its working life are usually poorly considered during the design and production phase of these materials [63, 68]. Therefore, plastic materials show a limited life, even if they are produced with considerable quantities of appropriate additives, included into the formulation with the aim to prolong their useful lifetime. All these attempts are usually conduced on a pure empirical basis, without any support of analytical formulation able to constitute a theoretical basis on which the designer of this material could start its analysis.

In this way, main factors able to play a significant role on the final product should be adequately taken into account, as ageing behavior of the material depending on its stress condition and contact with agrochemicals [28, 67] or on the external weather conditions, the influence that the stress condition may play on the radiometrical properties of the film, the role that the Melt Flow Index may play on the further recyclability, as well as the analysis of the results from cyclical mechanical tests.

In the case of degradable film, moreover, the problem of its design is mostly connected with the calculation of the effective working life after which, having concluded its mission, the material can completely degrade into the soil [7, 8, 9, 16, 54].

3.1. Innovative plastic material for agricultural application

Many efforts were devoted during the last decades from the industries to the production of new more efficient plastic film for agricultural application. The main results that were obtained so far may be summarized in the following way:

3.1.1. Traditional plastic film

A traditional film to be used as a covering material in protected cultivation should have mechanical characteristics sufficient for the stretching phase during the installation of the film. Moreover, the percentage elongation at break should be sufficient for the final recovery of the material, at the end of its useful working life. With this aim, the Italian Standard [65] established that a lowering below the limit of 50% of this parameter compared with the value at new is the indicator that the material has finished its working life and has to be removed before that its mechanical characteristics become so poor that its removal and further mechanical recycling could be impossible.

Fig. 1 shows the mechanical characteristics of a thin (25 μm) plastic film – a three-layers co-extruded transparent LDPE-EVA-LDPE added with mineral fillers – that was tested during a project performed at the University of Basilicata under the framework of a EU-funded Programme (POP-FESR) co-funded at Regional level [42].

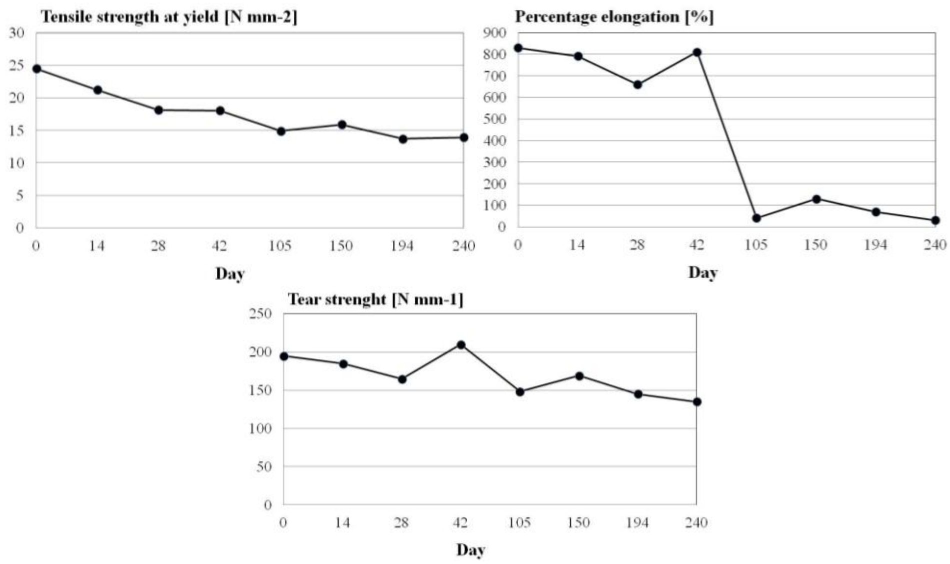

Fig. 1: Evolution in time of the mechanical characteristics (tensile strength, elongation at break and tear strength) of a thin (25 μm) plastic film.

The spectro-radiometrical characteristics that could be performed by an efficient plastic film for protected cultivation should be of high transmissivity in the solar band, mainly in the PAR wavelength [400 ÷ 700] nm, joined with a low transmissivity and quite high reflectivity in the long Infrared wavelength, mainly for those materials that will be employed as soil mulching, low- or medium-tunnels, and soil solarization.

The film should be black or grey in case of mulching. It should be opaque in all the spectral bands of the solar radiation; this characteristic should remain during all the time for the mulching application of the film. Figs. 2 and 3 show the spectro-radiometrical properties over time of the same material that was presented above, a thin (25 μm) three-layers co-extruded transparent LDPE-EVA-LDPE plastic film with mineral fillers [42].

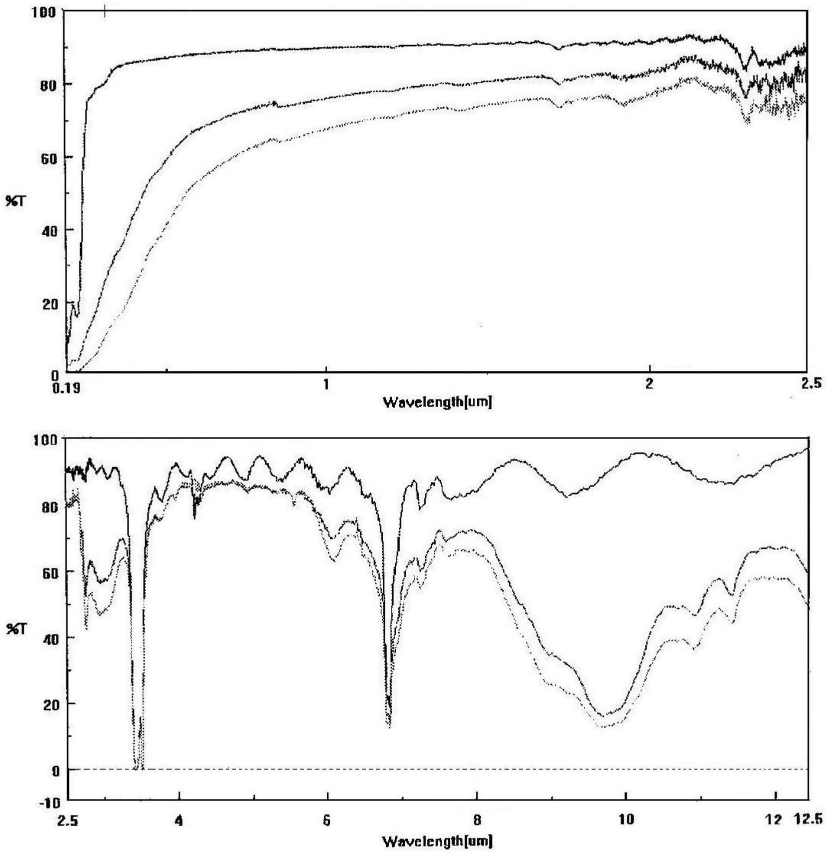

Fig. 2: Radiometrical spectra in total transmission UV-VIS-NIR (upper) and IR (lower) of a thin plastic film. The curves refer to the material new (upper), aged 165 days (medium), aged 270 days (lower) [42].

An interesting application deriving from the laboratory spectro-radiometrical tests [18] is the possibility to obtain an information about the ageing of the material from the evaluation of the Carbonyl Index, defined as [42]:

$$C_I = \varepsilon \frac{A^t - A^0}{S}, \tag{2}$$

where:

C_I = Carbonyl Index, [%];
A^t = Absorbance of the Carbonyl Index in the range [5380 – 6060] nm at time t, [%];
A^0 = Absorbance of the Carbonyl Index in the range [5380 – 6060] nm at time 0, [%];
ε = Molar absorbance coefficient, m;
S = film thickness, m.

The Carbonyl Index seems an affordable parameter, useful for the evaluation of the ageing level of a plastic film in which the carbonyl groups, even absent in the polymer when new, grow their concentration during the exposition to the external weather factors so modifying their absorbance in the range [5380 – 6060] nm, showing a peak (Fig. 4) in the sub-range [5715 – 5850] nm.

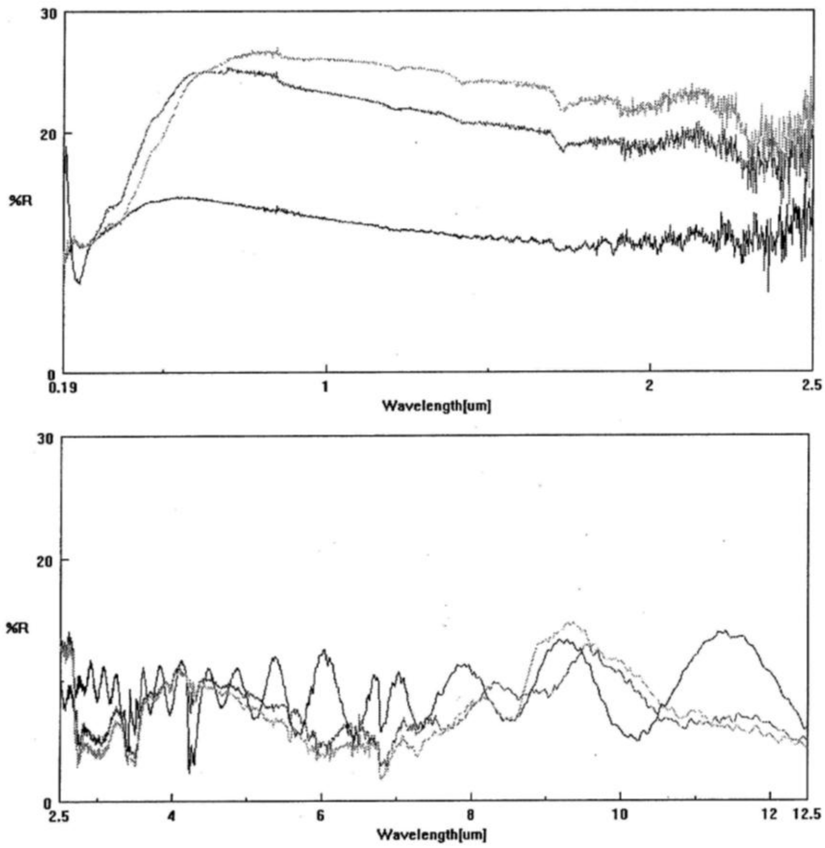

Fig. 3: Radiometrical spectra in total reflection UV-VIS-NIR (upper) and IR (lower) of a thin plastic film. The curves refer to the material new (upper), aged 165 days (medium), aged 270 days (lower) [42].

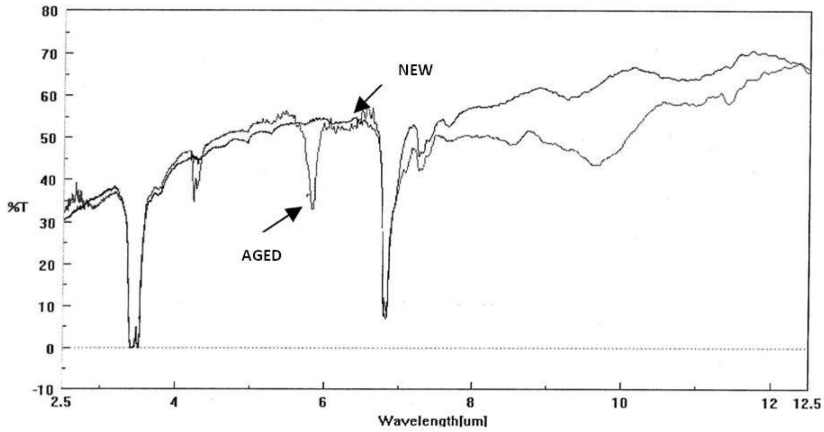

Fig. 4: Spectro-radiometrical diagram of a plastic film before and after ageing. The effect of Carbonyl Index is showed by the arrows [42].

3.1.2. Biodegradable film

Two main categories of biodegradable materials, based on two different concepts, are at the moment under development with the support of intensive research efforts world-wide [8]. In particular, among the materials developed included are fully biodegradable films but also partially biodegradable films or even films of controlled degradation. These latter, currently known as "*oxo-degradable*", are made by blending an additive to provide an oxidative and then a biological mechanism to degrade them. Degradation is a two stage process; first the plastic is converted by reaction with oxygen (light, heat and/or stress accelerates the process but is not essential) to low molecular-weight fragments that water can wet, and then these smaller oxidized molecules are biodegraded, *i.e.* converted into carbon dioxide, water and biomass by microorganisms. The process of biodegradation stops at a certain point, leaving fragments, then being followed by a questionable fate in the soil.

On the other hand, a really "*bio-degradable*" film should be a material that, after its pre-determined working life, can be buried in the soil along with the plant remains in order to be decomposed by microorganisms in to CO_2, water, minerals and a new biomass. This decomposition should leave no toxic substances in the soil or other undesirable by-products and should be fast enough so as not to result in accumulation during the consecutive cultivation periods. The development of new grades of bio-based biodegradable in soil mulching films represents a challenging research area associated with an attractive market [15, 37, 38].

Degradation of a plastic in general, is defined as a detrimental change in its appearance, mechanical and physical properties and chemical structure. It is important to make a distinction between the initiation of the degradation process (commencing in the extruder, at temperatures around 200°C, but controlled) and its manifestation during their useful lifetime. The degradation process may be delayed, enabling a longer useful lifetime of the plastic material, by a special balance of inhibitors engineered to the specific application and to the anticipated life expectancy of the plastic. Heat, ultra-violet radiation and stress can accelerate the degradation process of the material. Degradation of agricultural plastics during their useful lifetime is due to a combination of factors (mainly UV radiation) and may be controlled, to some extent, through the use of appropriate additives [1, 5, 6, 7, 11, 12, 49, 50, 66].

In Fig. 5 the time evolution of the main mechanical characteristics (tensile stress, percentage elongation and tear resistance) is reported for two biodegradable plastic films [42].

Further degradation of the aged agricultural plastic (*i.e.* agricultural plastic waste) following their useful lifetime is directly related to the various disposal options. In any case, degradation of agricultural plastic waste should not result in contamination of the soil and pollution of the environment (including aesthetic pollution) and the agricultural products safety. Describing plastics degradation, measuring it, and controlling it are all issues that are complicated by many technical, chemical and environmental factors [9, 24, 25, 37, 38].

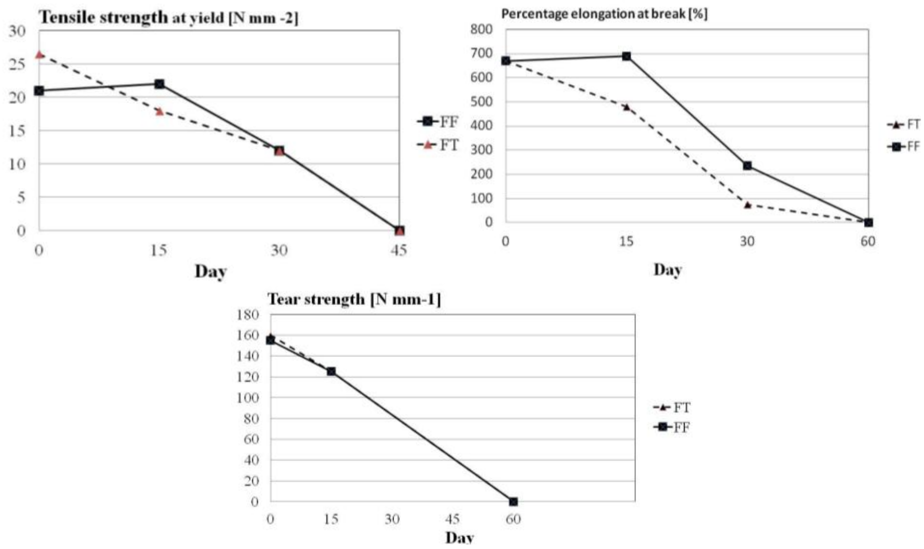

Fig. 5: Time evolution of the mechanical characteristics of two different biodegradable plastic films (initials: FT – FF) [42].

3.1.3. Recycled plastic film

Recycling plastic film with the aim to produce new plastic film is a quite new and not yet well-diffused technical application. In general, this application is possible if the post-consume plastic film has sufficient mechanical properties and a sufficient MFI, and if the plastic waste is well cleaned from other waste (*i.e.*, soil, stones, vegetal residue, *etc.*) that could be frequently present after application in the agricultural sector, mainly as mulching or low-tunnel covers, where the plastic material remains in contact with the agricultural soil [14]. One of the most diffused commercial application is the production of a recycled plastic film that, after the addition of some pigments (*e.g.*, carbon black) could be employed as different material (*i.e.*, black soil mulching, waste bag, *etc.*) [10].

During a recent research performed under the framework of the international EU-funded Project *Labelagriwaste* [48, 69] six recycled materials were tested for mechanical and spectral properties. Results show that, without adding any additive, materials can obtain satisfactory mechanical properties (Table 1) if they are extruded from mixture that consists of 75% of greenhouse covering materials and 25% low tunnel coverings.

The spectral analysis revealed that all tested samples with exception of F4 and Fd5 show a visible light transmittance higher than 80%. It can be concluded that good PAR transmittance can't be expected in the case where HDPE from agrochemical packaging is added to the blends for recycling. Some of the tested materials show good properties for being considered as thermal diffusion film, so, with addition of adequate additives these recycled material could find their implementation in horticulture as mulching or covering materials.

Table 1: Mechanical properties of recycled plastic films [48].

Material Type (mix of post-consume material)	Thickness [μm]	σ_{max} [MPa]	A [%]
F1 – recycled from 50% greenhouse film + 50% low-tunnel film	40	20.60	246.75
F2 - recycled from 75% greenhouse film + 25% low-tunnel film	40	35.71	310.51
F3 - recycled from 25% greenhouse film + 75% low-tunnel film	40	12.54	261.95
F4 - recycled from 25% F1+ 25% F2+ 25% F3+ 25% virgin HDPE	30	29.93	247.69
Fd5 – "*Densified*" recycled film	150	15.41	191.20
Fg5 – "*Granulated*" recycled film	70	18.72	190.87
100% virgin Low Density PolyEthylene (LDPE) film	50	21.74	439.90
100% virgin Ethylene Vinyl Acetate (EVA) film	160	34.54	536.44

The SEM analysis showed that materials were different in their chemical composition but that all were rich in minerals, oxides and chlorides that can influence the worsening of materials properties. The origin of chlorides and some minerals is mostly from the air. Kaolinite and Quartz indicate material contamination by the soil before recycling. Great attention must therefore be paid to collecting, classification, cleaning and storage of collected plastic materials since this can influence the final technical properties of materials [48].

3.2. The technical design of plastic material for agricultural application

Recent developments in materials science and technology led to the adoption of a wide range of innovations in the production of new covering materials for greenhouse. The possibilities of an improvement in the technical design of the agricultural plastic film, in terms of mechanical strength, radiometric properties and a better aptitude of the material for its further recycling, are connected with a closer link between its chemical formulation and the engineering performance of the material.

The main mechanical characteristics could be improved taking into account that their correlation with the exposure time during the working life is not linear. The influence of external weather factors may give initially even an effect of increasing the mechanical properties for a limited short period of time. This effect, usually connected with the creation of possible chemical reticulations, after this "recovery time" usually disappears.

Anyway, the consideration of the mere percentage elongation at break as the unique mechanical indicator of the reaching of the condition (after dropping lower than to 50% of this property of the material as new) for which the material should be considered [18] "*degraded*" and then removed, [6] before losing the mechanical characteristics sufficient for assuring its removal, seems to be questionable. From the mechanical tests, in fact, it is clear that other – even important – characteristics, as the tensile and the tear strength, could remain for a longer time unchanged, so enabling a longer useful lifetime of the material, and then a consequent lower impact on the agricultural environment [8].

The spectro-radiometrical characteristics of a plastic film could be improved by taking into account that the thickness plays an important role on these properties, and that the research of new, thinner material, should anyway cope with the need to assure a thermal effect to the plastic material able to exploit the incoming solar radiation. From this point of view, further research on plastic film and their additives appears as a crucial point for an improvement of this material in protected cultivation.

Mechanical recycling can represent the simplest way of managing plastic waste and, at the same time, obtaining new plastic materials that can be re-used in the agricultural sector. Further investigation should be made on blends optimization and on improving the spectral properties of the new recycled materials.

4. CONCLUSIONS

The formulation of plastic film is currently based on chemical consideration based on the composition of the polymer and its additives. The technical aspects about the performance of this material during its working life are usually poorly or totally not considered during the design and engineering phase of these materials. Therefore, plastic materials show a limited life, even if they are produced with considerable quantities of appropriate additives, included into the formulation with the aim of prolonging the useful lifetime of this material.

With the aim to explore how these different aspects could be improved, so that new more efficient formulation of plastic film for agricultural application could be defined, further experimental analysis should be conducted, both in open field and laboratory, aiming at the theoretical formulation of new equations able to predict the useful lifetime of an agricultural plastic film, on the basis of the main meteorological characteristics of the area where this material will be exposed, the working conditions (contact with pesticides, external pollution, *etc.*) and the correlation between radiometrical and mechanical characteristics.

Through natural and artificial ageing experimental tests, this work could be validated, in order to point out the role of the main factors causing degradation of plastic materials in protected cultivation, and draw useful indications to set up forecast models of the evolution of mechanical and radiometric characteristics over time.

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