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# Economic Evaluation of Biodegradable Plastic Films and Paper Mulches Used in Open-Air Grown Pepper (*Capsicum annum* L.) Crop

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**Abstract:** Black polyethylene (PE) is the most common mulching material used in horticultural crops in the world but its use represents a very serious environmental problem. Biodegradable films and paper mulches are available alternatives but farmers are reluctant to adopt them because of their high market prices. The aim of this paper is to evaluate the economic profitability of eight biodegradable mulching materials available for open-air pepper production. The economic evaluation is based on a four-year trial located in a semi-arid region of Spain. Three scenarios of PE waste management are examined: (i) absence of residues management, (ii) landfill accumulation, and (iii) total recycling. The inclusion of the costs of waste management and recycling under the current Spanish legislation only reduced the final net margin by 0.2%. The results show that an increase in subsidy rates of up to 50.1% on the market price would allow all biodegradable films to be economic alternatives to PE. The study supports the mandatory measures for the farmers to assume the costs of waste management and recycling. Despite savings in field conditioning costs, high market prices of biodegradable materials and papers are not compensated by the current level of subsidies, hampering their adoption in the fields.

**Keywords:** waste management; economic evaluation; biodegradable mulch; polyethylene

## 1. Introduction

Mulching materials have demonstrated many advantages in controlling weeds, [1,2] increasing soil temperature [3] and moisture [4] and reducing soil degradation [3]. These features finally influence in increasing crop yields [5]. In general, the literature recognizes that all these effects have positive outcomes on economic profitability because of water savings (up to 25%) and reduced labor costs for weed and pest control. [6–8]

Despite all these reported advantages, two major problems threaten such savings at a short and long-term. First, mulch application, removal, and disposal are labor-intensive and hence costly [9,10], and second, the most commonly used mulching materials (polyethylene and other fuel-based films) involve environmental risks in the long-term because their chemical structure is difficult to degrade [11]. The negative environmental effects [12] include the persistence of unrecovered plastic mulch in soil, their potential to alter soil quality by accelerating carbon and nitrogen metabolism, as well as potentially degrading soil organic matter. The presence of plastic residues in the soil can cause significant losses in production. For example, [13] reported that plant growth and yield of tomato crop were affected significantly when residual plastic mulch in soils reaches 160 kg $ha^{-1}$.

The most frequently used mulching materials in agriculture are manufactured mainly from petrol-based sheets like PE [14], low-density polyethylene (LD-PE) and linear low-density polyethylene (LLD-PE). These types of materials account for 17.5% of total demand by resin types in Europe [15]. The main tool to control weeds in vegetable crops is LD-PE film because it is a very cheap and easy-to-use material [16]. High amounts of waste generated by PE mulches both in the field and in landfills raise many concerns. Although plastic recycling is well established in central Europe, in other countries like Spain, agricultural plastic wastes generate 75,000 tons per year and most of them are tilled into the field, burned, or just left behind in adjacent areas [17–19]. In countries like China [18], it has been reported that the amount of waste in a common vegetable farming field could reach between 50 and 260 kg $ha^{-1}$. In this context, biodegradable variants of mulching are promising alternatives in vegetable production. The use of such mulches adds to the above-mentioned benefits and additionally reduces disposal costs for farmers while preventing environmental problems in the long-term. These mulching supplies include paper (cellulosic fiber), polylactic acid, polyester and corn, sugar cane, or potato starch [20].

Biodegradable films and paper mulches have been studied previously, demonstrating that productions are statistically the same than obtained with PE [1,21–24]. However, their market prices are higher than PE thus reducing its economic attractiveness for farmers in the short-term. In addition, there are no exhaustive studies including economic evaluations of PE and biodegradable mulches containing (i) an estimation of plastic removal costs; and (ii) a global consideration of short and long-term advantages and limitations of mulching materials [12].

The aim of this paper is to contribute new data to the literature by comparing the economic outcomes of PE and eight different mulching materials available for open-air pepper production. The economic evaluation is based on a four-year trial located in Aragon (Spain) with semi-arid climate conditions. Spain is currently the fifth highest world producer in pepper and the first in Europe [25] with more than 1.1 million annual tons and one of the highest average productivities in the world (6.11 kg $m^{-2}$). Fresh pepper is the main greenhouse vegetable cultivated in Spain, although the open-air cultivation is widespread in the country.

In order to promote the use of biodegradable materials, some regional authorities in Spain, like the Aragon Government, have implemented economic incentives for farmers who employ biodegradable mulching in vegetable production subjected to some other additional conditions. This study includes these incentives in economic calculations and evaluates their effectiveness in promoting the use of biodegradable mulches. The analysis contributes to the literature by providing data for discussion on the short- and long-term effects of the use of mulching materials.

## 2. Materials and Methods

### 2.1. Field Trials and Experimental Design

Field trials were conducted in an experimental field located in Zaragoza, Spain (41.43° N, 0.48° W) from May to October in 2012 to 2015, on a soil with a loamy texture (37.75% sand, 49.08% silt and 13.1% clay), with 2.1% organic matter and pH 7.95. Table 1 shows the main weather parameters during the cropping season in the years of trials.

**Table 1.** Average monthly temperature (°C), monthly solar radiation (h), solar radiation (MJ $m^{-1}$), rainfall (mm), days of rainfall, and number of days with gusts >10 m $s^{-1}$ from May to October from 2012 to 2015.

| Year | Month | Average Monthly Temperature (°C) | Monthly Solar Insolation (h) | Solar Radiation (MJ $m^{-1}$) | Rainfall (mm) | Days of Rainfall | Number of Days with Gusts >10 m $s^{-1}$ |
|---|---|---|---|---|---|---|---|
| 2012 | May | 19.8 | 306 | 360 | 3.3 | 6 | 4 |
| 2012 | Jun | 23.2 | 374 | 443 | 36.9 | 6 | 6 |
| 2012 | Jul | 23.7 | 395 | 467 | 2.8 | 3 | 5 |
| 2012 | Aug | 25.7 | 363 | 389 | 0.1 | 1 | 5 |
| 2012 | Sep | 20.3 | 305 | 252 | 18.5 | 6 | 7 |
| 2012 | Oct [i] | 17.0 | 164 | 97 | 12.6 | 3 | 3 |
| 2013 | May | 13.7 | 253 | 708.78 | 29 | 12 | 10 |
| 2013 | Jun | 19.6 | 285 | 769.9 | 32.9 | 5 | 8 |
| 2013 | Jul | 25.5 | 335 | 824.7 | 35.8 | 12 | 6 |
| 2013 | Aug | 23.7 | 312 | 749.1 | 17.8 | 3 | 3 |
| 2013 | Sep | 20.4 | 276 | 567.39 | 14.1 | 4 | 5 |
| 2013 | Oct | 16.9 | 261 | 405.82 | 17.1 | 7 | 4 |
| 2014 | May | 16.6 | 276 | 773.52 | 27.05 | 8 | 5 |
| 2014 | Jun | 22.0 | 296 | 798.61 | 18.82 | 8 | 9 |
| 2014 | Jul | 23.0 | 334 | 821.31 | 0.4 | 3 | 9 |
| 2014 | Aug | 23.2 | 308 | 739.53 | 12.06 | 5 | 5 |
| 2014 | Sep | 21.6 | 258 | 531.14 | 23.02 | 8 | 3 |
| 2014 | Oct | 17.3 | 250 | 388.8 | 9.02 | 6 | 3 |
| 2015 | May | 18.5 | 380.5 | 781.7 | 3.93 | 4 | 11 |
| 2015 | Jun | 22.7 | 371 | 808.01 | 24.31 | 8 | 8 |
| 2015 | Jul | 25.9 | 380.6 | 785.5 | 13.13 | 4 | 10 |
| 2015 | Aug | 23.8 | 355.5 | 727.14 | 26.27 | 10 | 2 |
| 2015 | Sep | 18.7 | 310.5 | 253.9 | 24.1 | 6 | - |
| 2015 | Oct | 15.0 | 260.5 | 145.7 | 36.6 | 14 | - |
| Av. | May | 17.2 | 263 | 736 * | 44 | 7.5 * | 7.5 * |
| Av. | Jun | 21.3 | 295 | 797 * | 31 | 6.8 * | 7.75 * |
| Av. | Jul | 24.5 | 337 | 829 * | 18 | 5.5 * | 7.5 * |
| Av. | Aug | 24.4 | 311 | 746 * | 17 | 4.8 * | 3.75 * |
| Av. | Sep | 20.7 | 231 | 475 * | 27 | 6 * | 5 * |
| Av. | Oct | 15.5 | 192 | 299 * | 30 | 7.5 * | 3.3 * |

[i] Average only with 18 days; Av. average period 1970–2010; * only average period 2012–2015.

Treatments were distributed randomly in a complete block design with four replicates. Elementary plots measured 0.7 m wide raised beds spaced 1.5 m from center to center and of 20 m longitude. Eight mulches (four biodegradable plastics and four papers) were tested and black polyethylene (PE) plastic was added as a control (Table 2). These materials were selected because they are available on the market, are still in the experimental phase, or have recently been marketed. All materials measured 1.2 m wide and were mechanically installed within five days after soil preparation prior to weed emergence. Soil preparation included soil tillage and bed formation. The irrigation system used was a 16 mm diameter drip tape in each line with an emitter every 20 cm and treatments were grouped into two different sectors, i.e., paper and plastic mulches, which were irrigated separately according to their water needs [26]. The irrigation moment was calculated with the soil moisture sensors (Aquameter ECH2O. Decagon Devices, Washington, DC, USA) thus the plants were irrigated before the stress of the crop (minimum balance) begins. The pepper variety was "Viriato" type Lamuyo. Pepper was transplanted with 0.3 m plant spacing, double row distribution, and 0.3 m between rows of crop. Marketable pepper fruits were harvested three times at the end of the season (during one month in all years).

Data on yield, inputs, and operational costs were collected each year from the trials in order to analyze the economic outcomes of each material. The analysis of yield data was performed using SAS (Statistical Analysis System V.9.4. SAS Institute, Cary, NC, USA). Homogeneity of variance and normality was tested before data analysis. Data were subjected to analysis of variance (ANOVA). Given that $p$ value of ANOVA was higher than 0.05 ($p$ = 0.45) mean separations were not performed.

For the economic part of the analysis, the operational costs, incomes, and net margins are presented separately.

**Table 2.** Type, name, main composition, thickness (μm) (plastic films) or grammage (g $m^{-2}$) (paper mulches), and color of materials used in the trials.

| Type of Mulching | Mulching Materials | Main Composition | Thickness–Grammage (μm–g $m^{-2}$) | Color |
|---|---|---|---|---|
| Non-degradable plastic film | PE | Low-density polyethylene | 15 | Black |
| Biodegradable films | Mater-Bi®[1] | Polycaprolactone, starch blend | 15 | Black |
| | Sphere®[2] | Potato starch, recycled polymers | 15 | Black |
| | Bioflex®[3] | Polylactic acid, co-polyester | 15 | Black |
| | Ecovio®[4] | Polylactic acid, polybutylene adipate terephthalate, starch | 15 | Black |
| Paper | Arrosi® 69[5] | Cellulosic fiber | 80 | Light brown |
| | Arrosi® G1a[5] | Cellulosic fiber | 100 | Light brown |
| | Arrosi® 240[5] | Cellulosic fiber | 80 | Light brown |
| | Mimgreen®[6] | Cellulosic fiber | 85 | Black |

[1] Novamont S.p.A. Novara, Italy. [2] Sphere Group Spain S.L. Zaragoza, Spain. [3] FKuR Kunststoff GmbH. Willich, Germany. [4] Fábrica de Papeles Crepados Arrosi S.A. Gipuzkoa, Spain. [6] Mimcord S.A. Barcelona, Spain.

### 2.2. Costs

Table 3 shows the inputs used and operational costs considered including fuel consumption. Inputs costs include pepper seedlings, pre-transplanting manure, herbicides, chemical dressing, irrigation water, and mulching materials used in trials. Pre-transplanting manure, chemical dressing, and some field preparation labors were taken from the experimental trial and the rest of the time costs considered for each operation were obtained from an interview with a local pepper producer. Labor costs are calculated using official data available in [27]. Amounts and type of fertilizers and doses of active matters used in chemical dressing can be consulted in [28].

Prices of mulching materials were obtained directly from the manufacturers thus they are final market prices. The costs of mechanical installation of paper mulches were calculated using data published by [1] for the case of tomato crop, adding an extra cost derived from the considered speed in the specific case of paper mulches, which need to be installed slower because they are not flexible and break easily. Additionally, a PE roll usually contains 2400 linear meters while a paper roll contains approximately 250 linear meters. Therefore, the number of times that workers have to stop to change roller in order to mulch a field of the same surface has also been considered. Similarly, the time needed to bury the endpoint of the mulch in each line in order to fix the material to the soil is considered.

Irrigation costs include an annual quota (proportional to the amount of hectares), energy costs, and drip line purchase cost. Operational costs include labor and machinery costs for soil preparation, crop and mulching installation and removal, application of fertilizers and herbicides, harvesting, and final field conditioning.

The cost of transplanting operation varies depending on the hired company and its availability at the time of the operation. Hence, an average costs from two different local companies was used. Chemical dressing was applied by fertirrigation and fractioned 6 times and labor cost was included. Herbicide application between line crops and manual weeding in the transplanting holes are common tasks and the costs are quite variable among years so an average rate provided by the farmer was used. Harvesting is one of the most expensive operations in the case of pepper for fresh consumption because the fruits are manually collected between three to four times at the end of the cropping season.

**Table 3.** Costs (€ ha$^{-1}$) of inputs and operations in open-air pepper production.

| **Inputs** | | **Cost (€ ha$^{-1}$)** |
|---|---|---|
| Pepper seedlings | | 1350 |
| Pre-transplanting manure | | 900 |
| Herbicides | | 24.3 |
| Chemical dressing | | 810 |
| Irrigation | Annual payment | 123 |
| | Electric consumption | 290 |
| | Drip line | 238 |
| Mulches [a] | PE | 404 |
| | Mater-Bi® | 1164 |
| | Sphere® | 772 |
| | Bioflex® | 931 |
| | Ecovio® | 505 |
| | Mimgreen® | 1086 |
| | Arrosi® 69 | 1024 |
| | Arrosi® G 1a | 1358 |
| | Arrosi® 240 | 1024 |
| **Operations** | | |
| Subsoiler | | 113 |
| Cultivator tillage | | 51 |
| Rotatory tiller | | 230 |
| Pre-transplanting manure application | | 103 |
| Burying fertilizer | | 51 |
| Installation irrigation system | | 244 |
| Bed formation + drip line installation + plastic mulching | | 144 |
| Bed formation + drip line installation + paper mulching | | 178 |
| Crop installation/transplant | | 475 |
| Chemical dressing application | | 17.5 |
| Herbicide between lines | | 9 |
| Manual weeding transplanting holes | | 350 |
| Manual harvest | | 2340 |
| Irrigation system removal | | 130 |
| Crop removal | | 51 |
| PE removal | | 176.5 |
| Landfill [b] | | 186 |
| Recycling [b] | | 192 |
| Cultivator tillage | | 51 |

[a] For 0.7 m bed width and 1.5 separation between lines; [b] For a plastic consumption of 160 kg ha$^{-1}$; Management of plastic, transport time, landfill and recycling costs included.

Field conditioning involves manual removal of the irrigation system, crop rests removal (which is a combined mechanical and manual operation) and plastic elimination in the case of non-biodegradable films which is a mechanical operation with a rotatory machine coupled to the tractor. The cost of landfill must be considered because under the current Spanish Law, farmers are responsible of ensuring proper treatment of wastes produced in their fields. However, as they are not required to assume the cost of recycling farmers usually store their waste and transport it to an authorized recovery point. Although recycling is not mandatory for farmers in Spain, we consider a scenario of plastic recycling in order to evaluate its effect on the final profitability. As a consequence, three different scenarios are considered: (i) the most widespread situation where farmers do not conduct any waste treatment, just remove the plastic residues from the field and leave them stored, buried or burned; (ii) the landfill scenario, where farmers transport plastic residues to the recovery point, and (iii) the recycling situation, when the farmers transport the residues to the recycling plant and assume the recycling cost. The consideration of the no waste treatment as a baseline scenario will allow us to assess how profitability is affected by waste treatment, which is a contribution of this paper.

The costs of manipulation and transport (including fuel) of the plastic waste from field to the recovery point (or the recycling plant) are included in scenarios (ii) and (iii) as an externalized task. This cost includes plastic removal from the field with a specific rotatory machine and the transport of the residues to the final destination with a tractor provided with a tow. A distance of 30 km from the field to the recovery point has been considered for the calculations. For the recycling scenario, the cost was obtained from a local recycling plant which amounts 62 € $t^{-1}$. Usually, film mulches have impurities such as soil, debris, pesticides, or fertilizers, which can represent up to 85% of the total remnants by weight and recycling plants usually do not accept plastic films with more than 5% impurities [29]. However, the local plant considered does not establish a limit for impurities.

Finally, cultivator tillage cost for soil preparation for the next season is included as field conditioning. Costs of using machinery shown in Table 1 includes the cost of fuel which is proportionally distributed in proportion to the time cost of each operation.

### 2.3. Incomes and Net Margins

The calculation of incomes includes the market value for the crop outputs. The "Lamuyo" pepper market price considered is 876 € $t^{-1}$, which is an average from the last three years from available data [27]. We assume that this market price is not different between materials because we have not observed that different mulches modifies the harvest time in the case of pepper crop.

Although there were no statistical differences among materials [28], yields obtained in three to four years of the experiment were very low (about 10 t $ha^{-1}$) in comparison to the average obtained in the region which amounts 29.8 t $ha^{-1}$ [30]. Pepper is a delicate crop concerning water and humidity variations and during 2012 and 2013, technical problems in irrigation caused pepper seedlings mortality that could not be replaced. In addition, 12 days of rainfall were reported in 2013 (7.5 days is the usual) (see Table 1). Although the amount of rainfall was not excessive, it caused a delay in the field works, which led to planting peppers to a very late date (15 June). This is a handicap to get good production in our area.

In 2015, temperature, insolation, and radiation parameters during May and June were much higher than normal, which caused the degradation of many biodegradable plastics and thinner papers and interfering dramatically with flowering. Subsequently these materials broke more easily by the action of the wind, which was also stronger than usual from May to October if we look at the days of wind with gusts greater than 10 m $s^{-1}$.

Therefore, yield data used in this study is from year 2014 where pepper yields are considered normal compared to the average production in the area and no agronomic and climatic problems were observed.

Additionally, farmers can obtain subsidies from the Aragon Government (funded by the European Union) offering the possibility to receive 35% of the material costs when biodegradable mulching is used. In such case, farmers must also meet some demanding requirements, such as belonging to a horticultural producers' association developing operative and investment programs in improving the quality of their products including the development of protected designations of origin and geographical indications [31]. According to current legislation, paper mulches are not considered as biodegradable and therefore do not receive subsidies. Consequently, two different scenarios are considered in the economic analysis: (i) when no subsidies are received; (ii) when farmers are compensated for the cost of using biodegradable mulches. This comparison sheds light on practical insights to improve the knowledge of the effectiveness of such subsidies in promoting the use of biodegradable materials.

Finally, the economic profitability of each material is compared using the net margin, which is calculated as the difference between incomes (value of the crop output with or without regional subsidies) and total costs (inputs, operations, labor, etc.).

## 3. Results

### 3.1. Costs and Incomes

Comparing the cost of the considered mulches, biodegradable materials are between 25% and 188% more expensive than PE while paper mulches are between 153% and 236% more expensive (see Table 3). Among biodegradable materials, Ecovio® is the cheapest one and Arrosi® 69 and Arrosi® 240 are the cheapest papers.

Table 4 shows the aggregated costs by operations calculated in the trials. The name "field preparation" includes subsoiler, cultivator tillage, rotatory tillering, and the application and burial of pre-transplanting manure. "Crop season operations" comprised irrigation, herbicide application and chemical dressing among others. "Plastic and paper mechanical mulching" includes the costs of materials and mechanical installation on the field. Finally, the concept of "field conditioning" includes irrigation system and crop removal, waste management for the non-biodegradable scenarios, and, finally, a cultivator pass.

**Table 4.** Costs (€ $ha^{-1}$) for fresh pepper crop production.

| Operations | | Costs (€ $ha^{-1}$) |
|---|---|---|
| Field preparation | | 1448 |
| Crop season operations | | 3931 |
| Plastic mechanical mulching | PE | 548 |
| | Mater-Bi® | 1308 |
| | Sphere® | 916 |
| | Bioflex® | 1075 |
| | Ecovio® | 649 |
| Paper mechanical mulching | Mimgreen® | 1264 |
| | Arrosi® 69 | 1202 |
| | Arrosi® G 1a | 1536 |
| | Arrosi® 240 | 1202 |
| Harvest | | 2340 |
| Field conditioning non-biodegradable mulch scenario [a] | No waste management | 408.5 |
| | Landfill | 418 |
| | Recycling | 424 |
| Field conditioning biodegradable mulch scenario | | 232 |

[a] For a plastic consumption of 160 kg $ha^{-1}$. Management of plastic, transport time, and landfill and recycling costs included.

If the use of PE with no waste management is considered as a benchmark, then mulching represents 6.3% of the total costs for pepper production. The biggest expenditure of these operations corresponds to crop season operations (mainly transplant and pepper seedlings costs) with 45.3% and the following is the harvest with 27% because it is a manual task. For the rest of the cases, mulching materials represents between 7.5% and 14.1% of the total costs in biodegradable and between 13.1% and 16.2% in paper types (Table 4). Regarding irrigation costs, although we expected to save water with plastics with respect to papers, water consumption was very similar for both types of materials.

The analysis of field conditioning costs for PE scenario shows that this cost represents 4.7% of the total when no waste management is carried out. This cost increases to 4.8% when the farmer transports the waste to the recycling point (landfill scenario) and up to 4.9% if the complete recycling cost is assumed. By contrast, using biodegradable mulches allows a saving in field conditioning of a minimum of 54.7% and a maximum of 56.7% with respect to PE.

Table 5 shows the results obtained for yield, subsidies, and incomes. Despite no statistically differences are found among mulching materials, PE obtained one of the lowest yields. Mater-Bi® and Arrosi®240 obtained amounts close to 30 t $ha^{-1}$, which are similar to the average yields recorded in Spain (29 t $ha^{-1}$). Final incomes were calculated including the subsidies available to cover 35% of the biodegradable plastic cost.

**Table 5.** Experimental yield (t ha$^{-1}$), subsidies, and total income obtained for mulching materials in open-air conditions in 2014.

| Type of Mulching | Mulching Materials | Yield (t ha$^{-1}$) | Subsidies (€ ha$^{-1}$) | Income with Subsidies (€ ha$^{-1}$) |
|---|---|---|---|---|
| Non-degradable film | PE | 24.6 a | - | 21,549.6 |
| Biodegradable films | Mater-Bi® | 29.2 a | 407.4 | 25,986.6 |
| | Sphere® | 25.8 a | 270.2 | 22,871.0 |
| | Bioflex® | 24.4 a | 325.9 | 21,700.3 |
| | Ecovio® | 23.3 a | 176.8 | 20,587.6 |
| Paper mulch | Mimgreen® | 26.7 a | - | 23,389.2 |
| | Arrosi®69 | 25.3 a | - | 22,162.8 |
| | Arrosi®G 1a | 26.9 a | - | 23,564.4 |
| | Arrosi®240 | 28.5 a | - | 24,966.0 |

Same letters in yield mean no statistical differences among treatments ($p$ = 0.45).

### 3.2. Net Margins

Table 6 summarizes the main economic variables analyzed. Net margins are calculated under the three waste management scenarios considered for PE and under the two scenarios for biodegradable materials (with and without subsidies). In addition, the percentage with respect to PE without waste management (baseline scenario) is calculated in order to present a comparative analysis of alternative materials.

For biodegradable materials, the total costs are between 2.2% and 9.3% higher than those of PE. The only exception is Ecovio®, which is cheaper than PE because the additional material cost is less than disposal costs. Regarding final profitability, two bio-degradable materials (Mater-Bi® and Sphere®) present higher profitability than PE (with and without subsidies) while Bioflex® and Ecovio® are the worse options, with reductions of 1.6% and 6.9% with respect to the benchmark due to low yields obtained in the trials. Mater-Bi® is the best biodegradable option, with an increase of 29.9% with respect to PE.

**Table 6.** Incomes, costs, and net margins of different mulching materials (€ ha$^{-1}$).

| Type of Mulching | Mulching Materials | Scenarios | Incomes | Costs | Net Margin | % with Respect to PE |
|---|---|---|---|---|---|---|
| Non-degradable film | PE | No waste management | 21,549.6 | 8675.3 | 12,874.3 | - |
| | | Landfill | 21,549.6 | 8684.8 | 12,864.8 | 99.9 |
| | | Recycling | 21,549.6 | 8690.8 | 12,858.8 | 99.9 |
| Biodegradable films | Mater-Bi® | No subsidies | 25,579.2 | 9258.8 | 16,320.4 | 126.8 |
| | | With subsidies | 25,986.6 | | 16,727.8 | 129.9 |
| | Sphere® | No subsidies | 22,600.8 | 8866.8 | 13,734.0 | 106.7 |
| | | With subsidies | 22,871.0 | | 14,004.2 | 108.8 |
| | Bioflex® | No subsidies | 21,374.4 | 9025.8 | 12,348.6 | 95.9 |
| | | With subsidies | 21,700.3 | | 12,674.5 | 98.4 |
| | Ecovio® | No subsidies | 20,410.8 | 8599.8 | 11,811.0 | 91.7 |
| | | With subsidies | 20,587.6 | | 11,987.8 | 93.1 |
| Paper | Mimgreen® | No subsidies | 23,389.2 | 9214.8 | 14,174.4 | 110.1 |
| | Arrosi®69 | No subsidies | 22,162.8 | 9152.8 | 13,010.0 | 101.1 |
| | Arrosi®G 1a | No subsidies | 23,564.4 | 9486.8 | 14,077.6 | 109.3 |
| | Arrosi®240 | No subsidies | 24,966.0 | 9152.8 | 15,813.2 | 122.8 |

## 4. Discussion

### 4.1. Economic Evaluation

The results shown in Table 5 indicate that all materials had similar yields to PE film, but the trend is that some of the biodegradable materials obtain higher yields, confirming previous evidences such as that of [32] who reported higher pepper yields with similar biodegradable materials compared to PE.

Total costs and net margins (Table 6) in the PE situations are quite similar, with an increase of 0.11% in the costs when considering landfill and 0.18% when plastic is recycled. These results suggest that the cost of waste treatment and recycling do not significantly affect final profitability. This contrasts strongly with the widespread perception among farmers that waste management is costly in terms of time and money. Our estimations support the authorities' efforts to hold farmers responsible for the wastes they generate in their activities until the end of their cycle.

However, given that there are no significant yield differences between materials, it is important to note that subsidies would be insufficient to compensate for the extra cost of the material if identical yields were obtained, with the only exception of Ecovio® and Sphere®. This result is maintained even taking into account the total recycling cost. Therefore, the current level of subsidies (35%) does not seem to be a strong enough incentive for all the biodegradable materials to be adopted by farmers. An alternative to the current system should provide for compensation to cover the difference in cost with regard to PE. Calculations show that the rate of subsidy should be 50.1% for Mater-Bi® and 37.6% for Bioflex® to assure these options to be as profitable as PE. When the total cost of recycling is considered, then the necessary subsidy would reach 48.7% for Mater-Bi® and 35.9% for Bioflex®.

With regard to paper mulches, although their costs are between 5.5% and 9.3% higher than PE, they obtain higher net margins due to the influence of savings on field conditioning operations and higher yields. Arrosi®240 is the best option among paper mulches, with increases in net margin by 22.8%. Once again, this result is highly dependent on the higher yields. When yields are considered the same as obtained by PE, then the over-cost of paper materials is not compensated by savings in waste management costs. In this case, the percentage of subsidies needed to make them as profitable as the PE option would be 48.2% for Mimgreen®, 45.1% for Arrosi® 69 and Arrosi® 240, and 58.6% for Arrosi® G1a.

In summary, although six of the eight materials evaluated as alternatives to PE have proved to be more profitable, only two of them (Ecovio® and Sphere®) are good potential alternatives from an economic point of view under the current subsidies received despite their higher market price. Two main reasons explain this result: first, because they achieve crop yields similar to PE, and secondly, because they save waste treatment costs that compensate their higher market prices. Biodegradable plastics benefit from public support to compensate for part of the rise in market prices but the results show that the current subsidies system does not guarantee the profitability of all the materials analyzed. In fact, the most expensive materials (Mater-Bi® and Bioflex®) are not good economic alternatives when the yields are the same as PE. Similarly, [1] showed that the use of biodegradable mulches with tomato crop in different localities was only profitable in certain specific locations and with some materials.

Interestingly, two of the evaluated biodegradable films (Ecovio® and Sphere®) are good economic alternatives to PE under the current public payment system. This contrasts with the widespread use of the PE, which probably comes from its low cost in comparison with biodegradable materials. By contrast, our calculations show that biodegradable films can be better alternatives in the short-term even in the case of no waste management. The net margins when using these biodegradable materials are even better when recycling is considered mandatory. Of course, there may be other non-economic reasons that may inhibit broader adoption of bio materials and papers. Breakdown during the growing season and fragments of mulches after tillage may be aesthetically displeasing to farmers and consumers thus inhibiting their adoption. In the case of papers, it may also exist a negative perception linked to the greater discomfort for their installation beyond the cost of time that has been included in our calculations.

### *4.2. Environmental Implications of the Use of Plastic Films and Papers*

In addition to the short-term economic considerations, other environmental aspects related to the use of mulching materials should be taken into account. It is necessary to emphasize the increasing problems caused in the environment by the plastics. For example, [33] indicated that the presence of PE in horticultural soils in Argentina can represent around 10% of the soil and [34] affirmed that the amount of plastic waste in an average vegetable field of China could reach 317.4 kg $ha^{-1}$. Although no similar data have been found for Europe, there is strong evidence that the presence of plastic residues also affect the soil quality. For example, [13] reported that amounts of residual mulch films of 320 kg ha$^{-1}$ could interfere in tomato crop yields, causing decreases by 5.9% in yields. It has been demonstrated that this effect on the soil's productive capacity increases with the concentration of plastic particles in the soil. This evidence is a further argument in favor of making the complete management of waste mandatory for farmers, and therefore a strong support for the use of other biodegradable materials.

However, it should be remembered that there is a growing number of studies warning of the consequences of the use of many of the so-called "biodegradable" materials, as they do not degrade completely in soil. A recent study of [23] hypothesized the case where a farmer tills all the biodegradable mulch at the end of the crop cycle into the soil. The standard method tests applied to plastics (ASTM D5988 and ISO 17556) consider a degradation rate of 90% biodegradation rate within to 2 years; considering this, 45% of this plastic will remain in the field during the first year. After the second year, a 10% of the first year plastic will probably remain in soil and the plastic from the second application with its 10% remaining to the third year. If this 10% is assumed never to degrade, then it will accumulate every year. The authors hypothesize that 350 kg ha$^{-1}$ of non-degradable plastic will represent 6.45% decreased yield on the fifth year of using biodegradable films and tilling them at the end of the crop season. Unfortunately, there is no standard method to measure the rate of degradation after incorporation in the soil and the percentages could be very variable.

In the case of some of our tested materials, some evidences are reported in literature. [35] established that Bioflex® material lost 73% of their initial weight after 145 days after soil incorporation (DASI), while Sphere lost only 42% in the same period. On the other hand, Mater-Bi® generated fragments of a wide range of sizes (up to 2664 mm$^2$) which maybe will interfere with tillage, another aspect to take into consideration. By contrast, the paper Mimgreen® presented the smallest fragments and surface after 200 DASI.

With regard to paper mulches, no waste management has to be implemented and no accumulation of waste in the soil is expected to interfere with the crop, so, in principle, their effects are likely to be less harmful than plastics. However, papers are insufficiently explored until now and their environmental effects in the long-term and these advantages have to be proven. If these advantages are verified, then the papers should be eligible for public support.

## 5. Conclusions

The extensive use of PE mulching materials owes to their lower market prices compared to biodegradable materials. However, our results show that the inclusion of the costs of waste management and recycling is crucial for a proper evaluation of the economic profitability of different options in the short-term. The inclusion of such costs under the current Spanish legislation only increases the costs by 9.5 € ha$^{-1}$ with respect to the no waste management scenario and 15.5 € ha$^{-1}$ if total recycling cost is considered. These increases represent a reduction in the final net margin of 0.1%. This is supporting the mandatory measures for farmers to assume the costs of waste management and recycling.

Economic consideration of current Spanish government support of biodegradable mulching materials allows us to affirm that only two materials (Ecovio® and Sphere®) are profitable alternatives to PE when the same yield is considered. Despite the saving in costs of field conditioning with regard to PE, the high market prices of biodegradable and paper materials are not compensated with the current level of subsidies, thus impeding their adoption in fields. An increase in subsidies rates of up to 50.1% would allow all biodegradable films to be better alternatives than PE.

Although no fully conclusive evidence has been found on the environmental effects of long-term use of the specific materials analyzed, the consideration of soil quality effects supports measures towards mandatory full recycling of waste and for the use of biodegradable and paper materials. Correct assessment of environmental damages of materials would require other types of field experiments than those conducted here. These data could be included in a long-term economic model based on the analysis of the net present value of discounted future social costs (economic plus environmental damages) and benefits (yield gains and reduced environmental damages). In addition, an adequate evaluation must take into account that subsidies provide an economic incentive for the adoption of bio-materials, but also an opportunity cost to society, thus a proper design must be ensured.

Finally, although this study refers to field trials with pepper crops, the results may be representative of the open-air growing conditions for other summer horticultural crops under similar climatic conditions, mainly in the Ebro Valley, where mulches are often used.

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