Universitat de Lleida

Acolchados y su efecto sobre el control y la biología de la juncia (Cyperus rotundus L.) o Mulches and their effect on control and biology of purple nutsedge (Cyperus rotundus L.)

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Universitat de Lleida

TESI DOCTORAL

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Mulches and their effect on control and biology of purple nutsedge (*Cyperus rotundus* L.)

Ana Isabel Marí León

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Summary

One of the most troublesome weeds at worldwide level is *Cyperus rotundus* L. (purple nutsedge); this weed affects mostly irrigated vegetable crops. Polyethylene (PE) plastic mulches are frequently used as weed control method, providing moreover other advantages as crop earliness and water-use efficiency. One of the main drawbacks of this method is that *C. rotundus* pierces the sheet of the mulch easily and remains as the only uncontrolled species. Another negative aspect of the PE use is the need to remove all the material after harvest. If this action is conducted mechanically, the sheets break into small pieces that, apart from polluting the soil, can interfere in the implementation and development of the next crop. Therefore, there is a need of searching for alternative materials presenting the same advantages than PE but without leaving the undesirable residues in the soil and controlling *C. rotundus* more efficiently.

Several trials have been carried out in this context to study the properties of several biodegradable materials, both plastics and papers, as possible alternatives to PE use. To achieve the objective from different points of view the following trials were developed: i) laboratory characterization of the paper mulches using the international standard for plastic to the test the grammage, thickness, resistance to punction and traction. At the same time, the CIE LAB colour scale was determined. This data supports the interpretation of the results obtained in the field trials, specially the mechanical installation, weed control and degradation of the materials. The generated information on the physical properties of the papers may contribute in determining, which are the characters to be improved in the papers and which material should be recommended for each situation (Chapter 1).

ii) Field trial during four years with pepper crop installed on 11 different biodegradable mulching materials. The evaluated parameters were: nutsedge vegetative development and control with each material, degradation time of the mulches and, finally, pepper yield obtained for each material. A specific trial for nutsedge was included by tuber installation in confined mesh cubes to describe the nutsedge reproduction under the different mulching materials (Chapter 2).

iii) Semi-field trial in pots with nutsedge tubers covered by 10 different mulching materials with different degree of translucency and flexibility (Chapter 3).

iv) Growing chamber trial with three different mulching materials and sowing nutsedge with the purpose of knowing the depth from which the nutsedge is capable of sprout and pierce the materials, as well as to quantify the aerial and underground biomass of *C. rotundus* generated in each situation (Chapter 3). The implementation costs from the trial i), the costs of each material and their mechanical

installation in the field (and removal in the case of PE) and the yield values, together with the existing institutional subsidies for farmers for using the biodegradable plastic mulches, served to calculate the balance of incomes and costs. The economic viability of all the possible scenarios was compared (Chapter 4).

The characterization trial of the different paper mulches showed very variable grammage and thickness rates. The crepe materials are thicker than rigid or non-flexible papers so the rolls present a bigger volume for the same length. Crepe papers in most of the cases are brown and allow a higher quantity of light to pass through the sheet compared to opaque materials. The tested opaque materials are also more rigid. Crepe or flexible materials present higher capacity of elongation; therefore, they also resist higher tensions. Nonetheless, non-flexible materials had a lower elongation capacity so they will break easily in contact with sharp objects or localized tensions produced by, for example, stones. Papers with intermediate grammage and thickness and opaque ones have shown to be the most promising materials for an efficient installation in the field and a good nutsedge control.

The main results from trials ii), iii) and iv) are that biodegradable plastics do not control nutsedge efficiently, because this weed pierces them even more than PE. Additionally, results from trials iii) and iv) show that biodegradable plastics allow *C. rotundus* generating more aboveground and underground biomass and more tubers than when growing under PE. When placed in the soil at up to 10 cm depth, nutsedge tubers pierce both Mater-Bi® and PE in a similar proportion regardless of the depth. Results of trial ii) show that the above-ground degradation of the biodegradable plastics can be very variable depending on the material and on the year and, in some cases does not allow a correct weed control. The underground part of paper mulches degrades quicker than of the biodegradable plastics, what can be an important drawback in windy areas. Hilling 10-15 days after installation can prevent this problem.

The main benefit by using paper mulches is that they are not pierced by nutsedge in the tested conditions. Trials ii) and iii) show that opaque papers not only impede *C. rotundus* to emerge but also to generate biomass between the soil and the paper film and also strongly reduce the tuber production. Opposite, the translucent papers, even if they are also not pierced, allow the generation of biomass and a high tuber production in a similar amount than in the unweeded control, but less than when using biodegradable plastic mulches. Therefore, paper mulches, especially the opaque ones, control *C. rotundus* better than PE. Concerning pepper yield, no significant differences have been found between the tested materials in all 4 years following trial ii) despite the tendency was higher yield for the opaque papers than for PE.

Concerning the economic study, both papers and biodegradable plastics are more expensive than PE and installation costs of papers are higher than for plastics as installation speed is slower and adjustments of the laying-down machine are required to avoid tensions that produce breaks. Opposite, PE use is associated to removal costs and waste management that are, however, lower than the overcosts of the biodegradable materials compared to PE. When considering the individual yield data obtained in the field for each mulching material, all biodegradables mulches were found economically viable, even more than PE for the materials Sphere® 4 and Ecovio®. Opposite, if a general mean yield of the area is considered for all mulch materials, the current subsidies to enhance the use of biodegradable materials are not sufficient to equate the benefits of using biodegradable mulches compared to those obtained by using PE.

Future work should consider the real degradation capacity of the biodegradable plastics because plastic rests could be accumulating in a long-term in the fields because, following the legislation, these materials must degrade in 90% in two years, without knowing the fate of the remaining 10%. It is also considered interesting to continue with the development of flexible and at the same time opaque mulching papers.

Resumen

Una de las malas hierbas más problemáticas a nivel mundial es el *Cyperus rotundus* L. (juncia) afecta sobre todo a cultivos hortícolas de regadío. Los acolchados plásticos con polietileno (PE) se usan frecuentemente como método de control de malas hierbas en estas condiciones porque, además, proporcionan precocidad al cultivo y una mejor eficiencia del uso del agua de riego. Uno de los principales inconvenientes de este método es que *C. rotundus* perfora la lámina de acolchado con mucha facilidad quedando como única especie sin controlar. Otro inconveniente del uso de PE es que debe retirarse de la parcela tras la cosecha. Si la recolección del cultivo es mecánica, las láminas se rompen quedando fragmentos que, aparte de contaminar el suelo, pueden interferir en la implantación y desarrollo del cultivo siguiente. Por tanto, existe la necesidad de buscar materiales alternativos que mantengan las ventajas del PE pero no dejen residuos indeseables en el suelo y/o tengan un control más eficaz sobre *C. rotundus*.

En este contexto se realizaron diversos ensayos para estudiar las propiedades de varios materiales biodegradables, tanto plásticos como papeles, como posibles alternativas al PE. Para acometer la temática desde diferentes puntos de vista complementarios se han llevado a cabo los siguientes ensayos: i) Se han caracterizado en laboratorio los acolchados de papel siguiendo las normas estándar para plástico de acuerdo a los parámetros de gramaje, espesor, punción y tracción; a su vez, se determinó el color mediante la escala CIE LAB. Estos datos permiten ayudar a interpretar los resultados obtenidos en los ensayos de campo, especialmente en la instalación en campo, control de malas hierbas y degradación. De esta forma se pretende conocer cuáles son los caracteres que se deben mejorar y en qué medida según la situación a la que queramos adaptar el material (Capítulo 1).

(ii) Ensayo en campo con cultivo de pimiento durante 4 años en los que se ensayaron 11 materiales biodegradables con el fin de evaluar el desarrollo vegetativo y el control de juncia en cada material, estimar su tiempo de degradación en campo y, finalmente, establecer el rendimiento del pimiento en cada material. En este ensayo se incluyó un estudio específico para juncia mediante la instalación de tubérculos en una zona delimitada con malla para describir su multiplicación bajo los distintos acolchados (Capítulo 2).

(iii) Ensayo de semi campo en macetas con tubérculos de juncia cubiertos con 10 materiales biodegradables distintos con el objetivo principal de relacionar el desarrollo de la juncia con el distinto grado de traslucidez y flexibilidad de estos materiales (Capítulo 3).

(iv) Ensayo en cámara de cultivo con tres materiales de acolchado y juncia con la finalidad de conocer la profundidad a partir de la cual los tubérculos de *C. rotundus* son capaces de emerger y

perforar los distintos materiales, así como la cantidad de biomasa, aérea y subterránea de *C. rotundus* que se genera en cada situación (Capítulo 3). Con los datos de implantación de cultivo del ensayo i), los costes de cada material, los derivados de su instalación en campo (y retirada en el caso del PE) y la cosecha de ese ensayo, junto con las ayudas institucionales a que los agricultores pueden optar en el caso de usar los plásticos biodegradables se realizaron balances de ingresos y costes, para comparar la viabilidad económica de todas las opciones (Capítulo 4).

Los datos de caracterización de los acolchados de papel estudiados muestran unos valores de gramaje y espesor muy variables. Los materiales crepados son más gruesos que los rígidos o no flexibles, por lo que las bobinas tendrán un mayor volumen. Los papeles crepados, que son en su mayoría de color marrón claro, dejan pasar una mayor cantidad de luz en comparación con los papeles opacos que son, además, rígidos. Los materiales flexibles o crepados tienen mayor capacidad de elongación y de resistencia a la punción que los no flexibles, por lo que resisten mayores tensiones. A pesar de ello, los materiales no flexibles tienen una capacidad de elongación menor por lo que se romperán con mayor facilidad en contacto con objetos punzantes o tensiones puntuales como las producidas por piedras. Los materiales flexibles con caracteres intermedio de espesor y gramaje medio y que no dejen pasar la luz han mostrado ser los más prometedores para una eficiente instalación en campo y un buen control de la juncia.

De los ensayos ii), iii) y iv) podemos concluir que los plásticos biodegradables no suponen una mejora frente al PE en cuanto al control de la juncia, ya que los perfora con la misma o incluso mayor facilidad que al primero. A su vez, de los ensayos (iii) y (iv) se deduce que los plásticos biodegradables permiten a *C. rotundus* generar más biomasa aérea, subterránea y un mayor número de tubérculos que bajo el PE. También se concluye que la profundidad de colocación de los tubérculos no influye en la capacidad de *C. rotundus* para perforar los plásticos Mater-Bi® y PE, al menos en los diez primeros cm de profundidad. Los resultados en el ensayo (ii) muestran que la degradación exterior de los plásticos biodegradables es muy variable según el material ensayado y el año y, en algunos casos, no permite un control adecuado de las malas hierbas. Haciendo referencia a los papeles, se ha corroborado que la parte enterrada se degrada más rápido que en los plásticos biodegradables, lo que puede ser un gran inconveniente en zonas de viento. Este problema se puede prevenir con un aporcado a los 10-15 días después de la colocación en campo.

La importante ventaja de los papeles es que no son perforados por juncia en las condiciones ensayadas. En los ensayos (ii) y (iii) se observa que los papeles opacos, además de ser una barrera física frente a *C. rotundus,* también impiden la generación de biomasa aérea entre ellos y el suelo, además de reducir fuertemente la producción de tubérculos. Sin embargo, los papeles traslúcidos, aunque tampoco son perforados, sí que permiten que se genere biomasa entre el suelo y la lámina y

una gran cantidad de tubérculos, similar al escenario sin acolchados, pero menos que con los acolchados plásticos biodegradables. Por tanto, los papeles, sobre todo los opacos, suponen una mejora de control de *C. rotundus* frente al PE. En cuanto al rendimiento del cultivo, según los resultados del ensayo (ii), no se han producido diferencias significativas entre todos los materiales ensayados en ninguno de los 4 años estudiados, aunque la tendencia es que el rendimiento obtenido sobre los papeles opacos fue mayor que el obtenido sobre PE.

En relación al estudio económico, hay que señalar que tanto los papeles como los plásticos biodegradables son más caros que el PE y que los costes de instalación del papel son mayores que para los plásticos, ya que la velocidad de instalación es menor y se requieren ajustes en la máquina acolchadora para evitar tensiones que producen roturas. Por el contrario, PE lleva asociados unos costes de recogida y gestión de residuos que, no obstante, son menores al sobrecoste de los materiales biodegradables frente al PE. Considerando los rendimientos obtenidos en los ensayos de campo para cada tratamiento por separado, todos los materiales biodegradables son económicamente viables, incluso más rentables que el PE en el caso de Sphere® 4 y Ecovio®. En cambio, si consideramos un rendimiento medio de la zona para todos los materiales, las ayudas económicas actuales para fomentar el uso de materiales biodegradables no son suficientes para que los beneficios obtenidos para los materiales biodegradables se puedan equiparar a los del PE.

Nuevos estudios deberían considerar la capacidad de degradación real de los plásticos biodegradables, ya que se podría estar acumulando restos de material plástico en los campos a largo plazo porque, según la normativa se exige una degradación de estos acolchados de un 90% en dos años, desconociéndose el destino del 10 % restante. También se cree oportuno continuar en el desarrollo de papeles para acolchado que sean al mismo tiempo flexibles y opacos.

Resum

Una de les males herbes més problemàtiques a nivell mundial es el *Cyperus rotundus* L. (castanyola) i afecta sobretot a cultius hortícoles de regadiu. Els encoixinats plàstics amb polietilè (PE) s'usen freqüentment com a mètode de control de males herbes en aquestes condicions perquè, a més, proporcionen precocitat al cultiu i una major eficiència de l'ús de l'aigua de reg. Un dels principals inconvenients d'aquest mètode es que *C. rotundus* perfora la làmina de encoixinat amb molta facilitat quedant com a única espècie sense controlar. Un altre inconvenient de l'ús del PE és que hi ha que retirar-ho de la parcel·la un cop s'ha fet la collita. Si aquesta és mecànica, les làmines es rompen quedant fragments que, a part de contaminar el sòl, poden interferir en la implantació i desenvolupament del següent cultiu. Per tant, existeix la necessitat de buscar materials alternatius que mantinguin els avantatges del PE però no deixin residus indesitjables en el sòl i/o tinguin un control més eficaç sobre *C. rotundus.*

En aquest context es varen realitzar diversos assajos per estudiar les propietats de diversos materials biodegradables, tant plàstics como papers, com possibles alternatives al PE. Per emprendre la temàtica des de diferents punts de vista complementaris es va dur a terme els següents assajos: i) es varen caracteritzar en laboratori els encoixinats de paper seguint les normes estàndard per el plàstic per els paràmetres de gramatge, espessor, punció i tracció, a més, es va determinar el color mitjançant l'escala CIE LAB. Aquestes dades permeten interpretar els resultats obtinguts en els assajos de camp, especialment en la instal·lació de camp, control de males herbes i degradació. D'aquesta manera es pretén conèixer quines són les característiques que es tenen que millorar i en quina mesura segons la situació a la que volem adaptar el material (Capítol 1). ii) Assaig de camp amb cultiu de pebrot durant 4 anys en els quals es varen testejar 11 materials biodegradables amb el fi d'avaluar el desenvolupament vegetatiu i el control sobre la castanyola en cada material, estimar el temps de degradació en camp i, finalment, establir el rendiment del pebrot en cada material. En aquest assaig es va incloure un estudi específic per la castanyola mitjançant d'instal·lació de tubercles en una zona de limitada amb malla per descriure la seua reproducció baix els diferents materials (Capítol 2). iii) assaig de semi camp en contenidors amb tubercles de castanyola coberts amb 10 materials biodegradables

amb l'objectiu principal de relacionar el desenvolupament de la castanyola amb el grau de translucidesa i flexibilitat d'aquests materials (Capítol 3). iv) assaig en càmera de cultiu amb tres materials d'encoixinat i castanyola amb la finalitat de conèixer la profunditat a partir de la qual els tubercles de *C. rotundus* són capaços d'emergir i perforar els diferents materials, així com la quantitat

de biomassa aèria i subterrània de *C. rotundus* que és genera en cada situació (Capítol 3). Amb les dades d'implantació de cultiu de l'assaig i), els costs de cada material, els derivats d'instal·lació en camp (i retirada en cas del PE) i la collita d'aquest assaig, junt amb les ajudes institucionals a que els agricultors podem optar en el cas d'utilitzar plàstics biodegradables es realitzaren balanços d'ingressos i costs, per compara la viabilitat econòmica de totes les opcions (Capítol 4).

Les dades de caracterització dels encoixinats de paper estudiats varen mostrar uns valors de gramatge i espessor variables. Els materials crepats són més gruixuts que els rígids o no flexibles, per lo que les bobines tindran major volum. Els papers crepats, que són en la gran majoria de color marró clar, deixen passar una quantitat de llum major en comparació amb els papers opacs que són, a més, rígids. Els materials flexibles o crepats tenen major capacitat d'elongació i de resistència a la punció que els no flexibles, per lo que resisteixen majors tensions. Els materials flexibles o crepats tenen una major capacitat d'elongació i de resistència que els no flexibles, per lo que resisteixen majors tensions. Malgrat això, els materials no flexibles tenen una capacitat d'elongació menor per lo que es romprien amb major facilitat en contacte amb objectes punxants o tensions puntuals como les produïdes per pedres. Els materials flexibles amb caràcter intermedi d'espessor i gramatge i que no deixen passar la llum són els més prometedors per una instal·lació eficient en camp i un bon control de la castanyola.

Dels assajos ii), iii) i iv) podem concloure que el els plàstics biodegradables no suposen una millora front al PE en quant al control de castanyola, ja que els perfora amb la mateixa o inclòs amb major facilitat que al primer. A més, dels assajos iii) i iv) es dedueix que els plàstics biodegradables permeten a *C. rotundus* generar més biomassa aèria, subterrània i un major número de tubercles que baix el PE. També es conclou que la profunditat de col·locació dels tubercles no influeix en la capacitat de *C. rotundus* de perforar els plàstics Mater-Bi® i PE, al menys en els deu primers cm de profunditat. Els resultats en l'assaig ii) mostren que la degradació exterior del plàstics biodegradables es molt variable segons el material assajat i l'any i, en alguns casos, no permet el control adequat de les males herbes. Fent referència als papers, s'ha corroborat que la part enterrada es degrada més ràpid que en el plàstics biodegradables, lo que pots ser un gran inconvenient en zones de vent. Aquest problema es pot prevenir amb una aplicació de terra als 10-15 dies després de la col·locació en camp.

L'avantatge important dels papers és que no són perforats per la castanyola en les condicions assajades. En els assajos ii) i iii) s'observa que els papers opacs, a més de ser una barrera física front *C. rotundus*, també impedeix la generació de biomassa aèria entre ells i el sòl, i de reduir dràsticament la producció de tubercles. No obstant, els papers translúcids, encara que tampoc són perforats, sí que permeten que es generi biomassa entre el sòl i la làmina i una gran quantitat de tubercles, similar a l’escenari sense encoixinats però menys que amb els encoixinats biodegradables plàstics. Per tant, els papers, sobretot els opacs, suposen una millora de control de *C. rotundus* enfront al PE. En quant al rendiment del cultiu, segons el resultats de l’assaig ii), s’han produït diferències significatives entre tots els materials assajats en ningun dels quatre anys estudiats encara que la tendència es que el rendiment obtingut en els papers opacs va ser major que en l’obtingut en PE.

En relació amb l’estudi econòmic, cal assenyalar que tant els papers com els plàstics biodegradables són més cars que el PE i que els cots d’instal·lació del paper són majors que per els plàstics, ja que la velocitat d’instal·lació es menor i es requereixen ajustos en la màquina d’encoixinar per evitar tensions que produeixin trencaments. Al contrari, el PE du associats uns costs de recollida i gestió de residus que, no obstant això, són menors al sobrecost dels materials biodegradables enfront del PE. Considerant els rendiments obtinguts als assajos de camp per cada tractament per separat, tots els materials biodegradables són econòmicament viables, inclús més rentables que el PE en el cas de Sphere® 4 y Ecovio®. En canvi, si considerem un rendiment mitjà de la zona per a tots els materials, les ajudes econòmiques actuals per fomentar l’ús de materials biodegradables no són suficients per a que el beneficis obtinguts per els materials biodegradables es puguin comparar amb els del PE. Nous estudis tindrien que considerar la capacitat de degradació real del plàstics biodegradables, ja que, es podria estar acumulant restos de material plàstic als camps a curt termini perquè, segons la normativa s’exigeix una degradació d’aquests encoixinats d’un 90% en dos anys, desconeixent-se el destí del 10% restant. També es creu oportú continuar amb el desenvolupament de papers d’encoixinat que siguin al mateix temps flexibles i opacs.

General Introduction and Objectives

Mulching and the plastic waste management problem. Mulching as a weed control method has been present in agriculture since ancient times (Aerts *et al.* 2010). Several types of materials starting with vegetable remains to papers have been used to cover the surface and provide with several benefits known by famers. The most notable benefit has been achieved by plastic mulching with low density polyethylene (LDPE) because it promotes water savings and reduces labour costs for weed and pest control (Ingman *et. al*. 2015; Jabran *et al.* 2015) also better quality of the fruits and harvest earliness have been reported (Fan *et al.* 2005; Ibarra-Jiménez *et al.* 2011).

In 2016, the world plastic production reached 335 million tons of plastic and 19% came from Europe, the second producer after China; the demand is increasing every year (PlasticsEurope 2017). Plastic films in Europe for agricultural use covered an area of 4270 km^2, which is four times larger than the one covered by greenhouses (Scarascia-Mugnozza *et al.* 2011). Mulching with plastic films in Spain got popular in the 60's because LDPE entered into the market. Some properties of PE films as elasticity made this material appropriate for intensive production allowing applying several rolls at the same time. The rolls can be up to 2500 m long with a weight of 40 kg, approximately, so the installation in large fields is not expensive. Moreover, there is a wide range of PE types adapting to different crops and labour conditions (Lamont 2005). It is the preferred intense farming method for most vegetable crops (Zhang *et al*. 2013).

Another drawback of plastic films as a weed control method is the incapacity of controlling purple nutsedge because this plant can pierce the film (Anzalone *et al*. 2010; Webster 2006). When harvest in fields mulched with plastic film is mechanized, as for example in processing tomato, part of the layer ends broken into small fragments that will remain in the field. In the case of small size crops as spinach and pees these plastic pieces can be harvested together with the crop and jeopardize the acceptance of the harvest by the canning industry (MAPAMA 2015). Eventually, the pieces can measure 700 μm^2 (Kyrikou & Briassoulis 2007) and this micro plastic waste accumulation threatens the terrestrial and aquatic wildlife (Barnes *et al.* 2009). For want of alternatives, the great part of this waste can be piled up in adjacent areas to the field, burned or tilled into the soil (Liu *et al*. 2014; Moreno *et al*. 2014; PlasticsEurope 2017).

Fortunately, the management of the enormous quantity of plastic waste generated in Europe is changing. Since 10 year ago, recycling has increased almost 80% and in 2016, for the first, recycling overcomes landfill. Despite this, almost 30% of plastic waste (7.4 m t) still ends up in the landfill. Agricultural plastic waste is difficult to manage because of the seasonality of the generation, the different dimensions and the aleatory distribution of the farms and the heterogeneity of the waste; they can come from fences to greenhouses structures and packaging or films (MAPAMA 2015). In Spain, some town halls provide a recovery point where farmers can leave the plastics residues against a small payment. The biggest problem in plastic recycling are the impurities present in the films as soil and agrochemicals (González-Sánchez *et al.* 2014). Moreover, those pesticides were transferred to the soil matrix once they are resting in the soil (Ramos *et al*. 2015). Generally, recycling plants do not accept films with more than 5% of the total weight of the mulch (Clarke 1996) but in Spain it depends on the recycling plant policy and, normally, plastics coming from greenhouses or tunnels have up to 80% of impurities (Guimire & Miles 2016; MAPAMA 2015).

Besides, Ohtake *et al.* (1998) estimated a 60µm thin LDPE layer required a period of 300 years for complete degradation, therefore, the effect of the plastic in the environment will last during long time and the soil quality will be deeply affected as soil degradation is accelerated and the communities of soil organisms vary (Steinmetz *et al.* 2016). In most favorable cases, the plastic will end in an incineration plant for energy recovery but, unfortunately, they are scarce or do not exist in some areas (Martín-Closas *et al.* 2017).

In order to try to improve the management of agricultural plastic waste, the Spanish Ministry of Agriculture, Food and Environment prepared the National Integral Waste Plan to comply with the Waste Framework Directive 2008/98/CE that specifies the management of plastic for agricultural use (MAPAMA 2015). The final decisions are taken at local level and the management has been proved to accomplish different levels of action depending on the dimension of the problem. For example, Navarra is one of the most important horticultural regions in Spain and the only with has an exhausting monitoring of the agricultural plastics (AP) used and the path they follow once they become waste. Interesting data as 60% of these AP come from mulching films and more than 96% (2511 t) of them were wrongly managed o landfilled because the few specific recycling plants that received this kind of waste closed recently (PIGRN 2017). Andalucía consumes 58% of total national plastic dedicated to crop protection and the local government created ‘Cicloagro’, an integrated management system for AP in order to try to optimize the process. In parallel, the Xunta of Galicia has created a plastic collection system that covers collection, transport and treatment of AP since 2004 (MAPAMA 2015).

New materials and the importance of characterizing them. Biodegradable plastic films were introduced in the agronomical scene in the late 90’s to curtail the problems of the PE with waste disposal (Hussain & Hamid 2003) and because their lifetime adjusts to the crop cycle (Martín-Closas *et al.* 2009). One of the fist biodegradable plastic films introduced in the market was Mater-Bi® and is made from cornstarch. Nowadays, even the National Integral Waste Plan established a strategic line in order to improve the management of the plastic waste by using biodegradable and compostable plastics that follows the European norms EN-13432 and EN-14995 (MAPAMA 2015). Although companies sometimes recommend these films as biodegradable for agricultural applications, the certification of the material establishes they are compostable under specific conditions but does not ensure their biodegradability in the soil. This is the case for products made with Bioflex® or Bioplast®, among others (Martín-Closas *et al.* 2017). Although the oxo-degradable films are not considered biodegradable anymore because they break into small non-degradable pieces (Selke *et al.* 2015) some farmers still use them to substitute LDPE. Even a regional Spanish subsidy (Gobierno de Aragón 2018) contemplates the use of biodegradable and 'oxo-biodegradable' indistinctly in order to diminish the use of LDPE. However, biodegradable plastics may not solve the waste problems entirely.

In addition to the risks originated from LDPE waste accumulation in the environment, when evaluating the impact of the continuous use of biodegradable plastic films on the crop was evaluated in an 8-year scenario by Miles *et al*. (2017) the researchers found that if degrades 90% at the end of two years, which are the requirements of the ISO 17556 or the ASTM D5988, the amount of plastic accumulated in the soil could exceed twice the amount of the mulch applied per year. The small fragments of biodegradable plastic film can reach an average of 41 mm^2 (Moreno *et al*. 2017).

***General aspects of* Cyperus rotundus.** Purple nutsedge is a troublesome weed causing severe problems in agriculture at temperate and tropical regions of the world affecting several crops as vegetables, rice, sugarcane or cotton (Holm *et al*. 1977; Webster 2002) and is considered one of the "world worst weeds" specific. This plant has an underground root system formed by roots, basal bulbs and tubers connected by rhizomes and a low bearing aerial part with grass-like leaves in a rosette form (Betria & Montaldi 1974). The tuber chain is the main reason this plant is so difficult to manage because they can deepen up to 45 cm depth where herbicides cannot reach them (Holm *et al*. 1977). Purple nutsedge belongs to the plants with photosynthetic C4 metabolism, being capable to use water with higher efficiency than plants with C3 metabolism causing a fast growth in warm climates with high radiation levels (Moore *et al*. 1995). However, this efficiency decreases rapidly when not enough sunlight arrives to the plant's organs and it has been proved that both the aerial biomass and tuber production reduce dramatically in shaded conditions (Lazo & Ascencio 2010).

However, as commented previously, *C. rotundus* is capable of piercing LDPE films and depends on the quantity of light passing through the film, as found by Patterson (1998) using different translucent polyethylene (PE) mulches, introducing a space between the plastic layer and the soil (Chase *et al.* 1998). The control also depends on the position of the nutsedge tubers in the soil i.e. its depth (Roozkhosh *et al*. 2017) and on the thickness of the plastic (Patterson 1998). For example, when transparent PE is used in certain crops to obtain crop precocity, purple nutsedge unfolds its leaves as soon as they emerge from the soil and receive sunlight, remaining under the plastic film without piercing it (Chase *et al*. 1998; Webster 2005). These plants will produce viable tubers and, even with a very low density, they will be able to reinfest the field (Miles *et al*. 1996, Silveira *et al*. 2010). Opposite, when using opaque PE nutsedge leaves remain grouped in needle position growing vertically until reaching the sunlight after piercing the film and unfolding the leaves afterwards. Unfortunately, this thickness adds a higher prize to the mulch and, therefore, it is not a viable option for annual crops.

Biodegradable plastic films used as alternative to PE are generally even less efficient in controlling nutsedge than LDPE (Cirujeda *et al*. 2012a). Paper mulches have been tested as alternative to PE with the main advantage of generally resisting the punction of the nutsedge leaves as verified for several paper types (Cirujeda *et al*. 2012a; Marí 2013; Shogren & Hochmuth 2004). Additionally, to the benefit of controlling nutsedge, the obtained tomato yield on paper mulch was very similar to the production on PE (Cirujeda *et al.* 2012a). However, few data are available for other vegetable crops mulched with paper confirming that new trials are welcome. Opposite, some novel light brown crepe papers showed less constant results probably because these materials are in evaluation (Marí *et al*. 2016). These papers were less opaque than other papers used for mulching but were easier to install, so that these papers are considered potentially interesting.

Concerning the biological behavior of purple nutsedge under different mulches, especially reproduction, little has been investigated. The hypothesis is that reproduction is not possible when nutsedge plants are not able to pierce the opaque mulches but that needs to be proved. In addition, the effect of certain translucency of the mulches on *C. rotundus* biology is unknown. On the other hand, probably the tubers emerging from deeper soil layers might be weaker in piercing PE and biodegradables opening the opportunity to plow tubers in non-favorable positions by tillage before crop installation. It has been shown that 75% of purple nutsedge tubers are found in the first 15 cm depth (Bell *et al.* 1962; Marí 2013) and they are able to deepen up to 60 cm depth. However, as these plants are susceptible to frost, in cold areas there will not be many tubers in the first centimeters soil depth if ploughing does not turn over the soil and places the remaining tubers in the upper soil layer (Zaragoza pers. comm.)

The need of an economic study. Biodegradable films and paper mulches have been studied previously and have demonstrated that crop yields are statistically the same as that obtained with PE from Cirujeda *et al.* (2012b) studies. However, market prices of these materials are higher than non-biodegradable ones thus reducing its economic attractiveness for farmers in the short-term. In addition, there are no studies including PE and bio-based economic evaluations containing i) an estimation of plastic removal costs; and ii) a global consideration of short and long-term advantages and limitations of mulching materials (Steinmetz *et al.* 2016).

In order to promote the use of bio-based materials, some regional authorities in Spain, like Aragon government have recently implemented some economic incentives for farmers who employ biodegradable mulching in vegetable production subject to some other additional conditions. This study includes these incentives in economic calculations and evaluates their effectiveness in promoting the use of bio-based in fields.

The objectives of the present study are, therefore:

1. To characterize physical properties of different paper mulches in laboratory conditions.

    1.1. To describe the thickness, grammage and color of the different mulches tested in field and chamber trials.

    1.2. To carry out traction and punction tests under standardized regulations for plastic to be able to compare to PE.

2. To study the efficiency of different mulching materials on weeds with pepper crop for fresh consumption during 4 years.

    2.1. To find out the efficacy of the different mulches on the total weed emergence and, specifically, on *C. rotundus* through a specific three-year trial.

    2.2. To describe the degradation of the different mulches in field conditions.

    2.3. To determine the yield of the pepper production for each mulching treatment individually.

3. To study the effect of translucency and depth on development of purple nutsedge under biodegradable mulches.

    3.1. To study a possible relation between translucency of mulching materials and the sprouting, biomass and reproduction of *C. rotundus.*

    3.2. To analyze the possible influence of tuber depth on sprouting, biomass and reproduction of *C. rotundus.*

4. To prepare an economical study of different mulching materials used in pepper crop for fresh consumption in Aragon.

    4.1. To evaluate PE and bio-based mulches economic evaluations containing an estimation of different plastic waste management costs.

    4.2. To present global considerations of short and long-term advantages and limitations of mulching materials.

Each of these objectives is presented as a chapter in this thesis taking the form of a scientific paper with the corresponding sections: abstract, introduction, material and methods, results and discussion, conclusions and literature cited.

General Methodology

Physical characterization of biodegradable paper mulches: Chapter 1. The trails were conducted in the "Laboratori de degradació i biodegradació de materials orgànics", at the Lleida University (Catalonia, Spain) during 2016-2017. Mechanical properties were tested following the international standard for plastics UNE-EN-ISO in order to compare all paper mulches to PE. This standard specifies the size of the sample, the machines and their adjustments needed and the methodology to follow. Samples always stayed almost an hour at 23 °C ± 2 °C and 50 % RH before starting any test to homogenize because papers mulches loose humidity once the roll is opened. Thickness, grammage and color were determined and a traction and punction essay was carried out in 16 different paper mulches. Some of the mulches are experimental and others are commercial.

Purple nutsedge (**Cyperus rotundus*****) control with biodegradable mulches and its effect on fresh pepper production: Chapter 2.*** The field trials were conducted in an experimental field belonging to an Agricultural Research Centre of the Aragonese Government (41.43° N, 0.48° W) in Zaragoza, Aragón, Spain, from May to October in years 2012 to 2015. A pepper crop covered with different mulching materials was established each year in different parts of the plot. Treatments were distributed randomly in a complete block design with four replicates; 6 to 9 materials were tested each year, examining a total of 11 different mulching materials. An unweeded check control was included to calculate the control efficacy. Parameters evaluated were density and percentage of weed cover, degradation of the mulches and marketable fruit production.

Effect of translucency of mulching materials and burial depth on* Cyperus rotundus *growth and development: Chapter 3. *Translucency trials.* Trials were carried out on the same location as Chapter 2 during the months of May to November in years 2014 and 2015. A pot experiment was settled with 7 tubers of purple nutsedge in each pot; after sowing them they were covered with soil and 11 different mulching materials. Pots were randomly distributed in a single row accounting four replicates of each treatment. To describe the translucency of the mulching materials four samples of photosynthetic active radiation (PAR) were taken for each material with a linear ceptometer (AccuPAR, Decagon, USA). During the trial number of nutsedge mulch piercings in each pot were accounted periodically and, at the end of the season, all the biomass was extracted and separated in two different sections: buried biomass and unburied biomass. Net reproduction rate and percentage of healthy and dead tubers were estimated.

Tuber sprouting trials testing different depths. These trials were conducted under controlled conditions in a growth chamber in the Centro de Investigación y Tecnología Agroalimentaria de Aragón, Spain, during the months of January up to May 2014. Pots with two tubers each were covered by black PE, black biodegradable plastic Mater-Bi® and black paper Mimgreen® and were randomly distributed with three repetitions. The tubers were placed from 1 to 10 cm depth in 1 cm intervals. The same experiment was carried out three times and tubers were extracted each time from the soil after 30 days. The number of nutsedge pierces was periodically recorded as well as dry biomass data obtained for three fractions: aboveground, intermediate and underground and determined the same way than in the translucency experiments.

Economical study and environmental repercussions of plastic films and paper mulches used in open-air pepper (Capsicum annuum L.) crop: Chapter 4.

Field trials and experimental design. Yield data used in this chapter corresponds with the obtained in Chapter 2 and was used as a base for the economic analysis as well as the description of the experimental design.

Economic analysis. For the economic part of the analysis, the operational costs are separate from the incomes and, then, the net margin is calculated for the evaluated materials. Inputs and operational costs of the crop management were established from an interview to a local pepper producer as well as from the experimental field management. Incomes include market prize for the crop and net margins calculated as the difference between incomes (value of the crop yield and regional payments) and total costs (inputs, operations, labour, etc). Repayments for capital, taxes or insurance are not considered.

Statistical Analysis

The analysis of data was performed using SAS (Statistical Analysis System V.9.4. SAS Institute, Cary, NC, USA). Homogeneity of variance and normality was determined before data analysis and when data did not meet these assumptions Box-Cox recommendations to transform the data were followed (Bowley 1999). Square root and inverse transformations were applied in some cases indicated in each chapter. The data was subjected to analysis of variance (ANOVA). Mean comparisons were performed using the Student-Newman-Keuls test ($p<0.05$) when the effect was significant at $p<0.05$. When data still did not meet normality conditions after transformation data was analyzed with the non-parametric Kruskal-Wallis test. Contrast analysis was performed in Chapter 2 and lineal regressions on Chapter 3 also using SAS. For Chapter 1 the standard error was calculated.

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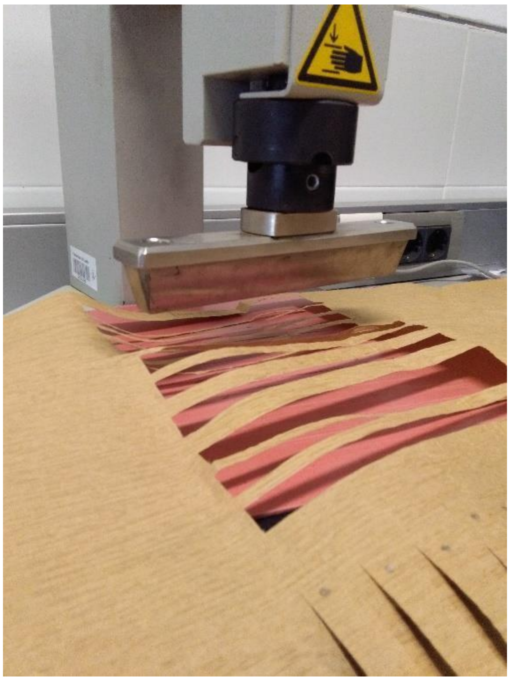
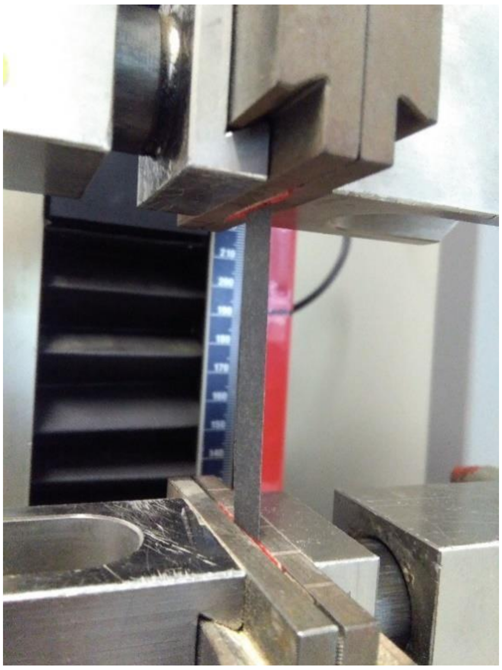
CHAPTER 1. Physical characterization of biodegradable paper mulches


Physical characterization of biodegradable paper mulches

Abstract

Characterizing mulches is essential in order to improve the mulching materials and recommend them depending on the needs of each case. Plastics mulches are well known because they are available in the market since several years, instead, paper mulches are quiet new and it is important to obtain information about their physical properties in order to try to explain the observations obtained in the field when using them. Grammage, thickness, color, puncture and traction tests were performed in laboratory conditions using 16 different paper mulches, six non-flexible papers and 10 flexible materials referred as crepe papers and following the standard of plastic. Grammage provided from the manufacturer presented 10% more weight than the obtained in the laboratory. Almost in all cases, crepe paper was 7-fold thicker than the non-flexible papers and this way become a limitation to the manageability of the rolls in the field because polyethylene are fifty times thinner than papers (0.015 µm *versus* 0.75 µm). Most of crepe papers are brown and this can contribute to the differences in growth observed in the field under the film. Traction tests demonstrated that crepe papers have the capacity to elongate more than the rigid papers. This particularity is useful for the mechanical installation. Punction determined that the tested non-flexible papers had less capacity to react in case nutsedge or some sharp stone touched the film. Concluding, very variable results have been found within the physical properties of the tested paper mulches so it would be possible to adjust the type of material used to the particular scenario each farmer has.

Introduction

Mulching with low-density black polyethylene (LDPE) is a widely distributed method for weed control, mostly used in vegetable crops because it provides countless advantages well known by their users (Lamont 2005). Unfortunately, this petroleum-based plastic is not biodegradable and the waste generated at the end of the lifetime is not managed correctly as burning o buring it are the regular actions (MAPAMA, 2015) instead of being recycled in specific factories or derived to energy recovery (PlasticsEurope 2017) producing serious environmental pollution. Biodegradable plastics were presented as a viable alternative because they can be tilled safely into the field and it has been proved that horticultural yields obtained with these materials can be the same as obtained with PE (Cirujeda *et al.* 2012a; Miles *et al.* 2012). Unfortunately, some of these mulches had shown irregular responses on the field sometimes with degradations already within the first month after installing them (Cirujeda et al. 2012a; Martín-Closas *et al*. 2016). Furthermore, degradation rates also demonstrated to be very variable depending on the soil conditions, climate and their feedstock (Hakkarainen 2002, Singh & Sharma 2008) and thus did not fulfill the only reference to the degradation rate for biodegradable bio based mulch films nowadays existing in Europe (7 CFR 205 NOP 2000). That rule establishes that a biodegradable material has to degrade at least 90% in less than 2 years. However, Li *et al.* (2014) found between 6 and 52% losses of the initial plastic weight of different biodegradable plastics after 2 years.

In the case of the oxo-degradable plastic films, also erroneously labeled as ‘biodegradable’, they contain PE and metals and they fragment into small pieces but not real degradation of the components occurs (Thomas *et al.* 2010) leading to soil problems and environment damage. The same situation has been reported for photodegradable plastic films (Riggle 1998). Therefore, an accumulation of the non-biodegradable plastic fragments will occur in time and has been quantified by Miles *et al*. (2017).

In the case of biodegradable mulches, the quantity of mulch residue found in the soil can be twice the amount applied per year in an 8-year-period of annual application of these films. Furthermore, plastic residues from non-degradable films accumulated in soils have been demonstrated to produce adownward trend in growth, yield and quality of tomato (Zou *et al*. 2017). In January 2018, the European Standard EN 17033:2018: ‘Plastics-Biodegradable mulch films for use in agriculture and horticulture-requirements and test methods’ was released and would help to clarify the situation of the biodegradable films regulating their composition, biodegradability in soil, effect on the soil environment (ecotoxicity), mechanical and optical properties, and the test procedures for each of the listed categories. It does not apply to mulch films that are being removed from the fields after use. Soil pollution resulting from a long-term and repeated use of biodegradable films and to advice the farmers in order to avoid further pollution problems (Brodhagen *et al*. 2017).

Several paper mulches have been tested on the field since the beginning of the 20th century as plain paper (Brault & Stewart. 2002), paper mulch combined with asphalt (Smith 1931), shredded newspaper (Munn 1992; Shogren 2000), coated paper with vegetable oil (Shogren & David 2006) and recently crepe paper (Haapala *et al*. 2015; Marí *et al.* 2016). Moreover, paper mulches are the only capable of controlling purple nutsedge (Anzalone *et al.* 2010; Cirujeda *et al*. 2012b, Shogren & Hochmuth 2004) a weed found worldwide and able to reduce yield of several crops drastically. Despite, paper mulches have limitations because the edges of paper in contact with the soil degrade in the first 15- 20 days after installation and the rest can be lifted in windy areas (Cirujeda *et al*. 2012b; Martín-Closas *et al.* 2016). Other drawbacks are heavier rolls containing less meters of material compared to plastic film rolls. In addition, installation speed is lower than with PE (Shogren & Hochmuth 2004). The transparency and the color of the mulch change the soil temperature as they absorb solar radiation and thereby heat the soil (Anderson *et al*. 1995). Opposite to the degradation problems explained for biodegradable plastic films, paper mulches loose almost 100% of their weight in 160 days (Moreno *et al*. 2017) and, as far as our knowledge, only Runham *et al*. (2000) determined soil samples with incorporate paper mulch residue. Their results showed similar levels of heavy metals and organic micro pollutants content in the soil compared to hand-weeded plots.

Characterization of the new mulching materials is very important allowing predicting which material suites better in each situation to overcome the shortcomings. Anderson *et al.* (1995) represents one of the few paper mulching characterizing works, lately, coated paper was studied (Salemi *et al*. 2008; Shogren 1999) but no recent research for this topic is available.

Owing to all these arguments, the present paper characterizes mechanical properties from different experimental and commercial paper mulches in comparison to polyethylene under standardized laboratory conditions.

Material and Methods

Tested mulching materials. Sixteen paper mulches were selected in order to study the widest range of characteristics as possible (Table 1.1). All these materials have been previously used in different agricultural trials in Zaragoza, Spain. We used LDPE plastic film as a control to compare results because of being the most used material for mulching nowadays. Several of the tested paper mulches are experimental and others are commercial. The main problem with experimental materials is that their characteristics may not be stable or constant. Ten paper mulches are crepe paper, a new line of potential mulching materials that provide flexibility and an easier installation in the field.

Characterization tests. The characterization trials were conducted in the "Laboratori de degradació i biodegradació de materials orgànics", at the Lleida University (Catalonia, Spain) during 2016-2017 and mechanical properties were tested. The international standard for plastics UNE-EN-ISO was followed in order to compare all paper mulches with PE. This standard specifies the size of the sample, the machines and their adjustments and the methodology for the tests. Samples were kept during an hour at 23 °C ± 2 °C and 50 % relative humidity before starting any test to homogenize the samples because papers mulches loose humidity once the roll is opened.

General characteristics.

Determination of thickness. Thickness along the roll was found to be very variable parameter. Thus, in order to have a real mean thickness rate, this parameter was estimated following the 'Spanish standard UNE-ISO 4593:2010 for plastics: films and plastic sheets' using the micrometer ND 287 (Heidenhain, Hamburg, Germany). A 10-cm wide sample was cut as long as the width of the roll in a random area of the whole length of the material. Twenty equidistant points were measured in the middle of the width of this band of material. In addition, the mean rate was calculated.

*Determination of grammage***.** UNE-EN ISO 536:2012 for paper and paperboard was measured to determine the grammage of the mulches (mass per unit area). Nine circles of 3.65 cm diameter distributed along the width of the roll were cut randomly and were weighed with the precision balance Ohaus Pioneer™. Grammage (g) was calculated for each sample as:

$$g = \frac{m}{A} x\, 10^6$$

Where 'm' is the sample mass expressed in grams (g) and 'A' is the sample area expressed in square millimeters (mm^2).

Colorimetry. We measured three samples, twice each, in the sun-exposed side of the material with the colorimeter by reflection Konica Minolta CR-200. The results were three values of the scale CIE 1976 (L*, a*, b*) known as CIELAB. This is based on the color scale of Hunter. The lightness or Luminance, L*, represents the darkest black at L* = 0, and the brightest white at L* = 100. (McGuire 1992). A representation of the colors from a LAB converter value from the different materials has been added in order to help the understanding of the different results (E-paint.co.ik. 2018).

Mechanical properties.

Traction and punction tests. The traction tests were conducted with the machine traction Zwick/Roel BZ1-MMZ2.5.ZW01 (Germany) with 5kN in the strength sensor and a crosshead speed of 50 mm/min as determined by the ISO 527-1. For the punction test, a 0.8 mm diameter head and a die TZCP 020 were incorporated. The 10 samples per mulch measured 10 cm x 10 cm and were taken from that part of the paper sample where the mean thickness rate that had been previously obtained, was closest to the mean. Five samples came from the longitudinal section (LS) and five from the cross section (CS).

Statistical analysis. To evaluate the differences between mulching materials the standard error of the mean rates between all the different materials and replicates were calculated in all trials using Excel worksheet v. 2016.

Table 1.1. Mean rates ± standard error of the different analyzed paper samples, manufacturer, observed color, factory thickness (µ) or grammage (g m^{-2}), measured grammage (g m^{-2}), measured thickness (mm).

Samples	Manufacturer	Color	Factory thickness or grammage	Measured grammage	Measured thickness
			µm / g m^{-2}	**g m^{-2}**	**mm**
PE	Several manufacturers	Black	15	-	-
Mimgreen®	Mimcord S.A., Spain	Black	85	91.9 ± 0.80	0.11 ± 0.002
Verso®	Verso Corporation, USA	Light grey	72	65.5 ± 0.37	0.07 ± 0.001
Saica140	Industrias Celulosa Aragonesa, Spain	Light brown	140	139.8 ± 0.45	0.18 ± 0.001
Saica200		Light brown	200	204.0 ± 1.13	0.27 ± 0.003
Stora-Enso®1	Stora Enso Oyj, Finland	Black/white	105	109.3 ± 0.37	0.13 ± 0.001
Stora-Enso®		Black	*	82.7 ± 0.21	0.10 ± 0.001
Walki®1	Walki Group Oy, Finland	Light grey waxed	*	130.7 ± 0.69	0.23 ± 0.005
Walki®2		Greenish brown	*	84.8 ± 0.42	0.48 ± 0.010
Arrosi® 103	Fábrica de Papeles Crepados Arrosi, Spain	Light brown	75	79.8 ± 0.77	0.42 ± 0.014
Arrosi® 130		Light brown	130	120.2 ± 0.46	0.75 ± 0.026
Arrosi® 240		Light brown	80	87.9 ± 0.48	0.39 ± 0.009
Arrosi® 69_14		Light brown	80	83.2 ± 0.71	0.39 ± 0.014
Arrosi® 69_15		Light brown	80	64.6 ± 0.25	0.23 ± 0.006
Arrosi® 70/90		Light brown	90	84.5 ± 0.40	0.43 ± 0.010
Arrosi® 90/100		Light brown	105	107.4 ± 0.54	0.32 ± 0.012
Arrosi® 3		Black-greenish	130	120.0 ± 0.64	0.42 ± 0.025

*Information not available.

Results and Discussion

Grammage and Thickness. The comparison of the grammage supplied by the manufacturer with the results measured in the laboratory showed small differences in most of the cases (Table 1.2) with a variation compared to the manufacturer weight of around 10%; with some Arrosi® papers, the weight was less than expected arriving to a 20 % less in the case of Arrosi® 69_15. Verso® paper was the lightest material (65.5 g m^{-2}) being three times lighter than the heaviest mulching material Saica200. Paper mulches Mimgreen®, Arrosi® 130 and Arrosi® 69_14 had the highest sample deviation while Stora-Enso® papers and Saica 140 presented the lowest variation so these materials presented a more homogeneous grammage.

Determination of thickness of the crepe papers had a technical difficulty because the micrometer took almost 30 minutes to stabilize after touching the sample, whereas in the rest of papers the rate stabilized within a few minutes. Thus, the final thickness data of the crepe paper corresponds to the materials after flattering the micro folds. These rates are probably intermediate between the thickness of the base paper used to obtain the final crepe paper and the final crepe paper thickness without flattening; however, this process was considered the only standardized way to measure the thickness of these papers.

Almost in all cases, crepe paper was thicker than the rest of papers. In the case of Arrosi® 130, the paper was almost 7–fold thicker (0.75 mm) than the thinnest materials Verso®, Mimgreen® and Stora-Enso® (Table 1.1). All these rates are very far from the thickness of the PE film most commonly used in agriculture, which measures 0.015 mm thick.

The combination of grammage and thickness will determine the volume and weight of the roll, which is a very important factor to take into account when installing the material in the field. Rolls weight between 25 to 40 kg approximately and are appropriate because two persons can handle them following the safety indications. In these conditions, a single plastic roll can mulch 2500 linear meters, in the case of paper, only 250 m. From this point of view all materials with less than 100 g m^{-2} and less thickness would be the best options as Mimgreen®, Stora-Enso®, Verso® and the worst would be Saica papers and Arrosi® 130, Arrosi® 90/100 and Arrosi® 3(Table 1.1).

Colorimetry. Following the results of lightness (L), the tested materials can be classified into two different groups: materials with color closer to black as PE and Stora-Enso® paper and brownish papers with L rates around 60 (Table 1.2). Haapala *et al* (2015) determined that paper mulches with dark color on the upper surface increase soil temperature more than the light-colored ones because dark color reflects and transmit less shortwave radiation. In addition, yield was higher and equally good comparing to biodegradable plastic film in the dark paper mulches rather than with the brown paper alone.

Mulching paper Walki®1 had a lighter grayish color corresponding to a higher L rate, closer to white. Moreover, this wax-coated material presents the highest transparency (35% PAR) compared to a non-mulched soil that will increase soil temperature and moisture as El-Nemr (2006) determined for a similar paper mulch compared to black polyethylene film. Light-colored papers and the wax- coated one have the disadvantage of allowing weeds to grow under them, Haapala *et al.* (2015) have validated it despite plants presented small size, and they did not affect the yield. Marí *et al.*(A) (unpublished data, Chapter 2 of this document) observed weeds growing under clear and wax-coated paper mulches, which did not pierce the sheet but reached in the tillering and elongation of the stem stage at the end of the experiment.

The ‘a’ scale was quite similar for all tested mulches; values closer to 0 in the matrix corresponding to grey tones. In the ‘b’ scale, the Arrosi® papers showed the highest rates (around 25) indicating that they had a yellow component in the matrix.

This group of brown paper is more transparent, from 2.5% of PAR compared to a non-mulches surface in the Arrosi® 130 to 12.5% in the Arrosi® 69, than the black ones 0.03% in the Mimgreen® and 1% in the Stora-Enso® (Marí *et al.* (B) unpublished data, Chapter 3 of this document). Quezada-Martín *et al*. (2004) determined that in the beginning of the pepper cultivation, when the foliage of the plants is poorly developed, brown and black plastic mulch reflected around 8% of the total radiation incident while white mulch reflected 30%. This reduction of radiation affects the growth and development of the crop. Brown plastic film raised soil temperature at the beginning of the season compared to bare ground but these differences diminished at the end of the season because of the shadow generated by the crop, as also validated by Haapala *et al*. (2015) in brown paper mulches. Despite this, black and white mulches had a much more interesting effect on the development of the pepper crop as well as the highest yields comparing to other colored sheets as brown. Despite these arguments, Ibarra-Jiménez (2008) proposed that different materials need to be studied and tested in each region to determine the local ground temperature and the consequent development of the crop.

Table 1.2. Mean L*, a*, b* rates ± standard error of the different paper mulching materials. Added Black color N61 from Australian Standard AS2700 Chart to compare. Represented colors from LAB rates using a LAB converter. L* lightness, a* = component of the bluish-green matrix/ red-purple, b* = component of the yellow/blue matrix.

Sample	Color parameters			LAB color
	L*	a*	b*	
Black N61	23.9	0	-0.5	
PE	28.1 ± 0.31	+0.4 ± 0.02	-1.2 ± 0.02	
Mimgreen®	29.7 ± 0.08	+0.6 ± 0.01	+2.4 ± 0.02	
Verso®	41.1 ± 0.13	+0.7 ± 0.01	+1.9 ± 0.04	
Saica140	57.5 ± 0.07	+5.5 ± 0.01	+21.5 ± 0.05	
Saica200	56.8 ± 0.08	+5.6 ± 0.02	+20.9 ± 0.03	
Stora-Enso® 1	29.3 ± 0.05	0.5 ± 0.01	-0.6 ± 0.01	
Stora-Enso®	30.4 ± 0.06	+0.9 ± 0.01	+2.5 ± 0.03	
Walki®1	67.2 ± 0.49	-0.5 ± 0.02	+6.7 ± 0.13	
Walki® 2	51.6 ± 0.23	+1.8 ± 0.04	+13.3 ± 0.09	
Arrosi® 103	64.4 ± 0.09	+3.9 ± 0.03	+24.2 ± 0.04	
Arrosi® 130	61.1 ± 0.21	+4.7 ± 0.05	+23.5 ± 0.06	
Arrosi® 240	61.6 ± 0.13	+6.6 ± 0.04	+24.1 ± 0.05	
Arrosi® 69_14	60.3 ± 0.14	+8.9 ± 0.05	+25.2 ± 0.05	
Arrosi® 69_15	66.9 ± 0.19	+7.4 ± 0.03	+24.0 ± 0.11	
Arrosi® 70/90	62.3 ± 0.11	+7.4 ± 0.04	+25.1 ± 0.08	
Arrosi® 90/100	64.6 ± 0.08	+3.0 ± 0.03	+16.1 ± 0.07	
Arrosi®3	23.4 ± 0.09	+0.4 ± 0.02	+1.2 ± 0.02	

Mechanical properties

Traction test. The needed tensile strength on the LS to break the crepe papers was very small (approx. 10 MPa) compared with the non-flexible paper mulches, which reached up to 86.2 MPa (Verso® paper) and more than 60 MPa for the Saica papers (Table 1.3). Therefore, when materials with low rate of tensile strength in the LS are installed mechanically, breaks are expected easily. According to the UNE EN 13655 (UNE-EN 13655, 2003) mulching films must have a tensile stress at break higher than 16 MPa which corresponds to the rate for black LDPE. Thus, all tested crepe papers rates were lower than these values so that all of them will probably need a certain tension reduction of the machine to allow mechanical installation.

Tensile strength of the CS was smaller compared to the tensile strength of the LS in all cases, which is a priori inconvenient for the laying-down. In some materials, the strength needed was 2.5- fold lower than in the LS (Verso®) while only 1.5-fold lower in crepe papers. Therefore, this section of the material would present less capacity to expand if an extra pressure is applied for example from the wheels of the mulching machine. Stora-Enso®, Verso® and Saica 140 only elongated 2% of their initial length, in the case of Arrosi® 130 it elongated more than 35% of its initial sheet length (Table 1.3). The literature shows that different coated papers had tensile strength rates between 45 to 85 MPa at the beginning of the season (Shogren 1999), all of them higher than all the tested crepe paper.

Those materials showing higher tensile strength also presented a higher breakage deformation both for the LS and CS and the way around (Table 1.3). Specifically, Arrosi® 90/100 was the crepe paper with the lowest capacity to elongate in the LS and Saica papers were the most rigid mulches. In the CS all materials had very low rates (from 2.7% to 10.6%) compared to PE (335%) (Touchaleaume *et al.* 2016). From this point of view, all tested materials may have an important limitation during installation because they will break easily when pressure is exerted. Elongation to break of different coated papers was at the beginning 3% and after two weeks of soil exposure it increased to 7% (Shogren 1999) those rates were similar to the non-flexible papers tested in the LS and CS and close to the CS in the crepe papers.

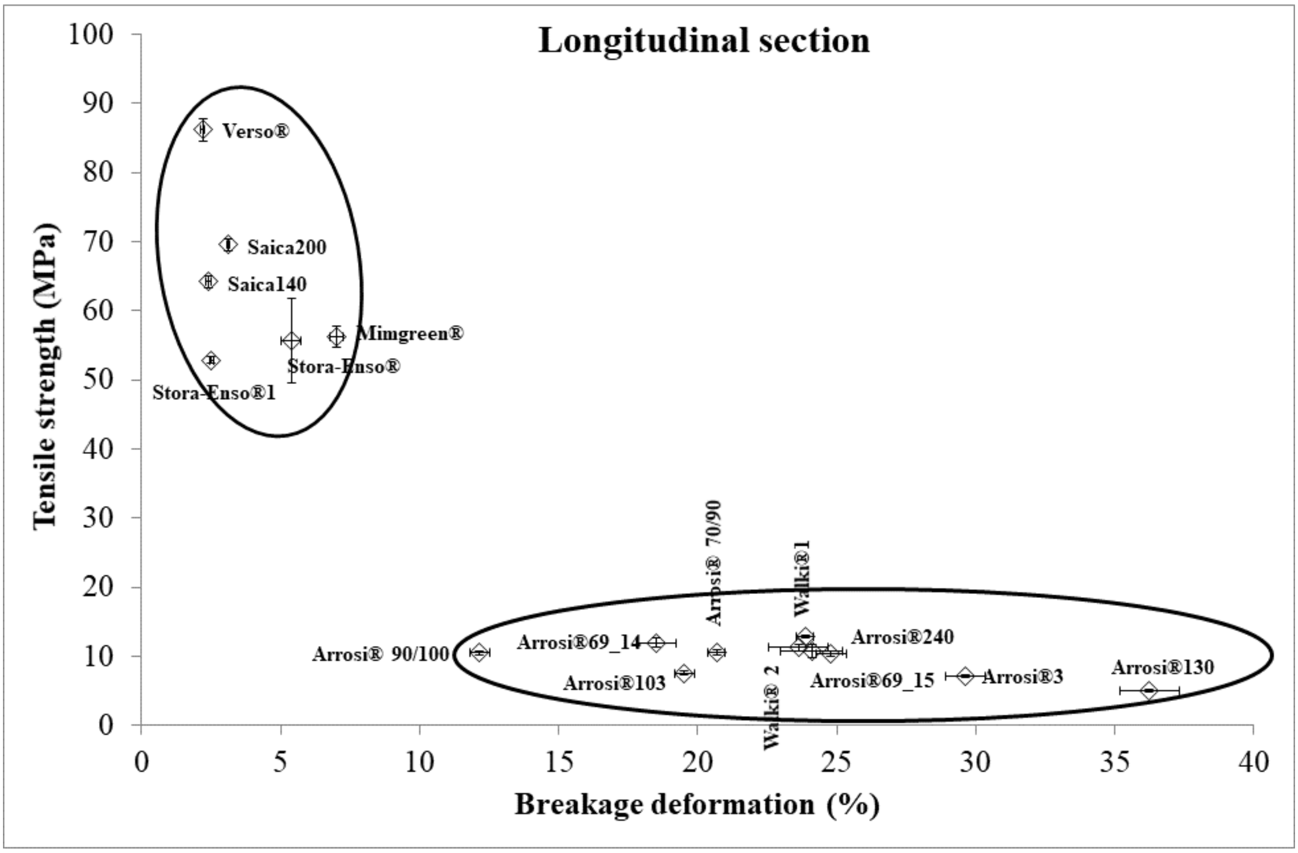


Figure 1.1. Relation between mean tensile strength (MPa) and mean breakage deformation (%) of the longitudinal section of all tested paper mulches.

Longitudinal section. When breakage deformation and tensile strength was measured in the LS (Figure 1.1) materials showed two clearly distinct groups that englobe on one hand the non-flexible materials and the crepe paper mulches on the other hand (Table 1.3). Non-flexible papers had the lowest percentage of breakage deformation but, opposite, they can bear highest strength. For example, Verso® paper had the smallest capacity to deform before breakage but, on the contrary, the required strength for breakage was the highest of all tested materials. Crepe papers could be deformed in some cases more than 35% of their initial length before they broke with a lower strength applied but others broke when they elongated only a 12% of their initial length (Arrosi® 90/100). Thus, it can be expected crepe papers will be installed mechanically better than rigid papers despite those are more resistant to possible breaks.

Cross section. When relating breakage deformation with tensile strength in the CS rates for both of them are lower if we compare to the LS rates (Figure 1.2). Non-flexible papers bear less strength than in the LS. In the case of the crepe papers, the percentage of deformation was lower than in the LS, they had similar response compared to the non-flexible papers.

Thus, the results predict the limitation of these materials when the mulch is installed mechanically in the field; however, in praxis, these materials could be mechanically installed after doing some modifications in the machinery to reduce the installation tension as Marí *et al*. (B) (unpublished data, Chapter 3 of this document) demonstrated. In the case of LS, only an adjustment of the tension by guiding the film straight avoiding s-shaped patterns and speed reduction were sufficient to avoid breaks as also described by Vox *et al.* (2013) when testing novel biodegradable mulches. Moreover, diminishing the wheel pressure of the mulch-laying machine when the sheet is buried because these tensions affects the CS as Ghimire & Miles (2016) determined.

Probably, materials with an intermediate combination of both characteristics as, for example, Arrosi® 69_15 and Walki® 2, will present a successful mechanical installation.

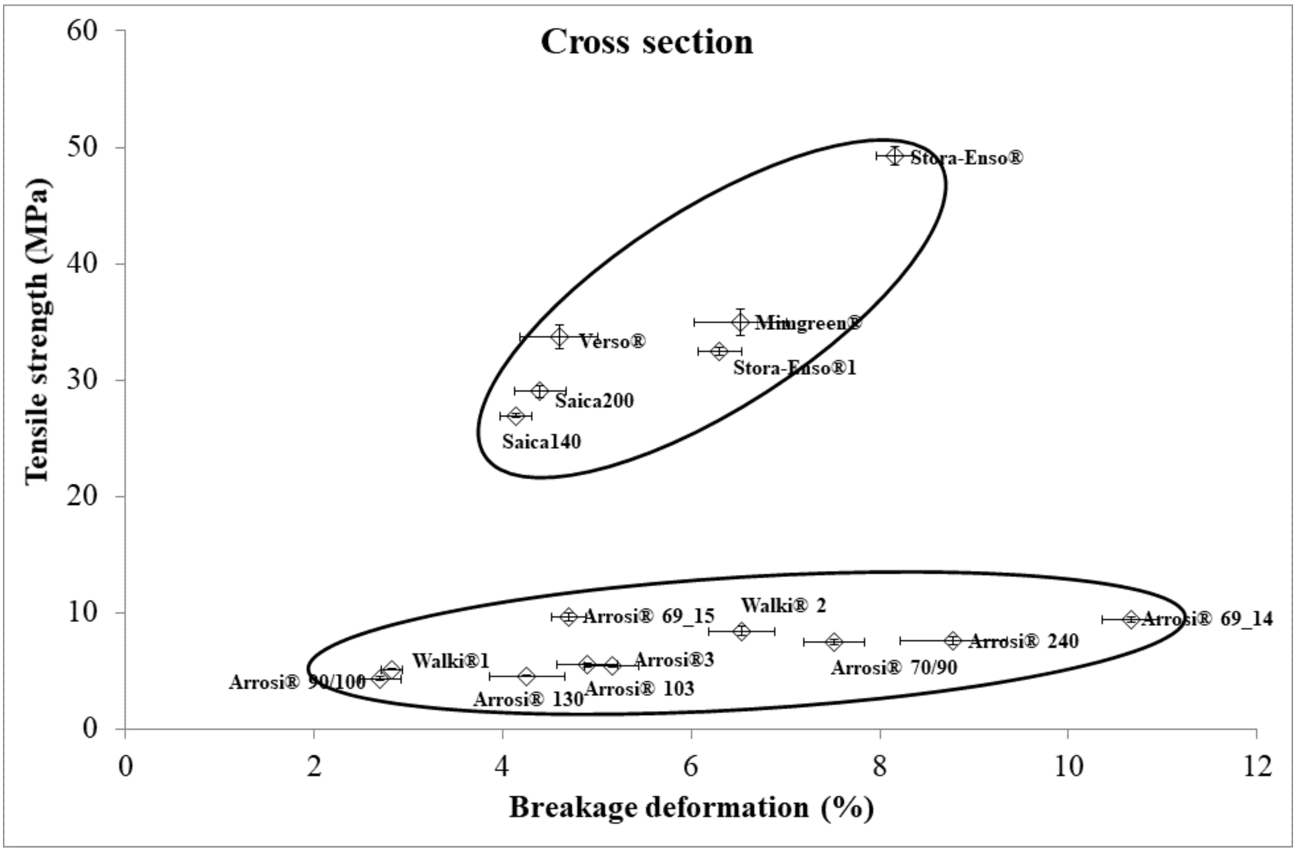


Figure 1.2. Relation between mean tensile strength (MPa) and mean breakage deformation (%) of the cross section of all tested paper mulches.

Table 1.3. Mean rates ± standard error of the tensile strength (σM in MPa), breakage deformation (εb in %) of the traction test and penetration strength (N), deformation to penetration (mm) of the punction test of both longitudinal section (LS) and cross section (CS) of all paper mulches studied and LDPE from Martín-Closas *et al.* (2008).

Samples	**Traction test**				**Punction test**			
	Tensile strength (σ_M) MPa		**Breakage deformation (εb) %**		**Penetration strength N**		**Deformation to mm**	
	LS	**CS**	**LS**	**CS**	**LS**	**CS**	**LS**	**CS**
LDPE	41.6 ± 4.80	27.4 ± 2.00	234.8 ±	710.9 ± 11.5	-	-	-	-
Mimgreen®	56.3 ± 1.55	35.0 ± 1.19	7.0 ± 0.23	6.5 ± 0.54	14.7 ± 0.99	16.2 ± 0.4	1.4 ± 0.06	1.7 ± 0.04
Verso®	86.2 ± 1.65	33.7 ± 1.03	2.2 ± 0.06	4.6 ± 0.42	5.6 ± 0.20	5.8 ± 0.40	0.7 ± 0.02	0.9 ± 0.03
Saica140	64.2 ± 0.92	26.9 ± 0.18	2.4 ± 0.09	4.1 ± 0.17	8.2 ± 0.28	10.5 ± 0.35	0.8 ± 0.01	1.1 ± 0.03
Saica200	69.6 ± 0.91	29.0 ± 0.53	3.1 ± 0.05	4.4 ± 0.28	16.3 ± 0.72	17.6 ± 0.62	1.0 ± 0.02	1.2 ± 0.03
Stora-Enso® 1	52.9 ± 0.52	32.5 ± 0.33	2.5 ± 0.06	6.3 ± 0.23	8.5 ± 0.35	10.4 ± 0.20	1.0 ± 0.04	1.1 ± 0.04
Stora-Enso®	55.6 ± 6.04	49.2 ± 0.80	5.4 ± 0.34	8.2 ± 0.19	12.5 ± 0.68	13.1 ± 1.23	1.2 ± 0.02	1.3 ± 0.07
Walki®1	12.9 ± 0.26	5.1 ± 0.06	23.9 ± 0.30	2.8 ± 0.11	6.0 ± 0.60	4.1 ± 0.25	1.9 ± 0.11	1.7 ± 0.04
Walki® 2	11.3 ± 0.52	8.4 ± 0.39	23.6 ± 1.07	6.5 ± 0.35	17.4 ± 0.98	15.4 ± 0.68	2.7 ± 0.09	2.4 ± 0.24
Arrosi® 103	7.5 ± 0.27	5.5 ± 0.19	19.5 ± 0.36	4.9 ± 0.32	10.4 ± 0.43	7.3 ± 0.58	2.3 ± 0.13	1.7 ± 0.06
Arrosi® 130	5.0 ± 0.20	4.8 ± 0.08	36.2 ± 1.06	4.3 ± 0.39	15.4 ± 0.96	8.4 ± 0.12	4.2 ± 0.32	2.1 ± 0.15
Arrosi® 240	10.4 ± 0.37	7.6 ± 0.35	24.8 ± 0.56	8.8 ± 0.57	14.9 ± 1.22	11.7 ± 0.92	2.8 ± 0.26	2.5 ± 0.13
Arrosi® 69_15	10.7 ± 1.01	9.6 ± 0.38	24.1 ± 1.10	4.7 ± 0.18	8.9 ± 0.59	7.1 ± 0.41	2.1 ± 0.07	1.7 ± 0.06
Arrosi® 69_14	12.0 ± 0,68	9.4 ± 0.25	18.5 ± 0.72	10.6 ± 0.31	15.3 ± 0.82	12.4 ± 0.54	2.1 ± 0.07	2.0 ± 0.05
Arrosi® 70/90	10.5 ± 0.35	7.5 ± 0.23	20.7 ±0.31	7.5 ± 0.32	14.8 ± 1.52	12.8 ± 0.50	3.0 ± 0.38	2.4 ± 0.11
Arrosi® 90/100	10.5 ± 0.26	4.3 ± 0.17	12.2 ± 0.35	2.7 ± 0.22	7.4 ± 0.61	5.2 ± 0.59	1.6 ± 0.09	1.9 ± 0.25
Arrosi® 3	7.2 ± 0.18	5.4 ± 0.07	29.6 ± 0.73	5.2 ± 0.28	12.7 ± 1.44	6.5 ± 0.35	3.5 ± 0.23	2.5 ± 0.09

Puncture test. Penetration strength (N) to pierce a sample in both the LS and CS was not dependent on whether the material was flexible or not. The crepe paper Walki® 2 got the highest rates in the LS (17.4 N) and Verso® paper the lowest (5.6 N), almost an opposite result to the traction test (Table 1.2). Maybe the creping process that was made in one direction favored this response.

Deformation to penetration presented similar rates in both sections unlike what was found for penetration strength. The non-flexible materials only elongated in the punction point around 1 mm in the LS. Flexible papers showed a wider range of rates from 1.6 mm in the Arrosi® 90/100 to 4.2 mm in the Arrosi® 130. Rates in the CS were variable depending on the material not in the flexibility. Materials with lower rates as Stora-Enso® 1, Verso® or Saica 140 will break easily if a sharp stone touches them when laying the mulch in field and because of their non-flexible nature, once they break, the tear will extend until the machine does not stop (Cirujeda, pers. comm.).

Conclusions

The mechanical properties of the tested paper mulches showed that these materials have a wide range of grammage, thickness and color. Strength to breakage and capacity to elongate of those materials was also very variable even when comparing the section of each material. This means that several options exist and it can be helpful to try to adjust the material to the particular scenario each farmer has.

Crepe materials as Arrosi® 240, Arrosi® 69, Arrosi® 70/90, Walki® 1 present intermediate rates of gammage and thickness; these materials also showed higher values in the traction and punction tests giving them certain resistance during the mechanical installation and also certain capacity to elongate when the material touches a sharp stone avoiding breakage will be the best options. The non- flexible papers Mimgreen® and Verso® did not accomplish with this optimal scenario but the dark color is an interesting and important factor to avoid weeds to grow below them having probably influence on the temperature and on the yield. Arrosi® 3 was the only tested dark-colored crepe paper showing similar characteristics to those crepe materials mentioned before but with a higher grammage that would represent inconveniences for handling the roll.

To conclude, the crepe papers available in the market achieve with most of the requirements for a good installation response in the field but it is needed to improve others as color. The explained results should be taken into account aiming to find new papers matching al the targeted mechanical properties.

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CHAPTER 2. Purple nutsedge (*Cyperus rotundus* L.) control with biodegradable mulches and its effect on fresh pepper (*Capsicum annuum* L.) production

Purple nutsedge (*Cyperus rotundus* L.) control with biodegradable mulches and its effect on fresh pepper (*Capsicum annuum* L.) production

Abstract

More than half of the plastic used in Spain for mulching in agriculture is black polyethylene (PE), due to the advantages it has for crops, its low price and its ease of installation. The mass use of this material entails a number of disadvantages: the cost of removing fragments from fields after use, the difficulty of managing the waste, and deficient weed control of some species such as purple nutsedge (*Cyperus rotundus* L.), which is capable of piercing the film. The objective of this work was thus to find alternative materials to PE in horticultural crops in order to reduce these drawbacks, especially in slow- growing crops such as pepper. In the present document, we describe the trials carried out in Zaragoza (Spain) from 2012 to 2015 in pepper with various different biodegradable materials in order to find agronomically viable alternatives to PE. Plots were distributed randomly in four blocks and 6 to 9 different treatments were studied depending on the year, including an unweeded plot. In total, 11 different mulches were tested: five biodegradable plastic films, five paper mulches and PE. Weed density, mulch degradation and pepper production were evaluated and weed efficacy was calculated. Biodegradable plastic films and PE were not good options for purple nutsedge control (mean efficacy of 48) and only paper mulches controlled this species effectively, as the leaves were unable to pierce the materials. The above-soil part of the mulches was intact 15 days after transplant (DAT), degradation was around 25% in most materials 45 DAT. Strong winds and unusually high sunshine hours accelerated degradation in 2013 and 2014. In-soil degradation was generally faster for papers than for biodegradable plastics, except in 2015, when the mulching materials suffered early fractures due to a windy spring with exceptionally high solar radiation. Rapid degradation of some mulches occurred before the crop covered the soil, which can be a serious problem in windy areas because the material can be lifted by gusts of wind. Earthing up along the edges of the materials 10 to 15 days after transplanting would solve this problem. Pepper production was similar for all materials in 2012-14 and the differences found in 2015 cannot be attributed to the mulches but to the weather conditions during that year. The biodegradable mulches tested are thus considered to be technically viable alternatives to PE use in pepper production in the tested conditions, provided early degradation is counteracted by earthing up before the materials are lifted by wind. Paper mulches are recommended for purple nutsedge infestations, while biodegradable films can be used for annual weed infestations.

Introduction

Plastic mulch became popular in Spanish horticultural crop production in the 1960's thanks to low-density polyethylene (PE). This is still the most commonly used material in Spain, where 57% of all plastic is dedicated to agriculture (MAPAMA 2015a) due to its advantages for crops. Moreover, PE is a flexible and long-lasting material (MAPAMA 2015b) which is cheap and easy to use and available in a wide range of colors, thicknesses and widths (Lamont 2005). The main drawback of this material is that it leaves remnants behind in the field after mechanized harvesting, as the film is usually shredded in the process. Those fragments that are not recovered become a risk for the soil, groundwater and flora and fauna because the wind scatters them, causing a negative impact on the landscape (MAPAMA 2015b). There is an additional problem with short-statured crops such as spinach or peas that are mechanically harvested, as the pieces of plastic can be accidentally harvested with the crop (MAPAMA 2015b).

Unfortunately the most common practices for remnant management are abandonment, burial and uncontrolled burning. Spain is one of the European countries where more than 50% of plastic waste ends up in landfills (PlasticsEurope 2015). Film mulches have impurities such as soil, debris, pesticides and fertilizers which can represent up to 85% of the total remnants by weight, while recycling plants do not accept plastic films with more than 5% impurities (Gartraud 2004). At the same time, the cost of removal from the field needs to be taken into account, and has been estimated as €115 ha^{-1} (Cirujeda *et al.* 2012a). The Spanish Ministry of Agriculture, Food and Environment prepared the National Integral Waste Plan to comply with European requirements from 2008 to 2015. This Plan continues until 2022 and includes a specific plan for the management of plastic for agricultural use, incorporating new European requirements such as an agricultural waste management section. The plan states that the availability of biodegradable plastic mulches in the market must be increased, thus encouraging the evaluation of available mulches and the development of new ones and justifying the present work.

However, biodegradable polymers have not entered into widespread use, despite the fact that they were introduced as an alternative to PE in the 1980's. The main reasons for not using them are insufficient knowledge, high cost and unpredictable tearing of the material, according to a recent survey among specialized growers, agricultural extension agents and mulch manufacturers (MAPAMA 2015a). Some authors have shown that using biodegradable mulches can be an economical alternative even though the base material is more expensive, because the costs of removing and recycling PE are high (Goldberger *et al.* 2013; Kasirajan & Ngouajio 2012).

Unfortunately, some of these mulches have shown irregular responses in the field, sometimes with degradation as early as within the first month after installation (Cirujeda *et al.* 2012a; Martín-Closas *et al.* 2016). Furthermore, degradation rates have also proven to be very variable depending on soil conditions, climate and the feedstock of the mulches (Hakkarainen 2002; Singh & Sharma 2008). Oxo-degradable plastic films, also erroneously labeled as 'biodegradable', contain PE and metals; they are broken down into small pieces but no real degradation of the components occurs (Thomas *et al.* 2010), leading to soil problems and environmental damage. The same situation has been reported for photodegradable plastic films (Riggle 1998).

In Spain, several studies conducted over a period of more than ten years have shown that biodegradable materials, both paper and plastic mulches, are capable of giving similar yield and weed control results in processing tomato to those of PE (Cirujeda *et al.* 2012a; Lahoz *et al*. 2014; Martín-Closas *et al.* 2008; Moreno *et al.* 2016). Anderson *et al*. (1995) also found similar results in tomato when comparing kraft paper and black PE, and Miles *et al.* (2012) tested several biodegradable mulches in tomato production in comparison to PE. In these trials, the crop showed fast horizontal growth, and was capable of covering the film in a short period, preventing early film degradation. Nevertheless, some authors (Johnson & Mullinix 2008; Waterer 2010) suggest that it is important to know the behavior of these materials when used with other crops with a slower growth rate such as pepper, because nutsedge is very susceptible to shading (Keeley & Tullen 1978; William 1976), and in crops with more vertical growth nutsedge will probably grow freely.

Purple nutsedge can pierce plastic films (Johnson & Mullinix *et al*. 2008; Cirujeda *et al.* 2012a), reducing the integrity and effectiveness of the mulching material. A larger number of perforations tend to occur in biodegradable plastic films than in PE, as the materials lose mechanical properties once they are laid in the field (Martín-Closas *et al.* 2016). Other biodegradable mulching materials tested were papers, which showed complete effectiveness in controlling purple nutsedge (Cirujeda *et al.* 2012b), with similar results to those found in strawberry with yellow nutsedge (Daugovish & Mochizuki 2010). Despite these advantages, the high prices of paper mulches have until now caused them to remain in the background. Further disadvantages are the need for more delicate mechanical installation than with plastics and the fact that some paper mulch undergoes faster degradation of the buried part (Kasirajan & Ngouajio 2012). Moreover, in Spain there are only two authorized herbicidal active ingredients for perennial species in pepper crops (MAPAMA 2016): glyphosate and pelargonic acid, of which is neither specific for nutsedge control nor selective for the crops. Consequently, their application is only possible in the non-cultivation period. Thus, purple nutsedge infestations pose a real problem for weed management in horticultural crops.

The objectives of this work were: a) to evaluate different biodegradable paper mulches, plastic films and PE and their effectiveness for weed control, especially for purple nutsedge; b) to describe the degradation of the mulching materials in the field during the cropping period and c) to compare how pepper yield was affected by the mulching materials tested.

Materials and Methods

General trial. The trials were conducted in an experimental field belonging to an Aragonese Government Agricultural Research Centre (41.43° N, 0.48° W) in Zaragoza, Aragon, Spain, from May to October in the years 2012 to 2015. The trials were located in a different part of the field each year to avoid possible cumulative effects from previous years. Soil preparation included soil tillage and bed formation. In spring, after soil preparation, cow manure was incorporated at a rate of 40 t ha^{-1} in the first year and 30 t ha^{-1} the following years. After crop transplant, chemical fertilization was applied through the irrigation system at weekly intervals taking into account the mineralization of the manure each year (Table 2.1).

Table 2.1. Field operations during the trials from 2012 to 2015.

	Basal Fertilizer Application Cow manure	**Top Fertilizer Application Chemical fertilizers**	**Mulching Date**	**Transplanting Date**	**Harvest**
	(N-P-K) F.U. kg trial^{-1}	**(N-P-K) F.U. kg trial^{-1}**			
2012	102 - 65 - 67	50 - 75 - 108	May 23	May 24	August 16 September 20 October 4 November 8
2013	9.5 - 6.3 - 6.1	140.5 - 119 - 144	June 5	June 15	September 19 October 4 October 24
2014	9.5 - 6.3 - 6.1	140.5 - 119 - 144	May 19	May 23	September 18 October 8 October 23 November 6
2015	9.5 - 6.3 - 6.1	140.5 - 119 - 144	May 18	May 26	September 10 September 30 October 28

All mulches measured 1.2 m in width and were installed mechanically within five days after soil preparation and prior to weed emergence. The mulch laying machine unrolls the material, which is tightened with pressure wheels; then approximately 15 cm of the edges of the material are buried with soil which has been previously loosened by other parts of the equipment.

Treatments were distributed randomly in a complete block design with four replicates; 6 to 9 materials were tested each year, with a total of 11 different mulching materials (Table 2.2). An unweeded control was included.

Table 2.2. Characteristics of mulch materials used in the trials from 2012 and 2015. Thickness (μm) is used for plastic films and weight (g m^{-2}) for paper mulches. All mulches are biodegradable except for polyethylene (PE).

Product name	**Manufacturers**	**Main composition**	**Thickness - Grammage**	**Color**	**Years included in trials**
			μm - g m^{-2}		
PE	Several manufacturers	Low-density polyethylene	15	Black	2012-2015
Sphere® 4	Sphere Spain. Zaragoza, Spain	Potato starch	15	Black	2012-2015
Sphere® 6	Sphere Spain. Zaragoza, Spain	Potato starch	15	Black	2012-2015
Mater-Bi®	Novamont S.p.A. Novara, Italy	Corn starch, co-polyester, vegetable oils	15	Black	2012-2015
Bioflex®	FKuR Kunststoff GmbH. Willich, Germany	Polylactic acid, co-polyester	15	Black	2013-2015
Ecovio®	BASF S.E. Ludwigshafen, Germany	Polylactic acid	15	Black	2014-2015
Arrosi® 240	Fábrica de Papeles Crepados Arrosi. Gipuzkoa, Spain	Cellulosic fiber	80	Light brown	2014-2015
Arrosi® 69	Fábrica de Papeles Crepados Arrosi. Gipuzkoa, Spain	Cellulosic fiber	80	Light brown	2014-2015
Arrosi® A90/100	Fábrica de Papeles Crepados Arrosi. Gipuzkoa, Spain	Cellulosic fiber	100	Light brown	2013
Mimgreen®	Mimcord S.A. Barcelona, Spain	Cellulosic fiber	85	Black	2012-2015
Verso®	Verso Corporation, USA	Cellulosic fiber	72	Dark gray	2012

A 16 mm diameter drip tape was used for irrigation in each line with an emitter every 20 cm and the treatments were grouped into three different sectors, i.e. paper mulches, plastic mulches and bare soil. In this way, each sector could be irrigated separately according to its water needs with the aim of avoiding unmulched plots receiving less water than needed (Vázquez *et al.* 2011). Soil moisture values were recorded daily using sensors (Aquameter ECH2O, Decagon or Divener, Sentek). The crop was irrigated immediately after planting to field capacity for all treatments and the measurement of each sensor at field capacity was recorded. Irrigation was conducted when the measurements were 15% below the value recorded at field capacity; duration and frequency of the irrigation periods were established based on these daily measurements.

The pepper variety planted was ‘Viriato’ type Lamuyo. The crop was planted manually, with 0.3 m plant spacing, double row distribution and 0.3 m between rows of crop. Plots were 6 m wide x 20 m long, including four crop rows and thus four beds, each spaced 1.5 m from center to center. Beds were 70 cm wide. Parameters evaluated in all plots were weed density, percentage of weed cover, degradation of the mulches and marketable fruit production. Four fixed quadrats, each measuring 0.2 x 1 m, were disposed in each plot; two of the quadrats were placed on the left of the row and two on the right, in an attempt to describe all possible situations. This is the most difficult area in which to conduct weed control by mechanical means or with herbicides, and is considered the main target area for mulching. Weed density (pl m^{-2}) was evaluated in these quadrats at 21, 42 and 63 days after transplant (DAT). For this purpose individual weed plants were counted separately for each species and density was obtained for each species. Weeds emerging from the transplanting holes were not included in the counts. Additionally, percentage of soil cover by all weeds was visually evaluated in the same areas. With total and specific nutsedge weed density data, expected control efficacy (ECE) (%) was calculated following Abbott formula:

$$ECE = 100 - (C/S9) \text{ X } 100$$

Where C = percentage of weed control exerted by treatment and S= percentage of weed control exerted by unweeded control.

The degradation rate was evaluated over one-meter-long pieces of material, both the unburied part (above-soil degradation) and the buried part (in-soil degradation). In each evaluation, a new part of the material was chosen to avoid repeating samples, which always suffer some damage during sampling. The evaluation scale used was a modification of the one developed by Shogren and Hochmuth (2004) extending the original scale of 5 to 9 categories in a qualitative degradation scale (Martín-Closas *et al.* 2016); where ‘1’ equals intact material in which no degradation has occurred, ‘2’ corresponds to 20% of the material degraded, ‘3’ to 30% degraded, ‘4’ to 40% degraded, ‘5’ to 50% degraded, ‘6’ to 60% degraded, ‘7’ to 70% degraded, ‘8’ to 80% degraded and ‘9’ to ‘completely degraded or very fragile’.

Marketable pepper fruits were harvested three times at the end of the season and the number of fruits and the total weight were calculated for each plot.

Specific nutsedge mesh trial. An additional trial was set up in the raised beds of the experiment explained in the previous chapter. The aim was of study the purple nutsedge biological behaviour under biodegradable mulches in more detail. With this purpose, meshes with a 40 x 40 x 40 cm mesh dimensions were delimited in the soil inside the raised plantation beds with the help of a plastic mesh of 1 mm size during the years 2012, 2013 and 2014. This depth was selected because 100% of tubers are found within the first 40 cm of the (Horowitz 1972). The meshes where installed under two papers, two plastic films and the unweeded control following the distribution of the previous trial and a couple of days before mulching the field (Table 2.1). The mesh was placed into the soil attached to a metal cast manufactured specifically for the trial. Once in the soil, the mold was filled with a 5 cm-layer of gravel (diameter of the stones of 2.5cm) to facilitate drainage and afterwards with soil of the same plot, which had been previously sieved to avoid introducing more *C. rotundus* tubers. At that depth, 16 nutsedge tubers (100 tuber m^{-2}) weighted from 0.5 to 1 g were sown (exceptionally 17 in 2013, 106.3 tuber m^{-2}). One mesh cube (exceptionally two in year 2013) were installed in each row and later covered with the corresponding mulches and the corresponding pepper plants were transplanted. Emerged *C. rotundus* plants in the plastic films were allowed to grow while all other species emerging in the unweeded control meshes were removed.

At 21, 42 and 63 DAP (days after planting) *C. rotundus* emergence (pl m^{-2}) was recorded in the mesh areas. After the last pepper harvest, the aerial part of the nutsedges was cut, dried up to stable weigh value at 60ºC (P Selecta DigiHeat) and weighed with a precision balance (± 1g). The underground net of tubers and rhizomes was carefully extracted after the last yield recollected each year (Table 2.1). Tubers and rhizomes were washed, counted and dried in the same conditions as the aerial part. The obtained categories were total tuber number, basal tuber number, rotten or healthy tuber number and total tuber weight. Healthy tubers were considered as those turgid and without any disturbance in their surface; basal bulbs are the structures formed very close to the soil surface that generate the aerial part.

Additional data collection. In 2012, some other data were collected: e.g., the number of leaves and their maximum length were measured and dry biomass of the leaves was determined. However, many leaves dried out during the trials suggesting that the utility of these measures were not relevant. Therefore, these determinations were not taken in 2013 and 2014 anymore.

Also in 2012, the depth where each tuber was found was additionally noted down. These data were not collected in 2014 and 2015 due to the huge work that this procedure represented and because the data confirmed the information already present in the bibliography that most of the tubers were formed in the first 15 cm depth.

Finally, the yield of the three pepper plants growing in the cube was determined aiming to relate the yield with *C. rotundus* density. Agronomic problems in irrigation and not suitable weather conditions caused low yield in many plants so that these determinations were not taken into account.

Statistical analysis. The analysis was performed using SAS (Statistical Analysis System V.9.4. SAS Institute, Cary, NC, USA). Data was tested for homogeneity of variance and normality before analysis.

Contrast analysis was performed on production (t ha^{-1}), weed density (pl m^{-2}) and % of cover and degradation index with pooled data for all four years in order to have an overall view of the results. Box-Cox-transformation suggestions were taken into account when data did not fulfil normality requirements and number of tubers m^{-2} and tuber weight m^{-2} were transformed using $(x)^{0.25}$, the number of emerged *C. rotundus* plants m^{-2} and the percentage of rotten tubers required $(x)^{0.3}$ transformation. Degradation and yield data was subjected to analysis of variance (ANOVA) using the procedure PROC GLM with SAS first on the complete data set of the 4 years taking into account into the model that the factor of block was nested into year. As the interaction of year by treatment was significant, data were analyzed for each year separately. Student-Newman-Keuls (SNK) mean separation test ($p<0.05$) were conducted when differences were significant. In case of significant interaction, a pairwise t-test was performed to allow single comparisons between treatments and years. Total weed and nutsedge efficacy, which did not meet normality conditions, were analyzed with the non-parametric Wilcoxon test.

Results and Discussion

General trial

Efficacy of Weed Control. The results of the contrast analysis for all four years showed that, as expected, the unweeded plot had a statistically mean weed density (pl m^{-2}) than the rest of the treatments ($p<0.0001$) (data not shown). For this reason, the results for the unweeded plots were excluded from the non-parametric analysis, with the aim of making comparisons only among the mulches (Figure 2.1). Weed cover in the unweeded plots was close to 100% in all four years (data not shown). The most common species in 2012, 2013 and 2015 were the summer dicotyledonous *Portulaca oleracea* L. and *Amaranthus retroflexus* L. and the summer grasses *Echinochloa colona* L. and *Setaria verticillata* L. Other authors found similar weed composition in summer vegetable crops (Coolong 2010; Harrington & Bedford 2004; Radics *et al.* 2006). In the first month of the 2014 trial, *Capsella bursa-pastoris* L. and *Malva sylvestris* L. dominated rather than typical summer species due to the low temperatures and higher rainfall than the historical average (Table 2.3).

Table 2.3. Average monthly temperature (ºC) and sunshine (hours) during the period of trials from May to October at Zaragoza weather station (Spain) compared to the 50-year historical average at Zaragoza airport weather station (Spain). Oficina del Regante, Government of Aragon, Spain.

	Average monthly temperature				**Historical average temperature**	**Average monthly sunshine**	**Historical average sunshine**
	2012	**2013**	**2014**	**2015**	**1971-2000**	**2015**	**1971-2000**
			C°		**C°**	**Hours**	
May	19.8	13.7	16.6	18.5	17.2	380.5	263
June	23.2	19.6	22.0	22.7	21.3	371.0	295
July	23.7	25.5	23.0	25.9	24.5	380.6	337
August	25.7	23.7	23.2	23.8	24.4	355.5	311
Septembe	20.3	20.4	21.6	18.7	20.7	310.5	231
October	17.0	16.9	17.3	15.0	15.5	260.5	192

In this study, most mulch materials obtained an efficacy higher than 85% compared to the non- weeded control (Figure 2.1). Paper mulches generally achieved higher weed control efficacy than biodegradable plastics except for the experimental paper Arrosi® 240 in 2015 (Figure 2.1). Some weeds grew under the brown Arrosi® papers, probably because of the amount of light that passes through them, as also happened in a trial with watermelon using paper mulch (Shogren & Hochmuth 2004).

Analyzing the years separately, in 2012, all mulching materials achieved more than 80% efficacy compared to the non-weeded control. Sphere® 4 and Mater-Bi®, with an efficacy higher than 90%, exceeded the efficacy of PE, which only reached 83%. Thus, the biodegradable films showed irregular control efficacy, unlike in Miles *et al.* (2012), where no differences in weed control were found when comparing different biodegradable mulches. However, the materials tested in the present trials were different from those tested in that trial. The two paper mulches tested in that year reached 100% efficacy, being both non-flexible and dark materials. In 2013, 5 out of 7 materials reached more than 90% control, similar to the results in 2012; the efficacy of the biodegradable plastic films was quite irregular, ranging from 75% in the case of Sphere® 6 to 92.2% for Mater-Bi®. The light brown paper Arrosi® 90/100 did not achieve 90% efficacy. In 2014, all materials exceeded 80% efficacy. All paper mulches, including the light brown ones, reached almost 100% efficacy. In 2015, those plastic films that suffered major degradation, probably due to the high sunshine hours that year (Table 2.3), showed an inefficient weed control of 30 to 65% efficacy, Sphere® 4 being the plastic mulch with the lowest efficacy and Mater-Bi® the highest, with 80% efficacy, close to that of PE. The paper Arrosi® 240 also developed tears, causing very low weed control (20%). Only Mimgreen® and Arrosi® 69 paper mulches worked as expected. The weed control efficacy of PE was only matched or surpassed in all years by Mater-Bi® and in three years by Sphere® 4; Ecovio®, Bioflex® and Sphere® 6 equal its weed control efficacy in one year only.

Efficacy of Nutsedge Control. Nutsedge populations had low densities in the unweeded plots (1 to 1.25 individuals m^{-2}) (data not shown), which is consistent with the findings of Keeley & Thullen (1978), who state that nutsedge is susceptible to competition from shading, and with those of Anzalone *et al.* (2010) in their research with biodegradable mulches. Exceptionally, nutsedge density was higher in the unweeded plots in 2014, reaching 75 individuals m^{-2} in one replicate due to a lower incidence of other summer annual weeds, as explained previously. For this reason, the results for the unweeded plots were excluded from the non-parametric analysis, with the aim of making comparisons only among the mulches.

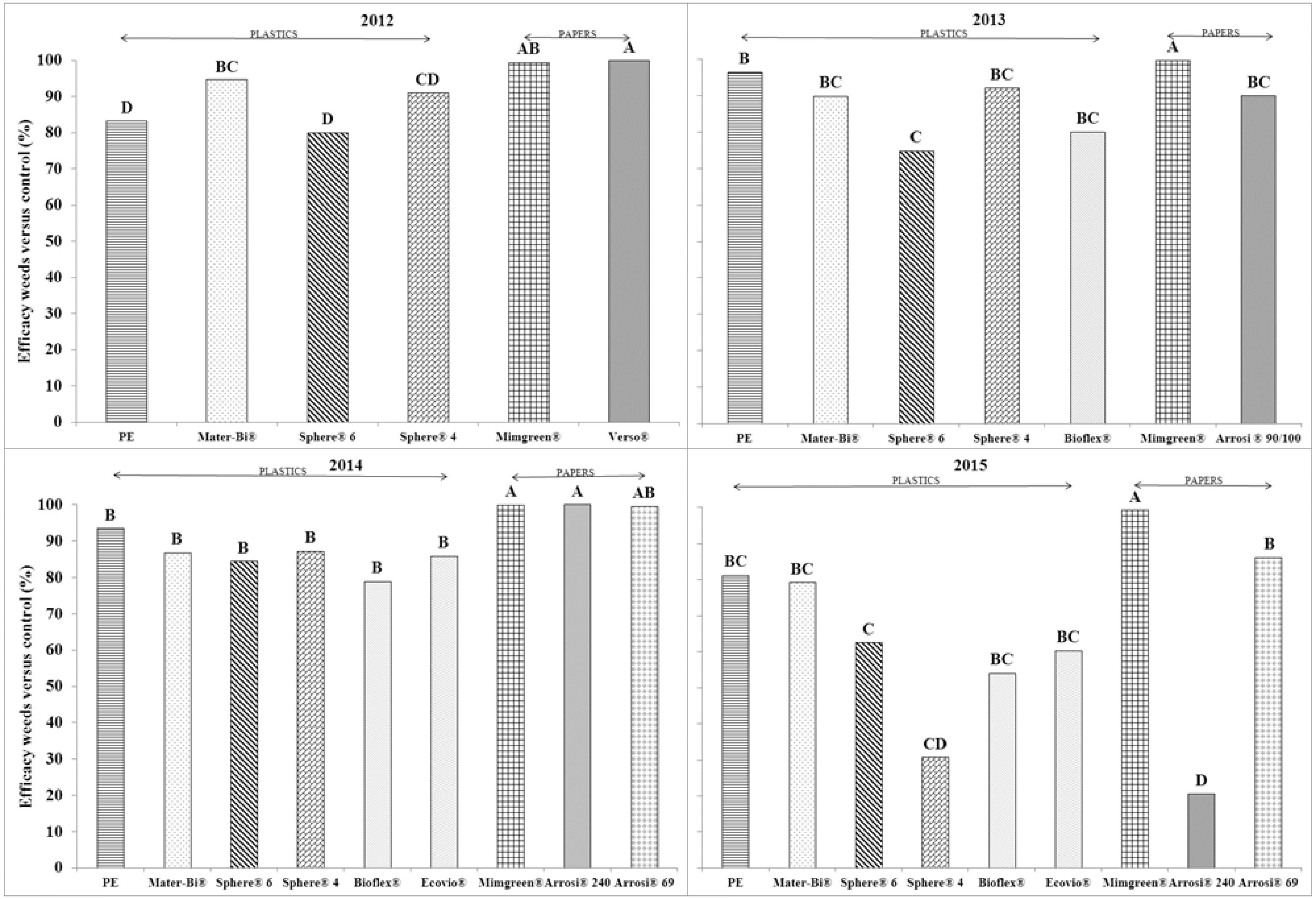

Figure 2.1. Mean efficacy of weed control over unweeded control plot (%) in each mulch treatment 63 days after transplant for the period 2012 to 2015. Mean values in each column followed by the same upper-case letters were no different at p<0.01 according to the Wilcoxon non-parametric test.

Paper mulches effectively controlled purple nutsedge in all four years except Arrosi® 90/100 in 2013 (Figure 2.2), as reported by Cirujeda *et al.* (2012b), Anzalone *et al.* (2010) and Shogren & Hochmuth (2004), who found only 11 plants m^{-2} under paper mulch in comparison to the 120 plants m^{-2} that emerged through PE. The only weeds that were found emerged in some transverse tears that occurred in some of the paper mulches a few days after installation when the paper dried out. Nutsedge sprouted under paper mulches; the leaves pressing against the mulch from below without piercing it, so that dried leaves were found after the materials were removed, similarly to the results reported by Shogren & Hochmuth (2004) in trials with watermelon and yellow nutsedge

In 2012, Arrosi® 90/100 exerted moderate control over nutsedge, because the mulch suffered tearing caused by the pressure of the weeds that grew under them. Once lifted, weeds grew abundantly. Plastic films showed low efficacy because they were easily pierced by the nutsedge leaves, as found by Webster (2005), who reported that nutsedges were capable of growing twice as much under PE as in the unweeded plot. Despite this, in 2012, Mater-Bi® biodegradable plastic film was the most efficient plastic film, with 65% efficacy, unlike Sphere® 6 and PE, with an efficacy of 35% and 30% respectively compared to the non-weeded control. In 2013, all materials displayed less than 60% efficacy. In 2014, only Sphere® 6 biodegradable plastic mulch reached 70% efficacy and Sphere® 4 even fell short of 40% compared to the non-weeded control. In 2015, due to the tears in the plastic films mentioned earlier, the lowest efficacy was found in the biodegradable plastic Ecovio®, with around 35% efficacy versus PE material (Figure 2.2). Thus, in three out of four years, PE showed higher purple nutsedge control than the biodegradable plastics, as found by Anzalone *et al.* (2010). Cirujeda *et al.* (2012a) and Moreno *et al.* (2017) also found that biodegradable plastic films were susceptible to piercing by nutsedges, probably due to their degradation and gradual loss of mechanical consistency over time, as confirmed in Martín-Closas *et al.* (2008).

Mulch Degradation. Generally, paper mulches showed higher degradation rates than biodegradable plastic films in the in-soil part (Tables 2.4, 2.5 and 2.6), as Moreno *et al.* (2017) also found recently. As expected, experimental materials showed a more heterogeneous response among the years (Table 2.6); some years these materials showed degradation rates than marketed materials. In 2015, degradation of the above-soil part of the mulches could not be assessed because of the excessive tearing at 45 DAT.

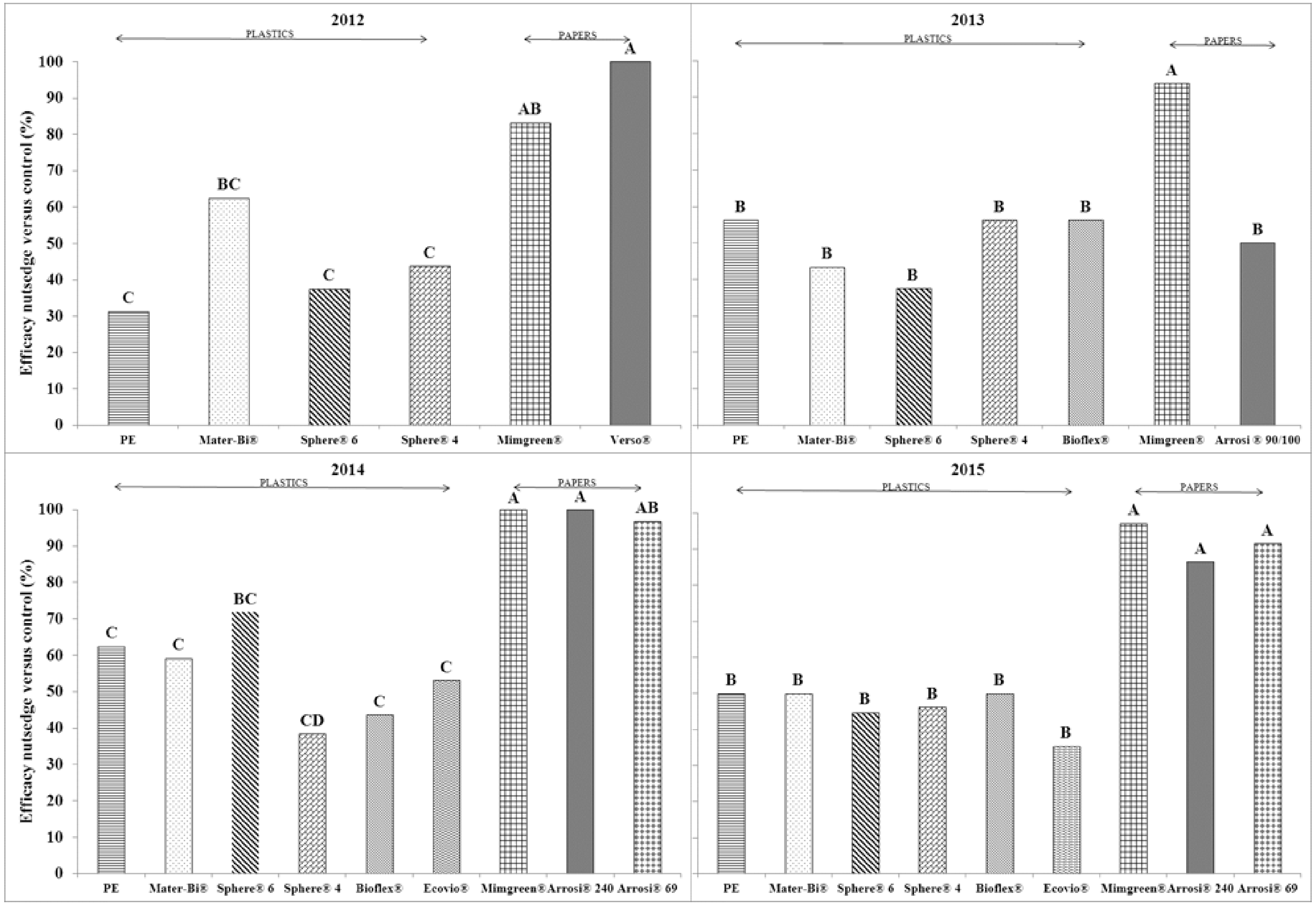

Figure 2.2. Mean efficacy of nutsedge control over unweeded control plot (%) in each treatment 63 days after transplant in the years 2012-2015. Data back-transformed from √x for the years 2012 and 2013. Mean values in each column followed by the same upper-case letters were no different at $p<0.01$ according to the SNK mean separation test for 2012 and 2013 values and to the Wilcoxon non-parametric test for 2014 and 2015 values.

At 15 DAT, the above-soil part of the plastic films and paper mulches was practically intact, except for Bioflex® in 2013, with an unusual degree of degradation of almost 30% of the film (Table 2.4). At 30 DAT most materials remained fairly intact in all years with the exception of two paper mulches in 2013 and the biodegradable plastics Sphere® 4 and Sphere® 6 in 2014 (Table 2.5). From May to October 2015, very strong winds and extremely high sunshine hours were recorded. In that period, 71 more sunshine hours were recorded than the historical 30-year average (Table 2.3), causing more tears than usual in the biodegradable mulches (Tables 2.4, 2.5 and 2.6), as confirmed by Moreno *et al.* (2017). Tears in the materials during the first month after transplant have also been found in other studies on biodegradable mulches (Waterer 2010; Zandstra *et al.* 2007). At 45 DAT, degradation of some biodegradable plastic films was similar to that of paper mulches, reaching about 25%; only Bioflex® and Arrosi® 90/100 showed more than 50% of the mulch degraded at that stage in 2013 (Table 2.6).

Table 2.4. In-soil and above-soil degradation mean rates in each mulching material tested from 2012 to 2015 at 15 DAT. Mean values in each column followed by different lower-case letters represent statistical differences at $p<0.01$ using the SNK mean comparison test.

15 DAT	**In-soil degradation**				**Above-soil degradation**			
Materials	**2012**	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**
PE	1.0 b	1.0 c	1.0 c	1.0 b	1.0 a	1.0 b	1.0 c	1.0 b
Mater-Bi®	1.5 b	2.0 c	2.8 bc	3.5 ab	1.0 a	1.3 b	1.0 c	1.0 b
Sphere® 6	1.5 b	3.0 c	2.8.bc	4.5 ab	1.0 a	1.5 b	1.0 c	1.0 b
Sphere® 4	2.8 b	5.0 b	4.0 b	4.0 ab	1.0 a	1.0 b	1.0 c	1.0 b
Bioflex®	-	2.0 c	2.5 bc	3.5 ab	-	1.3 b	1.0 c	1.0 b
Ecovio®	-	-	2.3 bc	4.5 ab	-	-	1.0 c	1.0 b
Mimgreen®	7.0 a	6.5 ab	6.5 a	5.0 ab	1.0 a	1.0 b	1.8 ab	1.0 b
Arrosi® 240	-	-	7.2 a	4.0 ab	-	-	2.0 a	2.0 a
Arrosi® 69	-	-	7.5 a	6.0 a	-	-	1.5 b	2.0 a
Verso®	7.8 a	-	-	-	2.5 a	-	-	-
Arrosi ® 90/100	-	7.0 a	-	-	-	3.0 a	-	-
	**	**	**	*	ns	**	**	**

ns No statistical differences.

** Statistical differences at $p<0.01$.

The slow growth rate and the erect habit of the pepper crop probably allowed more light to hit the film than with other crops, thus enhancing early film degradation. Indeed, Martín-Closas *et al.* (2016) and Moreno *et al.* (2017) indicated that the period of time elapsing between mulching, transplanting and maximum crop cover is the determining factor for mulch degradation, which supports the hypothesis.

As expected, in-soil degradation of paper mulches and plastic films was much faster than that of the above-ground part, probably due to the action of microorganisms. However, it was also quite variable, again as found in other trials (Martín-Closas *et al.* 2016). As mentioned earlier, in each evaluation a new part of the material was chosen. It is probably for this reason that some degradation rates were found to be slightly higher at 15 DAT than at 30 DAT (Tables 2.4, 2.5).

Table 2.5. In-soil and above-soil degradation mean rates in each mulching material tested from 2012 to 2015 at 30 DAT. Mean values in each column followed by different lower-case letters represent statistical differences at $p<0.01$ using the SNK mean comparison test.

30 DAT	**In-soil degradation**				**Above-soil degradation**			
Materials	**2012**	**2013**	**2014**	**2015**	**2012**	**2013**	**2014**	**2015**
PE	1.0 b	1.0 c	1.0c	1.0 e	1.3 a	1.0 c	1.0 c	1.0 b
Mater-Bi®	2.8 ab	3.3 b	1.5 c	5.3 cd	1.0 a	2.0 ab	1.5 ab	1.0 b
Sphere® 6	3.0 ab	4.0 ab	2.0 c	5.8 bcd	1.0 a	1.5 b	2.0 a	1.0 b
Sphere® 4	3.24 ab	4.5 ab	2.0 c	7.0 abc	1.3 a	1.8 b	1.5 a	1.0 b
Bioflex®	-	3.8 ab	1.5 c	4.3 d	-	2.0 ab	1.5 ab	1.0 b
Ecovio®	-	-	4.0 b	6.8 abc	-		1.5 bc	1.0 b
Mimgreen®	5.8 a	5.3 ab	8.0 a	7.8 ab	1.0 a	3.3 a	2.0 b	1.0 b
Arrosi® 240	-	-	8.0 a	7.5 abc	-		2.5 a	2.0 a
Arrosi® 69	-	-	8.0 a	8.3 a	-		2.0 a	2.0 a
Verso®	6.0 a	-	-	-	1.0 a		-	-
Arrosi ® 90/100	-	5.8 a	-	-	-	3.3 a	-	-
	**	**	**	**	ns	**	**	**

ns No statistical differences.

** Statistical differences at $p<0.01$.

In all years, the in-soil part of paper mulches already showed high degradation rates at 15 DAT, as Shogren also found (2000). In the case of Verso®, degradation at this time reached 80% in 2012. In contrast, few biodegradable plastic films reached such high degradation rates even at 45 DAT (Table 2.6).

In three out of four years, paper mulches were clearly more degraded than biodegradable films at 15 DAT, as also described by Martín-Closas *et al.* (2016). However, while biodegradable plastic film degradation increased with time, paper mulches maintained similar rates.

Table 2.6. In-soil and above-soil degradation mean rates in each mulching material tested from 2012 to 2015 at 45 DAT. Mean values in each column followed by different lower-case letters represent statistical differences at p<0.01 using the SNK mean comparison test.

45 DAT	**In-soil degradation**				**Above-soil degradation**
Materials	**2012**	**2013**	**2014**	**2015**	**2012-2015**
PE	2.0 d	1.0 c	1.0 d	1.0 b	1.0 abc
Mater-Bi®	5.3 bc	5.0 ab	4.0 c	4.8 a	4.1 a
Sphere® 6	3.5 cd	4.5 b	4.8 bc	5.8 a	1.7 cd
Sphere® 4	6.5 ab	5.3 ab	3.3 cd	5.0 a	2.2 abc
Bioflex®	-	6.8 ab	3.0 cd	6.5 a	1.8 cd
Ecovio®	-	-	4.8 bc	6.8 a	1.8 cd
Mimgreen®	6.0 ab	7.5 a	7.0 ab	8.3 a	1.5 cd
Arrosi® 240	-	-	8.3 a	6.8 a	1.3 c
Arrosi® 69	-	-	8.0 a	7.3 a	1.3 c
Verso®	8.0 a	-	-	-	2.0 abc
Arrosi ® 90/100	-	6.8 ab	-	-	2.5 ab
	**	**	**	**	**

** Statistical differences at p<0.01.

The biodegradable plastic film with the fastest degradation rate was Sphere® 4, which reached 50% at 15 DAT in 2013, corresponding to value 5 in the degradation scale (Table 2.4). In paper mulches, the edge between the buried part and the above-soil material generally degraded as early as 15 DAT. In this situation on a windy day, the paper mulches can be lifted, posing a problem. Thus, a slight earthing-up before this occurs is recommended. The same situation was observed in trials with tomato and pepper (Shogren & David 2006), lettuce and cabbage (Harrington & Bedford 2004) and strawberry (Weber 2003). In our trials, at 30 DAT (Table 2.5) most materials already displayed some degradation, and at 45 DAT the in-soil part of all paper mulches reached 90% degradation (Table 2.6), while biodegradable plastic films showed only 35 to 65% degradation. The materials were generally intact in 2012 and 2015, but in 2013 and 2014 all biodegradable materials showed some degradation exceeding 30%, while Sphere4® and Sphere6® biodegradable plastic films almost reached 60% degradation.

Pepper Production. In 2015, the pepper seedlings suffered high mortality and could not be replaced, so crop density was irregular and yield was very variable. The yield obtained on the unweeded plot was negligible because of the strong weed competition (data not shown), as found in other scientific studies (Cirujeda *et al*. 2012b; Morales-García *et al*. 2011), and was excluded from the statistical analysis. The factor 'year' had a statistical influence on yield for the reasons mentioned above, but when we analyze data from each year separately (Table 2.7) all mulching treatments gave a similar yield to that obtained by pepper grown on PE. In other trials with different crops, alternative mulching materials also lead to a similar yield to the one achieved with PE: this is the case with tomato (Anzalone *et al*. 2010; Cirujeda *et al*. 2012a), lettuce (Brault & Stewart 2002), cabbage (Coolong 2010) and again pepper (Shogren & David 2006; Waterer 2010; Zandstra *et al.* 2007).

However, the intense purple nutsedge infestations in the present trials could have been expected to cause yield losses in comparison to treatments that are capable of controlling this species while other mulching materials allowed the weed to grow. Moreover, following Motis *et al.* (2003), in the presence of serious *Cyperus esculentus* infestations, 10% yield losses can be avoided if the crop is weed-free from 3 to 5 weeks during the vegetative cycle. Concerning purple nutsedge, this species can cause up to 32% yield losses in the case of pepper (Morales-Payan 1997). Thus, the lack of yield differences in the present trials between plots highly infested with nutsedge and unweeded plots were probably due to other problems causing plant and fruit death such as meteorological factors and other agronomic difficulties ironing out the expected yield differences.

Table 2.7. Mean commercial pepper yield (red + green fruits) in t ha^{-1} obtained for each mulch from 2012 to 2015. Values in each column followed by different lower-case letters represent statistical differences at p<0.01 using the SNK mean comparison test.

Materials	**Annual marketable yield by year**			
	2012	**2013**	**2014**	**2015**
		t ha^{-1}		
PE	13.9 a	8.1 a	24.6 a	16.6 cd
Mater-Bi®	16.3 a	8.0 a	29.2 a	41.6 a
Sphere® 6	14.2 a	12.6 a	25.8 a	23.3 bc
Sphere® 4	13.7 a	7.7 a	25.3 a	18.7 cd
Bioflex®	-	10.1 a	24.4 a	13.4 de
Ecovio®	-	-	23.3 a	10.6 de
Mimgreen®	14.2 a	13.9 a	26.7 a	37.2 a
Arrosi® 240	-	-	28.5 a	28.6 ab
Arrosi® 69	-	-	25.3 a	7.8 e
Verso®	16.4 a	-	-	-

Arrosi® 90/100	-	9.7 a	-	-

Specific nutsedge mesh trial.

*Purple nutsedge emergence out of the meshes***.** In 2013 and 2014, highest emergence was observed in the unweeded control plots with up to 180 and 350 plants x m-^{2}, respectively (Figure 2.3). Taking into account that 106 in 2013 and 246 tubers m^{-2} were sown in 2012 and 2014, respectively, more than one plant emerged from each tuber. In 2013 and 2014 significantly less plants emerged in all mulches compared to the unweeded control; Mimgreen® and Verso® were the treatments with the lowers *C. rotundus* emergence in 2012 and Mimgreen® in 2013, while PE, MaterBi® and PE showed a similar control of this weed (Figure 2.3). Verso® and Arrosi® papers were not able to retain nutsedge emergence as much as the black paper Mimgreen®.

A lower control efficacy was expected for the biodegradable MaterBi© treatments all three years, as the counts in the fields showed a low control capacity (see Figure 2.2). Very probably the reason for finding a higher control capacity in the present trials than in the complete rows overall is that the meshes were placed in the centre of the raised beds where the distance between the soil and the mulch is higher. Pepper was placed in the soil in the staggered pattern (in diagonal) so that light entered into the mulch from the holes. Very probably many *C. rotundus* plants unfolded their leaves due to this fact and did not pierce the plastic. Moreover, the distance between the soil and the plastic

is higher in the central part of the rows than in the edges and the experiment was placed in the central part of the rows. Opposite, less light penetrates into the portion of the raised bed, which is on the sides of the raised beds due to a closer contact of the mulch films and the soil, thus, less light; in that parts, generally more *C. rotundus* plants pierced the plastic materials (data not shown).

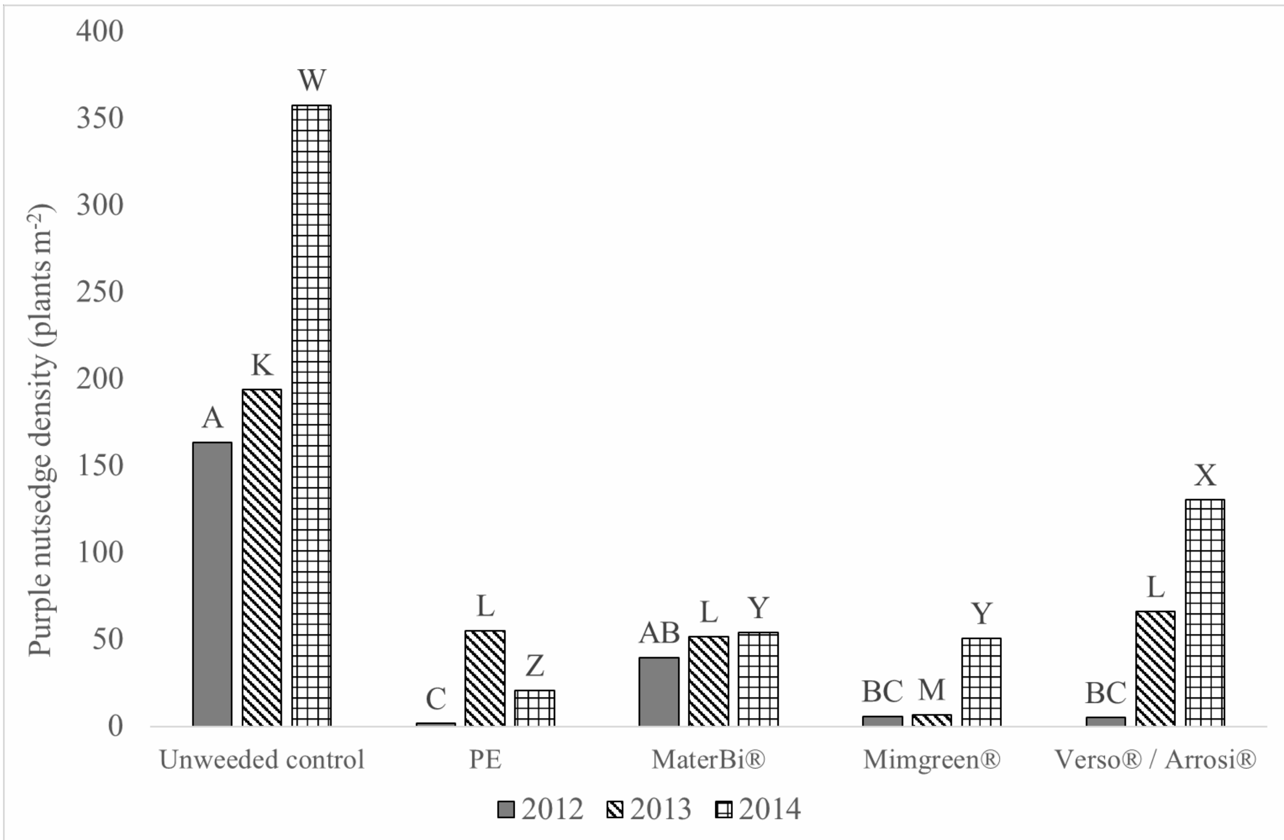

Figure 2.3: Mean *C. rotundus* density (pl m^{-2}) in the meshes at the end of the trial. Mean values in each year followed by the same upper-case letters were no different at $p<0.01$ according to the SNK mean comparison test. Means were transformed ($x^{0.3}$).

Purple nutsedge tuber production inside the meshes.

Depth of the tubers generated in the meshes. As explained in the "materials and methods" section, only in 2012 the depth of each tuber was recorded during the extraction. No significant differences were found within depth class. Most tubers were produced in the 1-8 cm soil layer regardless of the treatment exceeding the 75% of total tuber production in all cases (Figure 2.4). In addition, Davis & Hawkins (1943) and Tripathi (1969) found more than 80% of the tuber production in the first 15 cm.

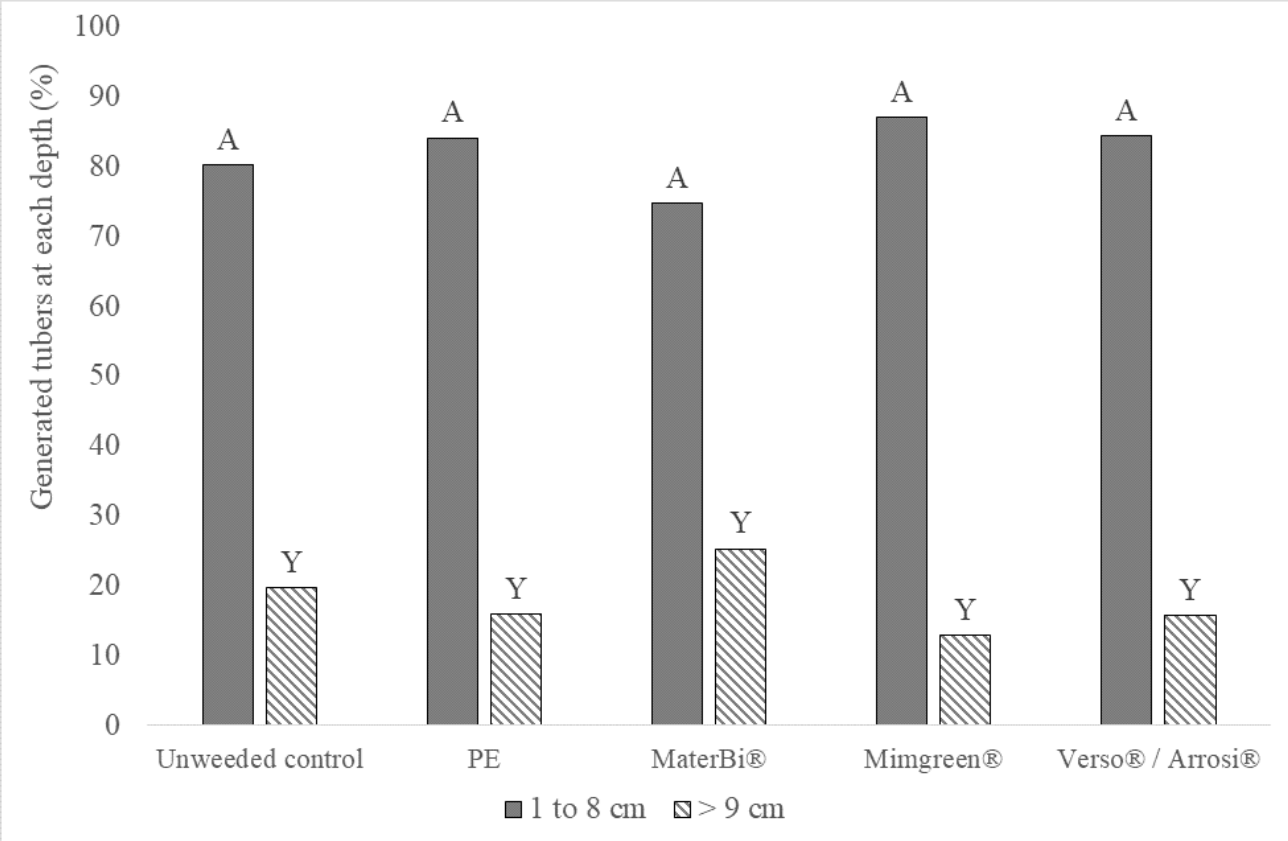

Figure 2.4. Mean percentage of *C. rotundus* tubers generated at the end of the cycle depending on the depth where they were found. Mean values in each depth followed by the same upper-case letters were no different at p<0.01 according to the SNK mean comparison test

Number of healthy tubers produced in the meshes. The significant interaction treatment x year (p<0.05) forced to analyse data of each year separately. Despite this, all three years a significantly highest amount of tubers was found for the unweeded control where only *C. rotundus* was allowed to grow. Thus, all mulching treatments achieved to reduce tuber production significantly.

The interaction referred mainly to different tuber production in a same treatment, which were slightly different between years (Figure 2.5). Tuber density in the unweeded control meshes was 9.1, 7 and 13.7-fold the initial density demonstrating a very high reproduction rate of this weed. Overall, Mimgreen® in 2013 stood out with the lowest tuber production, which was significantly lower than for all the other treatments excepting PE in 2012, PE in 2014 and Verso paper in 2012, which were similar but not lower than the rest according to the t-test comparison. Due to the reasons explained above a variable healthy tubers density were found under Mater-Bi® and PE. All three years more than initial tubers were found under both materials demonstrating that these materials are unsuitable for nutsedge control.

When comparing with the initial tubers placed in the meshes, it is striking that under the opaque paper Mimgreen® more than the initial tuber density was found in 2012. In this year, nutsedge plants emerging from the planting holes were not removed and included in the counts so that the found tubers must be partially non germinated tubers and newly generated ones. Opposite, in 2013 Mimgreen® less healthy tubers were found at the end of the cycle compared to the initially sown tubers, as expected. Concerning the translucent papers, tuber density found under both tested materials was, as expected, around two-fold higher than the mean initial density (2.3 tubers m^{-2} in 2013 and 4.4 tubers m^{-2} in 2014).

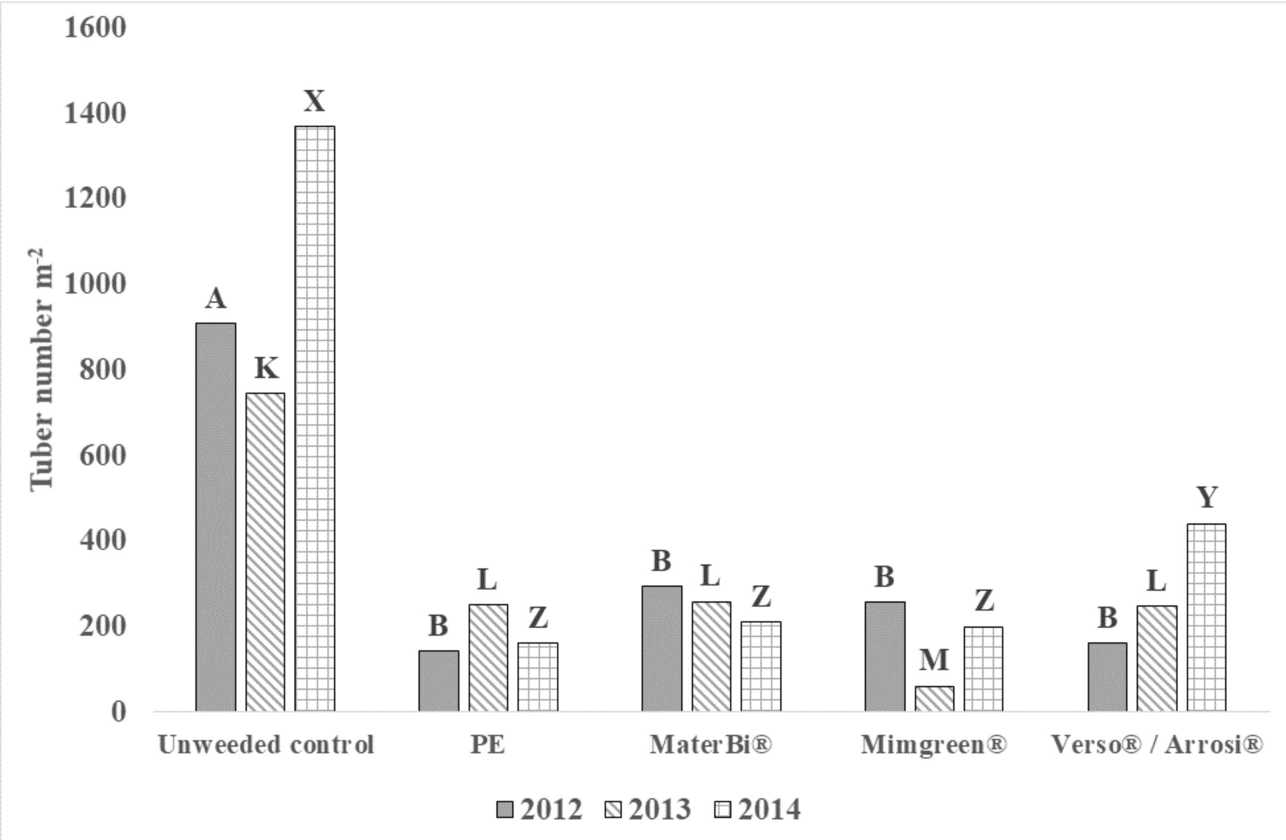

Figure 2.5. Number of healthy *C. rotundus* tubers found in the meshes at the final count at harvest (tubers/m^2). Mean values in each year followed by the same upper-case letters were no different at $p<0.01$ according to the SNK mean comparison test. Means were transformed ($x^{0.25}$).

Proportion of tuber type production: rotten, basal and health tubers. Overall, the fraction with the highest proportion of bulbs was the healthy one regardless of the treatment and the year excepting Mimgreen® in 2013 (Figure 2.6).

Concerning healthy tubers few statistical differences were found between treatments: in 2013 less healthy tubers were found under Mimgreen®. In 2014, less healthy tubers were generated under Mater-Bi® and PE than in the unweeded control (Figure 2.6). Consequently, significantly more rotten bulbs were found under Mimgreen® in 2013 and under the mulches Mater-Bi®, PE and Mimgreeen® in 2014. Thus, apart from hindering *C. rotundus* plant growth, the mulches additionally promoted the rotting of the nutsedge tubers, which is an interesting characteristic from the management point of view.

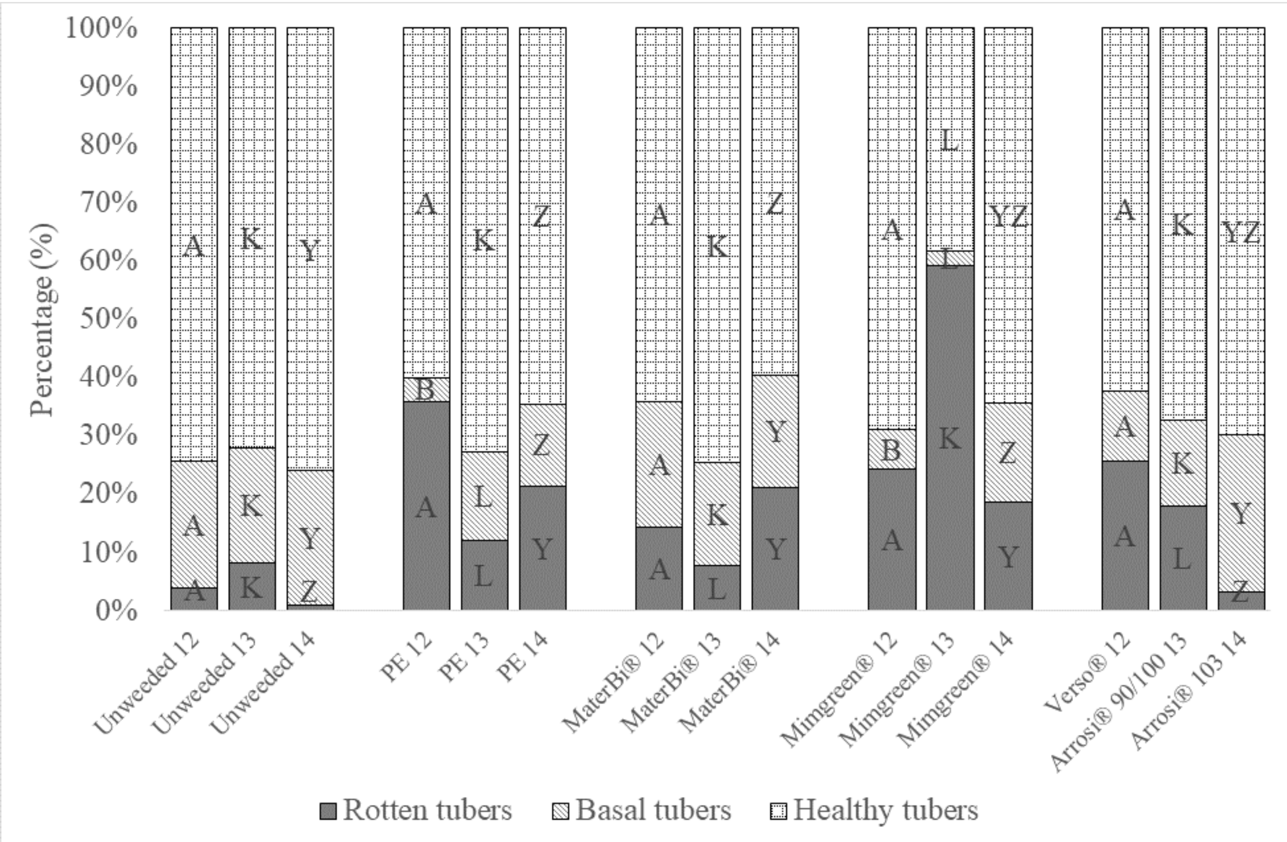

Figure 2.6. Percentage of rotten, basal and healthy *C. rotundus* tubers at the end of the cycle Mean values in each status followed by the same upper-case letters were no different at $p<0.01$ according to the SNK mean comparison test. Mean rotten tubers were transformed from ($x^{0.3}$).

Dry biomass of the healthy tubers in the meshes. As expected, all three years total tuber biomass was statistically highest in the unweeded control coincident with a higher tuber number (Figures 2.7, 2.5). However, differences between treatments slightly changed when comparing tuber number and tuber biomass. Therefore, in 2012, tuber number production was statistically the same for PE and Mater-Bi® but a statistically lower weight was found for PE. Thus, tubers produced under PE were lighter than those generated under Mater-Bi®, but only in 2012. The rest of differences were similar with the number of tubers found: in 2013 the lowest amount and weight of tubers was for Mimgreen® and in 2012 and 2014 all mulches produced less tubers and lower weight than in the unweeded control plots (Figures 2.7, 2.5).

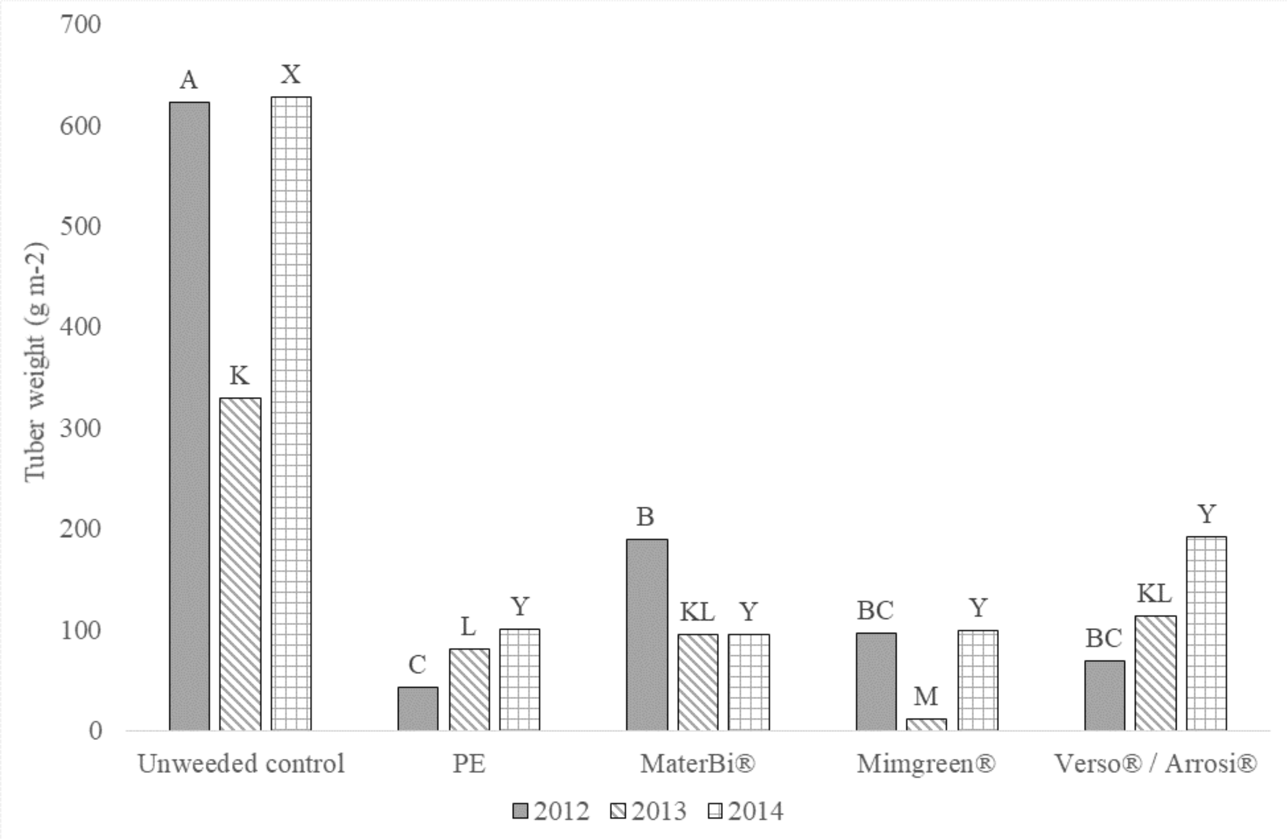

Figure 2.7. Mean dry *C. rotundus* tuber biomass (g m^{-2}) found in the meshes at the end of the trial. Due to the significant interaction between treatment and year, data was statistically analysed each year separately. Different letters refer to significant differences following Duncan mean separation test. Back-transformed means from (x) $^{0.25}$.

Main findings of the mesh trials. Despite creating a controlled environment for tuber production by placing the mesh in the soil and sowing out the nutsedge tubers, thus facilitating tuber extraction, other variables in the field trials could not be controlled easily. For example, drip irrigation in the field is subjected to the emitter distance, which was not identical in all the meshes thus causing a certain variability in the results.

Another factor is that the size of the meshes (40 x 40 x 40 cm), which is a smaller area than the whole width of the raised beds, caused that the tubers were only able to grow in the central part of the beds. As explained previously, this central part very probably received more light so that less *C. rotundus* plants were able to pierce the plastic mulches by unfolding the leaves prior to reaching the material. In year 2013, this effect was even bigger because the raised beds were a few centimetres higher in the edges than in the other years causing an even lower *C. rotundus* plant emergence.

Due to these facts, new complementary trials were designed to be conducted in controlled conditions in a growing chamber (Chapter 3).

Conclusions

Biodegradable plastic films generally controlled weeds efficiently except for purple nutsedge. Moreover, as no other species emerged through the plastic films, these materials are counterproductive: purple nutsedge grows without competition and its reproduction is thus promoted. Paper mulches were the only materials that were not pierced by the leaves of this species, so in the event of serious nutsedge infestations paper mulch is recommended. Despite confining nutsedge tubers in a mesh less plants pierced the plastic materials than in the overall trial demonstrating the difficulty in imitating the complete trial conditions. Nevertheless, the least tuber density were found under the opaque paper mulch Mimgreen®. A higher proportion of rotten tubers were found in all the mulching materials then in the unweeded control except for some translucent paper mulches.

Degradation of the in-soil part of paper mulches occurred as early as 15 DAT, which can become a problem in windy areas, because the mulch can be lifted before the crop is well established. Hilling shortly before 15 DAT can mitigate this problem. On the other hand, above-soil degradation did not occur and paper mulches remained intact for the first 45 DAT. In contrast, biodegradable plastic films displayed variable above-soil degradation, making them difficult to recommend; the biodegradable plastic Mater-Bi® is the most resistant one. The pepper yield obtained with biodegradable plastic films and paper mulches was equivalent to that obtained with PE, and even higher in the case of Mater-Bi®. Thus, any of the materials tested could be an alternative to PE for use with an erect vegetable crop such as pepper.

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CHAPTER 3. Effect of translucency of mulching materials and burial depth on *Cyperus rotundus* L. growth and development

Effect of translucency of mulching materials and burial depth on *Cyperus rotundus* L. growth and development

Abstract

Cyperus rotundus (purple nutsedge) is a perennial summer weed causing important yield decreases worldwide. However, shading has been found to reduce its development and therefore, mulching could be an important tool to control purple nutsedge. Nevertheless, it has been demonstrated that this species pierces some but not all mulches. Thus, the degree of translucency of mulching materials was evaluated in this work and its effect on the growth of purple nutsedge was tested under four plastic films and nine paper mulches with a gradient in translucency. The experimental design was a randomized completed block with four replicates repeated twice during spring-summer 2014-2015. At the end of the cycle both under and above dry biomass generated by purple nutsedge was assessed. Regardless of the translucency degree, plastic films were pierced by purple nutsedge and plants grew freely. Translucent paper mulches allowed nutsedge to grow under the mulch without piercing the materials; opposite, nutsedge did not develop under dark opaque paper mulch. The best option to control *C. rotundus* was thus opaque paper.

Burial depth nutsedge tubers is another factor considered to be important for the development of this species and the hypothesis of the second part of this work is that plants growing from deeper would not have the same ability to pierce the plastic films. With this purpose, two trials were conducted in year 2014 in growing chamber using three mulching materials and burying tubers at different depths (up to 10 cm in the first trial). No differences were found in the perforations or in the dry matter generated in the first 30 days within the first 10 cm in any of the three trials.

Introduction

Purple nutsedge (C. *rotundus* L.) cause severe problems in agriculture at wide areas of the world affecting several crops (Holm *et al*. 1977; Webster 2002) and is considered the "world worst weed" specific. Herbicides are available only in certain crops as maize using sulcotrione (MAPAMA 2017) but in horticultural crops this weed is commonly controlled either with localized glyphosate application or mechanically. The first one is risky and can lead to phytotoxic effects on the crop and the second methods need to be repeatedly to assure efficacy because sprouting is induced by breaking the tuber chain (Machado *et al*. 2005). Another common weed control practice in vegetables is mulching with low-density polyethylene (PE), an effective method to avoid weed germination excepting a few species including nutsedges. Mulching with PE even increase the nutsedge infestations compared to bare soil (Anzalone *et al.* 2010) because few species including nutsedge are capable to pierce this physical barrier. Once the layer is crossed nutsedges only have to compete against the crop remaining generally the rest of weed species under the mulch film (William 1976).

Purple nutsedge belongs to the plants with photosynthetic C4 metabolism, being capable to use water with higher efficiency than plants with C3 metabolism causing a fast growth in warm climates with high radiation levels (Moore *et al*. 1995). However, the photosynthetic efficiency decreases rapidly when not enough sunlight arrives to the plant's organs. Shading thus diminishes the plant growth and reproduction of this species and it has been proved that both the aerial biomass and tuber production reduce dramatically in shaded conditions (Neeser *et al*. 1997; Lazo & Ascencio 2010).

However, the capacity of piercing of PE films depends on the quantity of light passing through the film as Patterson (1998) found with different translucent polyethylene mulches, introducing a space between the plastic layer and the soil (Chase 1998), depending on the position of the nutsedge tubers in the soil i.e. its depth (Roozkhosh *et al*. 2017) and also on the thickness of the plastic (Chase *et al.* 1998; Patterson 1998). For example, when transparent PE is used in certain crops to obtain crop precocity, purple nutsedge unfolds its leaves as soon as they emerge from the soil and receive sunlight, remaining under the plastic film without piercing it (Chase *et al*. 1998; Webster 2005). These plants will produce viable tubers and, even with a very low density, they will be able to reinfest the field (Miles *et al*. 1996, Silveira *et al*. 2010). Opposite, when using opaque PE nutsedge leaves remain grouped in needle position growing vertically until reaching the sunlight after piercing the film and unfolding the leaves afterwards. However, as commented previously, in occasions it has been observed that if the distance between soil and mulch accounts some cm some nutsedge plants unfold their leaves previously even using dark films probably because of detecting some sunlight. Thicker PE anti-weed mesh used in gardening (45 µm) is capable to avoid nutsedge infestations to some more extent but not completely either. Opposite, biodegradable plastic films used as alternative to PE are generally weaker in controlling nutsedge (Cirujeda *et al*. 2012b). In addition, paper mulches have been tested as alternative to PE with the main advantage of generally resisting the punction of the nutsedge leaves as verified for several paper types (Cirujeda *et al*. 2012b; Marí 2013; Shogren & Hochmuth 2004). Additionally, to the benefit of controlling nutsedge, the obtained tomato yield on paper mulch was very similar to the production on PE (Cirujeda *et al.* 2012b). But these initial promising results were less constant when using light brown crepe paper (Marí *et al*. 2016). These papers were less opaque than other papers used for mulching suggesting the need of finding out the behavior of nutsedge under these materials.

Concerning the distance of the mulch respect to the soil surface, farmers generally install the materials as tight as possible to stick the material as much as possible to the soil. Loose plastic or paper mulches might have negative consequences on the crop plant stem if the material scrapes against them in windy days. It is thus not reasonable trying to modify this parameter. In addition, the mulching material thickness is difficult to modify as the minimum best working thickness is used by farmers due to economic reasons. However, tillage operations previous to crop installation might have an influence on the placement of nutsedge tubers in the soil. The hypothesis is that plants emerging from tubers placed deeper in the soil might be weaker in piercing PE and biodegradable plastic mulches. The minimum depth from which plants are able to emerge in spring is probably determined by the low temperatures in winter in the soil and depends thus of each area. In sub humid areas in Mauritius 60% of the tuber sproutings are found in the first 7.5 cm soil (Rochecouste 1956, Marí 2013) but in the continental climate of the study area few tubers are found in the first cm of soil after cold winters with low temperatures previous to soil tillage (C. Zaragoza, pers. comm.). Even though it has been shown that 75% of purple nutsedge tubers are found in the first 15 cm depth (Bell *et al.* 1962; Marí 2013) they are able to deepen up to 60 cm depth. The objectives of the following work are i) to test the effect of translucency of mulching materials on purple nutsedge leaf biomass and on reproductive parameters and ii) to find out if purple nutsedge tuber burial depth affect the capacity of piercing PE and biodegradable plastic films.

Materials and Methods

Translucency trials. Trials were carried out on the experimental farm belonging to the Centro de Investigación y Tecnología Agroalimentaria de Aragón (41.43° N, 0.48° W) at Montañana (Zaragoza, Spain) during the months of May to November in years 2014 and 2015. Purple nutsedge tubers were placed in 19-liter plastic pots buried in the soil up to the edge to modify soil temperatures as little as possible. 29.5 cm diameter and 28 cm height of the pots were considered to be sufficient to allow free tuber reproduction but confined conditions avoided a possible mix of tubers from nearby treatments and facilitated the extraction of the final tubers at the end of the trial. Seven tubers were placed in each pot at 8 cm depth, considered optimum sprouting depth (Marí, 2013). Tubers were extracted from a vegetable field with very high nutsedge infestation two days before trial installation and were classified in weight categories of small (0.5-1 g/tuber), middle (1-1.5 g/tuber) and big (1.5-2 g/tuber). After dividing the tubers among the 40 pots, each pot accounted 4 small tubers, 2 medium-sized tubers and 1 big tuber. Pots were filled with tuber-free clay loam soil from a nearby alfalfa plot with no history of nutsedge infestation, tubers distributed and covered with soil. Plastic mulch films and papers were placed on the pots and hold tight with rope. Unmulched pots were included as control treatment and were weeded periodically leaving only purple nutsedge. Pots were randomly distributed in a single row accounting four replicates of 10 treatments. The drip irrigation line was installed in the pots and, to guarantee sufficient irrigation in each pot, treatments were classified in three groups, i.e. bare soil, papers and plastics as different evapotranspiration is expected for each group (Vázquez *et al*. 2011).

To describe the translucency of the mulching materials four samples of photosynthetic active radiation (PAR) were taken for each material with a linear ceptometer (AccuPAR, Decagon, USA) infour individual 1m^2 intact material pieces discarding the first 10 meters of each roll. Light was measured in horizontal position at 12:00 noon on a cloudless day during May 2014 and 2015 and at the same height above soil for all materials. Four measures of the radiation without any material were also taken at the beginning of the measures (in μmol m^{-2}s^{-1}. Surprisingly, especially in the experimental biodegradable plastic Sphere® 6 translucency varied considerably from one year to the other (Table 3.1), possibly due to the need of manufacturing quite a lot of meters to obtain stable physical properties which might not have been guaranteed in these experimental cases. This fact might partly explain the variability in degradation and weed control in field conditions (data not shown). During the trial number of nutsedge mulch piercings in each pot was accounted periodically. At the end of the trial 155 days after sowing (DAS) nutsedge biomass was cut and separated into two fractions: biomass above the mulches and biomass emerged from the soil remaining under the mulches. When available, biomass from other weed species was also collected separately. Additionally, nutsedge tubers were extracted for each pot individually, cleaned from roots and rhizomes and dry biomass determined after drying at 60ºC the necessary days until constant weight (PSelecta Digitheat). Net reproduction rate was calculated following Neeser *et al*. (1997) considering the ration between the total number of tubers at the end of the trial compared to the initial tuber population. Percentage of healthy and dead tubers at the end respect to the total tuber production was calculated, too. Soft tubers, tubers with clear fungi mycelium on the surface and empty tubers were considered dead; turgid tubers without the previous characteristics were considered healthy. Proportion between dead and healthy tubers was calculated.

Tuber sprouting trials testing different depths. These trials were conducted under controlled conditions in a growth chamber constructed and owned by the Centro de Investigación y Tecnología Agroalimentaria de Aragón during the months of January up to May 2014. The applied photoperiod was 12 hours light / 12 hours darkness at 23 / 20ºC being 23ºC the highest possible temperature with that growing chamber and 20ºC considered the temperature they begin to sprout (Stoller & Sweet 1987). 1.5 l pots were used and measured 22 cm height x 14 cm side x 9.5 cm base. The substrate used to fill the pots was a mixture of 75% clay-loam local tuber-free soil with 25% turf and two middle-size (1-1.5 g/tuber) tubers were buried in each pot at the adequate depth. Tested depths were 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 cm depth and mulches were black PE, black biodegradable plastic Mater-Bi® and black biodegradable paper Mimgreen® (Table 3.1). Mulches were tied with a rubber band. Three replicates were randomly distributed in the growth chamber and the light distribution was an average 62 mmol (Phillips 36 V and 58 V). Irrigation was done manually applying the water indirectly in dishes placed under the plots to avoid having to lift the mulches. The same experiment was carried out three times; tubers were extracted each time from the soil immediately prior to trial establishment i.e. 31th January, 28th February and 8th April 2014, respectively. For each of the extraction dates day-degrees (DDG) were calculated since the 1st October (considered the moment when the aerial part of nutsedge starts drying out and the tubers start their sprouting break) until extraction date. DDG were calculated following Prentice *et al.* (1992) using temperature of each hour obtaining thus a much more precise calculation compared of using daily maximum and minimum values:

$$\text{DDG}= \int (T - Tb)dt$$

Where ‘T’ is the daily temperature each hour, ‘Tb’ is the base temperature for purple nutsedge, established at 12ºC by Lima *et al*. (2015). Due to non-available soil temperatures air the data was obtained from the nearest official meteorological station at Montañana (Zaragoza) Oficina del Regante (Oficina del Regante, 2017) (Figure 3.1). DGG calculation allowed establishing a lineal relationship between the temperature and plant development (Gadioli *et al*. 2000). The number of nutsedge pierces was periodically recorded. After seven days without new nutsedge pierces at any depth the trials were finished what occurred after 32, 32 and 34 days for the three trials, respectively. This period was considered to be enough as, following Ueki (1969), 90% of nutsedge tubers sprout the first 10 to 14 days after sowing the tubers. Furthermore, the critical period of competence in vegetables occurs mainly in the first month after crop establishment. Dry biomass data was obtained for three fractions aboveground, intermediate under the mulching materials and underground and determined the same way than in the translucency experiments.

Statistical analysis. Data was analyzed using the statistical package SAS (Statistical Analysis System V.9.4. SAS Institute, Cary, NC, USA). Data normality and homoscedasticity of variances were verified previous to analysis and Box-Cox recommendations were taken into account to transform data. ANOVAs were performed and when significant differences were detected with $p<0.05$, Student-Newman-Keuls test (SNK) were conducted for mean separation. Relationship between PAR of each mulching material and mean tuber production were adjusted with a linear regression. Net reproduction rate, percentage of dead and healthy tubers and dry biomass of nutsedge and of other weed species could not be transformed satisfactorily and were analyzed using the non-parametric Kruskal-Wallis test (McDonald 2014).

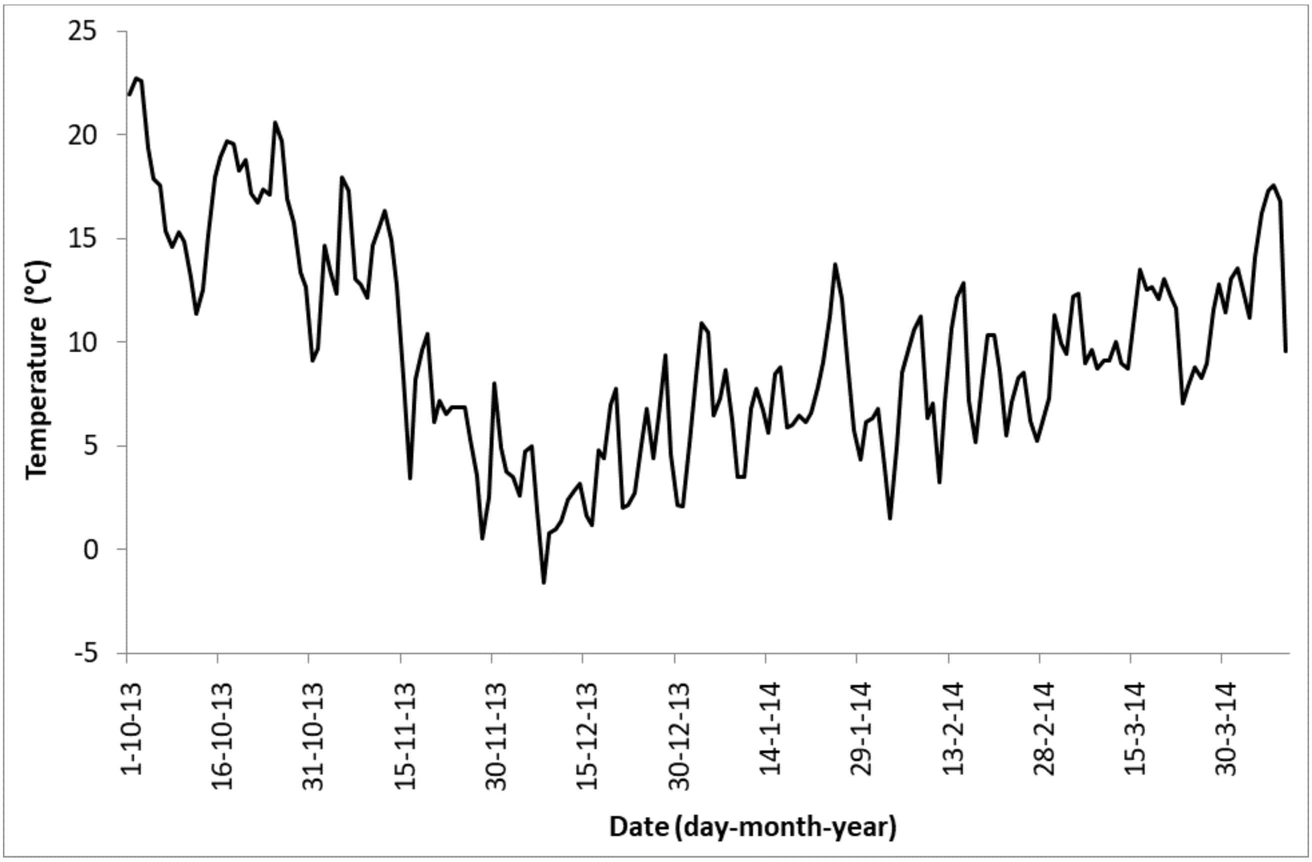

Figure 3.1. Daily mean temperature from October 1, 2013 until April 8th 2014 in the climatic station number 34 of Montañana (Zaragoza, Spain). (Oficina del Regante, Government of Aragon, Spain.).

Table 3.1. Treatment name, type of mulch, thickness for plastics (µ) or weight for papers (g/m2), source of the material ± standard error measured under the mulch for the translucency trials conducted in 2014 and 2015. PAR values (µmol m-2s-1) are the mean of 4 measures.

Treatment	Mulch Type	Color	Thickness/ Grammage	Source
			µm/g m^{-2}	
PE	Non-degradable plastic	Black	15	Petroleum
Mater-Bi®	Biodegradable plastic	Black	15	Polycaprolactone, starch blend
Sphere® 6	Biodegradable plastic	Black	15	Potato starch, recycled polymers
Bioflex®	Biodegradable plastic	Black	15	Polylactic acid, co-polyester
Mimgreen®	Paper	Black	85	Wood celulose
Arrosi® 240	Paper	Light Brown	80	Wood celulose
Arrosi® 69_14	Paper	Light brown	80	Wood celulose
Arrosi® 130	Paper	Light brown	100	Wood celulose
Arrosi® 70/90	Paper	Light Brown	90	Wood celulose
Stora-Enso® 1	Paper	Black	105	Wood celulose
Unmulched control	-	-	-	-

Results and Discussion

Translucency trials.

Nutsedge punctures and aerial dry biomass. Results of the non-parametric Kruskal-Wallis test for the number of punctures, dry nutsedge biomass and net reproduction rate were different for each year, excepting for dry biomass of other weed species, so data is presented for each year separately (Table 3.2). Opposite to the expected results and different to the biodegradable plastics, PE was poorly pierced in both years despite it is generally known that nutsedge perforates PE films in field conditions (Webster 2005; Cirujeda *et al.*, 2012a; Marí 2013). The number of punctures recorded in 2014 for the three tested biodegradable materials was consistent with the data found in literature reaching more than 300 punctures per m^2 for Bioflex®. Opposite, in 2015 less punctures occurred globally probably due to the fact that materials lost the initial strain very fast and despite theywere tight again manually they received less punctures. Moreover, in 2015 the top first cm of the pots were not filled with soil to improve irrigation which probably favored nutsedge leaves to unfold before piercing the mulch layers as found by Chase (1998) and Webster (2005). Both years no nutsedge was capable to cross any of the papers tested as found in other work (Cirujeda *et al*. 2012b; Marí 2013; Shogren & Hochmuth 2004).

In year 2014 treatments were statistically classified into three groups depending on the nutsedge aerial dry biomass: highest data for the biodegradable plastics and the uncovered control with around 30 g m^{-2}; a second group including the brown Arrosi® papers harbored intermediate nutsedge biomass which grew under the films during most of the time but in occasions lifted the paper growing freely some weeks; finally, papers Mimgreen® and Stora-Enso® 1 (unexpectedly together with PE) formed the group with lowest aerial nutsedge biomass, which was close to zero (Table 3.2). In these three materials dry brown nutsedge leaves were found under the mulching materials demonstrating that the tubers sprouted but died due to lack of light, confirming findings of Webster (2005) under similar conditions. Results in 2015 were different for the biodegradable plastics which were less pierced due to the mentioned reasons and the few plants piercing the plastics generated even non-measurable dry biomass in some cases (Table 3.2). Nutsedge biomass in the paper mulched pots was similar to 2014 and also to the findings in field conditions (Cirujeda *et al.* 2012b; Marí 2013).

Other spontaneous-emerging weed species were found in all cases excepting for the opaque paper Stora-Enso® 1 both years and in similar proportions both years (Table 3.2). The translucent Arrosi® papers and the biodegradable plastic Sphere® 6 were those materials favoring most the emergence and growth of other weeds but they were not able to pierce them. Main species belonged to the family of grasses, dominating *Setaria* spp. and *Echinochloa colona*.

Net nutsedge reproductive rate. The interaction year x treatment was again significant so that results are exposed by years. Nutsedge tubers were generated in all treatments without any exception (Table 3.2) being the non-mulched treatment the one with highest reproduction rate both years: 33 and 17.9 which corresponds to 3,397 and 1,845 tubers m^{-2}, respectively. Within the mulched treatments, most tubers were generated under Sphere® 6, reaching up to 2,65 tubers m^{-2}. Quite high reproduction rate values were also recorded for the translucent papers, especially for paper A69_14 in 2014. Fortunately, in some treatments reproduction rate was inferior to one, which means that those mulching treatments not only impeded nutsedge emergence but also reduced the amount of viable tubers in the soil. Unluckily all brown papers showed net reproductive rates superior to one, being the lowest values those obtained for A130 reaching 1.9 and 2.9 in 2014 and 2015, respectively. However, this rate would be enough to allow that the tubers remained viable in the soil increasing their density and producing yield losses (Horowitz, 1972). Results from both years show that from the reproductive point of view it is thus still more convenient in terms of nutsedge control to use a translucent paper than a biodegradables plastic that will probably be pierced by the nutsedge despite using opaque papers is confirmed to be the best method to avoid both nutsedge emergence and reproduction rate.

Healthy and dead nutsedge tubers. In both years, treatments showing more than 40% dead tubers were PE and papers Mimgreen® and Stora-Enso® 1; additionally, Mater-Bi® and Bioflex® had also high proportion of dead tubers in 2015 (Figure 3.2). These results are coherent with the previously explained piercing and nutsedge biomass data as these mulching materials were hardly pierced by nutsedge (Table 3.2).

Table 3.2. Mean number of photosynthetic active radiation (PAR), punctures per m^{-2} (mean ± standard error), mean dry biomass (g m^{-2}) of *C. rotundus* 155 days after seeding, mean dry biomass (g m^{-2}) of other weed species, when present, and net reproduction rate calculated as the quotient between number of tubers at the end of the trial divided between the initial tuber number for each treatments of the translucency trials. Different upper-letters in each column for dry nutsedge biomass and for net reproductive rate represent significant differences for $p<0.05$ with the non-parametric Kruskal-Wallis test and according to the SNK test for the aboveground biomass of other weeds.

Treatment	PAR		Punctures		Dry nutsedge biomass		Dry biomass of other	Net reproduction rate	
	2014	2015	2014	2015	2014	2015	2014-2015	2014	2015
	µmol $m^{-2}s^{-1}$		number m^{-2}		g m^{-2}				
PE	0.0 ± 0.00	0.0 ± 0.00	0 ± 0.0	4 ± 3.7	0.0 e	0.0 E	0.5 c	0.5 e	0.4 DE
Mater-Bi®	1.0 ± 0.43	3.8 ± 0.72	191 ± 26.2	7 ± 4.2	30.3 a	0.0 E	0.0 c	19.8 bc	0.5 DE
Sphere® 6	5.7 ± 1.09	123.5 ± 5.61	287 ± 43.5	11 ± 7.03	33.1 a	13.7	0.3 c	25.7 ab	13.6 AB
Bioflex®	23.7 ± 1.16	16.2 ± 0.75	320 ± 34.7	7 ± 4.2	30.1 a	0.0 E	1.6 bc	14.0 c	0.4 DE
Mimgreen®	0.5 ± 0.24	6.0 ± 0.31	0 ± 0.0	0 ± 0.0	0.6 d	0.1 E	0.2 c	0.5 ef	0.6 D
Arrosi® 240	76.5 ± 5.20	103.7 ± 1.78	0 ± 0.0	0 ± 0.0	10.7 b	14.2 A	0.8 c	5.9 d	5.8 B
Arrosi® 69_14	169.2 ± 3.99	186.8 ± 6.43	0 ± 0.0	0 ± 0.0	13.3 b	9.2 ABCD	3.4 a	8.0 d	5.4 BC
Arrosi® 130	33.8 ± 1.31	33.0 ± 0.99	0 ± 0.0	0 ± 0.0	3.5 c	7.7 ABCD	1.4 bc	1.9 e	2.9 C
Arrosi® 70/90	112.7 ± 0.94	109.8 ± 3.07	0 ± 0.0	0 ± 0.0	12.4 b	5.7 D	0.6 c	7.5 d	4.7 BC
Stora-Enso1 ®	13.7 ± 1.33	16.8 ± 0.43	0 ± 0.0	0 ± 0.0	0.8 d	0.0 E	0.0 c	0.5 ef	0.2 E
Unmulched control	1,357.7 ± 1.80	1,563.4 ± 0.9	-	-	33.5 a	13.1	1.4 bc	33.0 a	17.9 A

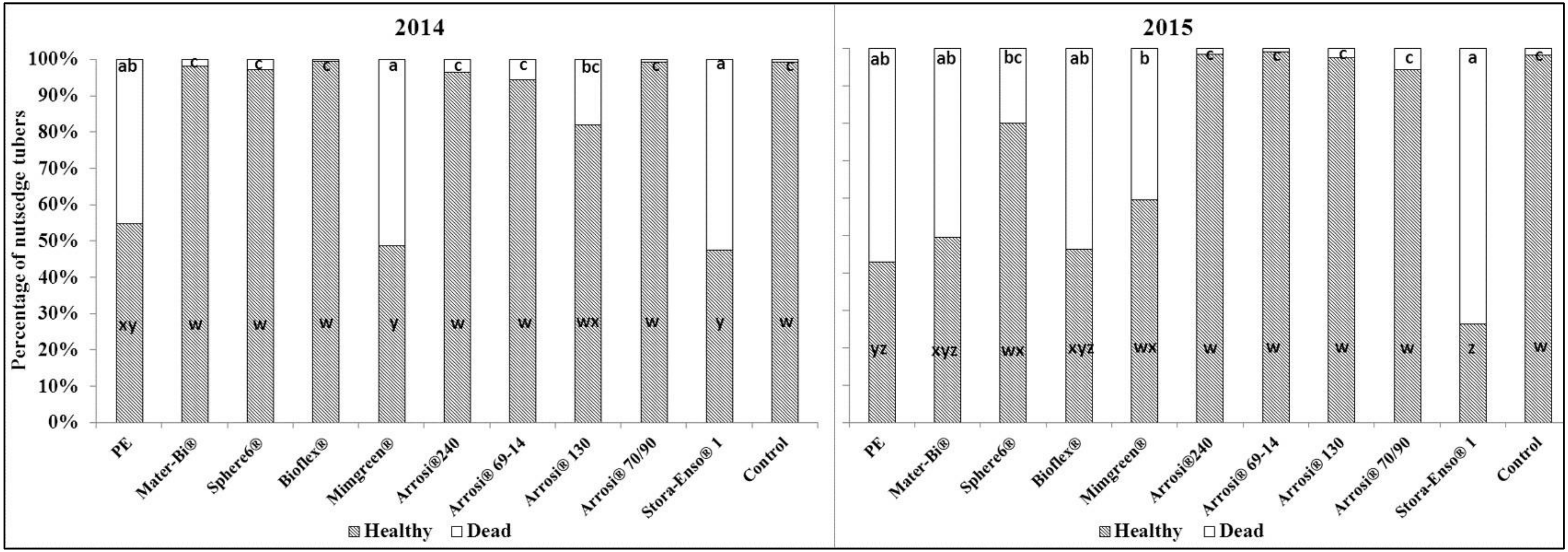

Figure 3.2. Mean percentage of healthy and dead nutsedge tubers produced at the end of the cycle under different mulching materials in years 2014 and 2015 in the translucency trials. Mean values in each column followed by different lower-case letters represent statistical differences at $p<0.05$ according to the non-parametric Kruskal-Wallis test.

Opposite, a high proportion of healthy tubers were found in the highly-pierced treatments as Mater-Bi®, Sphere® 6, Bioflex® in 2014 and in the translucent papers, which allowed nutsedge to grow and to develop under the papers. The effect on the proportion of healthy and dead tubers was thus related to the amount of generated nutsedge biomass (Figure 3.3).

The linear regression between the PAR passing through the mulching materials and the production of tubers allows a slope highly-significant different from zero ($p<0.0001$), and model fits reasonably ($R^2=0.79$) both years 2014 and 2015 (Figure 3.4). This confirms the results of Lazo & Ascencio (2010) who found that sunlight has a positive effect on nutsedge tuber sprout number, dry tuber biomass production and dry root biomass. Also Bielinski *et al*. (1997) demonstrated a linear response to shading level of shoot and tuber dry biomass.

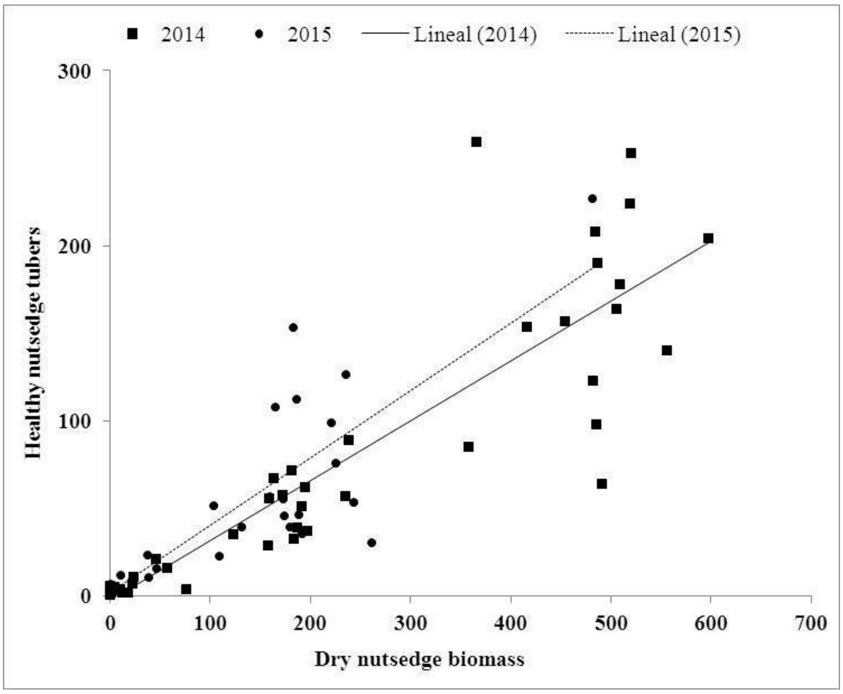

Figure 3.3. Linear regression between the mean of healthy tubers per m^{-2} at the end of the translucency trial and the total dry nutsedge biomass per m^{-2} in years 2014 and 2015. Equation for year 2014: healthy nutsedge tubers = 2.32 dry nutsedge biomass + 51.92, $R^2= 0.79$, $p<0.0001$; year 2015: healthy nutsedge tubers = 1.97 dry nutsedge biomass + 17.15, R^2 0.79, $p<0.0001$.

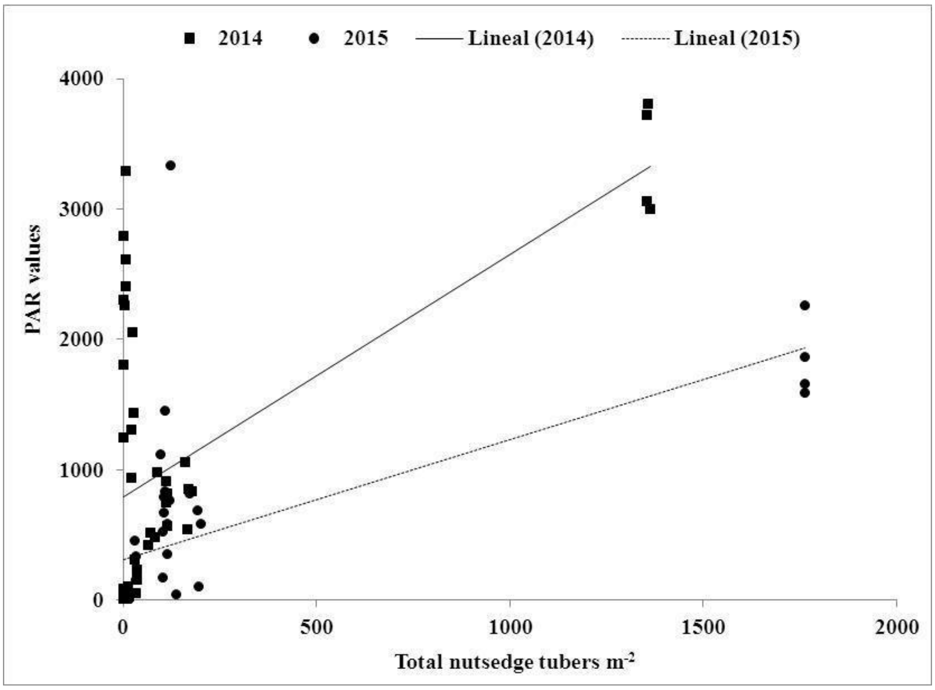

Figure 3.4. Linear regression between the total number of nutsedge tubers generated per m^{-2} at the end of the translucency trials and the amount of photosynthetic available radiation (PAR) radiation passing through the materials in years 2014 and 2015. Equation for year 2014: tubers m^{-2} = 792 + 1.86 PAR; R^2= 0,39, p<0.0001; year 2015: tubers m^{-2} = 309 + 0.92 PAR; R^2= 0,41, p<0.0001.

Despite the high significance in the present trials, the PAR explained only 39 and 41% of the model for years 2014 and 2015, respectively (Figure 3.4). Other factors contributing in this situation and that are not taken into account in the regression are the fact that some materials broke during the trial and that the amount of PAR passing the mulching materials varied thus in time, especially for the biodegradable plastics. Among others, these factors probably contribute in the final tuber production. In this sense, Sphere® 6 and the brown Arrosi® papers showed a high reproduction rate despite being those which initially allowed least PAR to arrive at the soil surface (Table 3.2.). This is most probably due to the tears produced by the nutsedges that completely changed the proportion of light arriving to the soil.

Tuber sprouting from different depths.

Tuber sprouts. As the number of tuber sprouts as well as the total dry biomass under the mulching material did not depend from the mulching material used or from the planting depth, data is not presented, confirming the results of Roozkhosh *et al*. (2017) who demonstrated that 30 cm depth are necessary to reduce sprouting to 50% after 60 days of trials. However, the repetition of the trial had a significant effect increasing the number of sprouts and total dry biomass significantly from the first to the third trial (Table 3.3). A possible explanation of the effect of trials repetition on the measured parameters could be that tubers were extracted from the soil at different moments and could be thus more or less dormant. No significant differences were found for the regression of DDG and number of tuber sprouting ($p>0.05$) which accounted 5267.3, 5608.9 and 7341.9 hours for trials 1, 2 and 3, respectively. The practical implementation of the fact that no differences in sprouting were found between 1 and 10 cm depth is that tubers should be buried deeper e.g. after harvesting a summer crop to place the remaining or newly-generated tubers in a non-favorable position. These results are in consonance with the findings of Kawabata & Nishimoto (2003) who reported that during the first month the nutsedge sprouts are probably only influenced by the initial biomass of the tubers, which all weighed similarly in the present trial. Mean tuber sprouts in the trial were 1.28 sprouts tuber $^{-1}$ which are similar to the data obtained by Muzik & Cruzado (1953). Opposite, in other trials 12 sprouts emerged from a single tuber in the first 35 days on bare soil after irrigation (Hershenhorn *et al*. 2015).

Nutsedge punctures. First piercings were recorded 8, 10 and 13 days after trial installation of trials 1-3, respectively. Despite PE with tubers placed at 1 cm depth was the first treatment to be pierced, rapidly tubers placed in the first 1, 2 and 3 cm covered with the biodegradable plastic Mater-Bi® emerged, too. Globally, there were 1.8, 2.5 and 3.2 times more nutsedge punctures of biodegradable plastic than of PE in the three trials, respectively, confirming the results obtained by Hershenhorn *et al*. (2015) and Cirujeda *et al*. (2012b). Despite the trials lasted only little more than 30 days, 38% of the total pots covered with PE were pierced, while 60% of those covered by Mater-Bi® displayed some piercings. Thus, increasing degradation of biodegradable plastic mulches might not be the only cause of increased nutsedge punction compared to PE as Mater-Bi® is pierced since the very beginning.

Dry biomass. Globally, only trial number gave significant differences in tuber sprout number and total dry biomass (Table 3.3). Sprout number increased from trial 1 to 3 while total dry biomass showed the opposite response ($p<0.05$).

Table 3.3. Mean number of nutsedge sprouts and total dry biomass generated at the end of the experiments in the depth trials determining the effect of depth on nutsedge. Mean values in each column followed by different lower-case letters represent statistical differences at $p<0.05$ according to the SNK test.

Trial number	Nutsedge sprouts	Total dry nutsedge biomass
	Mean number	g
1	1,61 c	1,4 y
2	2,07 b	1,01 yz
3	2,56 a	0,78 z

However, when analyzing each mulching material separately the non-parametric Kruskal- Wallis test showed for PE that biomass production in trial 1 was much higher than for trials 2 and 3 ($p<0.05$) so that that trial was analyzed separately (Table 3.4).

Table 3.4. Mean dry nutsedge biomass generated at the end of the experiments in the trials determining the effect of depth on nutsedge. Mean values in each column followed by different lower-case letters represent statistical differences at $p<0.05$ according to the non-parametric Kruskal-Wallis test. PE trials were analyzed separately due to significant differences in trial number.

Material	Trial number	Position	Dry biomass
			g
PE	1	Above mulching	0,40a
		Intermediate	0,45b
		Underground	1,57c
PE	2,3	Above mulching	0,07g
		Intermediate	0,14h
		Underground	0,70i
Mater-Bi®	1, 2, 3	Above mulching	0,07l
		Intermediate	0,29m
		Underground	1,03n
Mimgreen®	1, 2, 3	Above mulching	0x
		Intermediate	0,09y
		Underground	0,77z

For all mulching materials, underground biomass was higher than biomass generated between the soil and the mulching layer and the fraction emerging across the mulch film had the lowest biomass (Table 3.4).

The results analyzing the different fractions separately showed that the only important differences in total dry biomass were found in the aboveground fraction consistently in all three trials. In that fraction, significantly, more biomass was found for Mater-Bi®, followed by PE and no biomass was able to grow above Mimgreen® (Table 3.5).

Despite the thorough extraction of the tubers from the soil and the careful selection of the tubers used in the experiments, some did not show any activity because vegetative propagules also present dormancy (Nesser 1997; Nishimoto 2001). Trials need thus to be repeated many times to obtain homogeneous responses. Moreover, the top first cm of the pots were not filled with soil to guarantee correct irrigation and that had probably favoured nutsedge leaves to unfold before piercing the mulch layers as found by Chase (1998) and Webster (2005). As the same difficulty happens in field conditions, effective control methods should be applied during several years to assure weed control.

Table 3.5. Mean dry nutsedge biomass generated at the end of the experiments in the trials determining the effect of depth on nutsedge separated by position. Mean values in each column followed by different lower-case letters represent statistical differences at $p<0.05$ according to the non-parametric Kruskal-Wallis test. PE trials were analyzed separately due to significant differences in trial number.

Position	Trial number	Material	Dry biomass
			g
Above mulching	1, 2, 3	PE	0.078 b
		Mater-Bi®	0.12 a
		Mimgreen®	0 c
Intermediate	1	PE	0.068 a
		Mater-Bi®	0.056 a
		Mimgreen®	0.067 a
	2	PE	0.09 a
		Mater-Bi®	0.10 a
		Mimgreen®	0.05 b
	3	PE	0.16 a
		Mater-Bi®	0.11 a
		Mimgreen®	0.17 a
Underground	1	PE	0.59 a
		Mater-Bi®	0.65 a
		Mimgreen®	0.76 a
	2	PE	0.87 b
		Mater-Bi®	0.77 b
		Mimgreen®	0.98 a
	3	PE	0.55 a
		Mater-Bi®	0.58 a
		Mimgreen®	0.56 a

Conclusions

Concluding, the degree of translucency of the mulching materials affect nutsedge biomass production, because when a high amount of PAR crosses the material, nutsedge grows and develops under the mulch films even as well as in the unmulched control growing without any other weeds. Moreover, in the most translucent materials which are not pierced by the plants enough tubers are generated to assure the infestation of the field after removing the mulching material. In the present trials a higher DDG accumulation in the tubers was not responsible for higher tuber sprouting which depended from other factors as e.g. the nutrient supply of the tubers in that moment. The tubers placed in the first 10 cm of soil depth behaved similarly in their capacity of piercing mulching films, and in the number of sprouts 30 days after installing the trial. Biodegradable plastic was more intensively pierced than PE and paper mulch was not pierced at all. The amount of biomass generated by nutsedge in that period was not affected by the type of mulch or by the tuber planting depth. In most crops, it is important to assure little weed competition the first period after crop installation, thus the use of paper mulch could be recommended in high-infested nutsedge fields. In the second trial, lasting only 30 days, the leaf biomass under the mulch was still green but in the first trials, lasting 155 days, that biomass was dead and brown-colored. The results of the present trials show that nutsedge produces very similar amount of biomass even under opaque materials but mainly destined to underground biomass assuring new tubers. In future trials it should be confirmed if these freshly-produced tubers under opaque mulches are viable after remaining under opaque conditions in the soil during the complete cropping cycle of a horticultural crop.

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CHAPTER 4. Economic and environmental evaluation of biodegradable plastic films and paper mulches used in open-air grown pepper (*Capsicum annuum* L.) crop

Economic and environmental evaluation of biodegradable plastic films and paper mulches used in open-air grown pepper (*Capsicum annum* L.) crop

Abstract

Black polyethylene (PE) is the most common mulching material used in horticultural crops but its use represents a very serious environmental problem. At the end of the crop cycle, part of the plastic breaks into small pieces and most of waste is not properly managed. Biodegradable films and paper mulches are available alternatives but farmers are reluctant to introduce them because of their high market prices. However, these alternative materials have proven to lead to similar crop yields as when using PE films and have the advantage of saving costs in waste treatment. 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 experimental trial located in Aragon region (Spain) with semi-arid climate conditions in pepper crop with 9 different biodegradable plastics, papers and PE. Different scenarios of PE waste management are examined including the absence of residue management, the landfill and the recycling scenarios; in the case of biodegradable plastic public payments provided for the local government are included.

Although there were no statistically differences in yield, almost all pepper plants grown on the different mulching treatments tended to produce more yield than PE and six of eight materials presented higher net margins. The inclusion of the costs of waste management and recycling under the current Spanish legislation only reduced the final net margin by 0.2%. This is supporting the mandatory measures for the farmers to assume the costs of waste management and recycling. 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 slowing down their massive adoption in fields. The results show that an increase in subsidy rates of up to 41.7% on the market price would allow all biodegradable films to be alternatives than PE from the economic point of view.

Introduction

Mulching materials have demonstrated many advantages by controlling weeds (Cirujeda *et al.* 2012a, 2012b), increasing soil temperature (Zhang *et al*. 2013) and moisture (Abdul Kader *et al.* 2017)and reducing soil degradation (Zhang *et al*. 2013).These features finally influence in increasing crop yields (Miles *et al.* 2012). Mulches may also protect crops from insect pests or diseases as it is reported by Summers & Stapleton (2002). In general, literature recognize that all these effects have positive outcomes on economic profitability because of water savings (up to 25%) and reduced labour costs for weed and pest control (Ingman *et al.,* 2015; Jabran *et al.,* 2015).

Despite all these reported advantages, two major problems threaten such savings at a short and long-term. First, mulch application, but specially removal and disposal are labour and cost-intensive (Ghimire & Miles 2016; Shogren & Hochmuth 2004), and second, most commonly used mulching materials (PE and other fuel-based films) involve environmental risks in the long-term because their chemical structure is difficult to degrade (Immirzi *et al.* 2009). Among the negative environmental effect, Steinmetz *et al.* (2016) include the persistence of unrecovered plastic mulch in soil, their potential to alter soil quality by shifting the edaphic biocoenosis, accelerating carbon and nitrogen metabolism, as well as potentially degrading soil organic matter. Other pervasive effects of plastic mulching in the long-term, following the same authors, include inducing soil water repellence, increasing the risk of mycotoxins formation in soil and an enhanced release of climate relevant gases. The presence of plastic residues in the soil can cause significant losses in production. For example, Zou *et al.* (2017) reported that plant growth and yield of tomato crop were affected significantly when residual plastic mulch in soils attains 160 kg ha^{-1}. The most frequently used base materials in agriculture are manufactured mainly from petrol- based sheets like PE (Díaz-Pérez 2010), 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 (PlasticsEurope 2017). The main tool to control weeds in vegetable crops is LD-PE films because it is a very cheap and easy-to-use material (Lamont 2005). 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 Spain for example, 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 (MAPAMA, 2015) and these practices are also common in other countries (Liu *et al*. 2014; Scarascia- Mugnozza *et al*. 2011).

For example, Liu *et al.* (2014) reported that the amount of waste in a common Chinese vegetable farming field could reach between 50 and 260 kg ha^{-1}. In this context, biodegradable variants of mulching are a promising alternative in vegetable production. These mulching supplies include paper (cellulosic fibre), polylactic acid, polyester and corn, sugar cane or potato starch (Gross & Kalra, 2002). The use of such mulches adds to the above-mentioned benefits and additionally it reduces disposal costs for farmers while preventing environmental problems in the long-term.

Biodegradable films and paper mulches have been studied previously and it has been demonstrated in several field trials that productions are statistically the same than obtained with PE (Brault & Stewart 2002; Cirujeda *et al.* 2012a; Lahoz *et al*. 2014; Martín-Closas *et al*. 2008; Miles *et al*. 2012; Moreno *et al*. 2016). However, market prices of these materials are higher of 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 bio-based 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 (Steinmetz *et al.* 2016).

The aim of this paper is to contribute with new data to this literature by comparing the economic and environmental outcomes of PE and eight different mulching materials available for open-air pepper production. The economic evaluation is based on a four-year experimental trial located in Aragon region (Spain) with semi-arid climate conditions. Spain is currently the fifth country of the world with the highest production of pepper, and the first producer country in Europe (FAOSTAT, 2016) with more than 1.1 million annual tonnes and one of the highest average productivity in the world (6.11 kg m^{-2}). Fresh pepper is the main greenhouse vegetable cultivated in Spain although the open-air cultivation is also widespread in many regions of the country.

In order to promote the use of biodegradable materials, some regional authorities in Spain, like the Aragon government, have recently implemented some 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 in the fields. The analysis contributes to the literature by providing elements for debate on the short- and long-term effects of the use of different mulching materials.

Material and Methods

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. 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 measured 20 m longitude. Four biodegradable plastic mulches and four paper mulches were tested and black polyethylene (PE) plastic mulch was added as a control (Table 4.1). All materials measured 1.2 m wide and were mechanically installed within five days after soil preparation prior to weed emergence. The materials were selected because they are available on the market, while others are still in experimental phase or have been recently commercialized. 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 mulches and plastic mulches, which were irrigated separately according to their water needs (Vázquez *et al.* 2011). The irrigation moment was calculated with the soil moisture sensors (Aquameter ECH2O, Decagon or Divener, Sentek). The pepper variety used was 'Viriato' type Lamuyo. Pepper was manually 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.

Each year yield, inputs, and operational costs data were collected from the trials in order to analyze the economic outcomes of each mulching material. The analysis of yield data (t ha^{-1}) was performed using SAS (Statistical Analysis System V.9.4. SAS Institute, Cary, NC, USA). Homogeneity of variance and normality was determined before data analysis and the data was subjected to analysis of variance (ANOVA). When factors were significantly different, multiple mean comparisons were performed using the Student-Newman-Keuls test at $p<0.05$.

Table 4.1. Type, name, manufacturer, main composition, thickness (μm) (plastic films) or grammage (g m^{-2}) (paper mulches) and color of mulching materials used in the open-air trials.

Type of mulching	Mulching materials	Manufacturers	Main composition	Thickness - Grammage	Color
				μm - g m^{-2}	
Non-degradable plastic film	**PE**	Several manufacturers	Low-density polyethylene	15	Black
Biodegradable plastic films	**Mater-Bi®**	Novamont S.p.A. Novara, Italy	Polycaprolactone, starch blend	15	Black
	Sphere®	Sphere Spain. Zaragoza, Spain	Potato starch, recycled polymers	15	Black
	Bioflex®	FKuR Kunststoff GmbH. Willich, Germany	Polylactic acid, co-polyester	15	Black
	Ecovio®	BASF S.E. Ludwigshafen, Germany	Polylactic acid, polybutylene adipate terephthalate, starch	15	Black
Paper mulches	**Arrosi® 69**	Fábrica de Papeles Crepados Arrosi. Gipuzkoa, Spain	Cellulosic fiber	80	Light brown
	Arrosi® G1a		Cellulosic fiber	100	Light brown
	Arrosi® 240		Cellulosic fiber	80	Light brown
	Mimgreen®	Mimcord S.A. Barcelona, Spain	Cellulosic fiber	85	Black

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

Table 4.2. 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	290
	Drip line	238
Mulches*	PE	404
	Mater-Bi®	1164
	Sphere®	772
	Bioflex®	931
	Ecovio®	505
	Mimgreen®	1086
	Arrosi® 69	1024
	Arrosi® G 1a	1358
	Arrosi® 240	1024
Total fuel consumption		200
Operations		
Subsoiler		100
Cultivator tillage		50
Rotatory tiller		200
Pre-transplanting manure application		100
Burying fertilizer		50
Installation irrigation system		200
Bed formation+drip line installation+plastic		130
Bed formation+drip line installation+paper		164
Crop installation/manual transplant		398
Chemical dressing application		14.3
Herbicide between lines		7.2
Manual weeding holes		350
Manual harvest		2340
Irrigation system removal		120
Crop removal		50
Plastic removal		176.5
Landfill**		186
Recycling**		192
Cultivator tillage		50

* For 0.7 m bed width and 1.5 separation between lines.

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

Costs. Table 4.2 shows all the inputs used and operational costs considered. Inputs costs include pepper seedlings, pre-transplanting manure, herbicides, chemical dressing, irrigation water, fuel consumption and mulching materials used in experimental 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. Labour costs are calculated using official data available in MAPAMA (2017). Amounts and type of fertilizers and doses of active matters used in chemical dressing in the trials can be consulted in Marí *et al*. (B) (unpublished data, Chapter 2 of this document).

Prices of mulching materials were obtained directly from suppliers. Biodegradable materials are between 25% and 188% more expensive than PE while paper mulches are between 153% and 236% more expensive. Among biodegradable materials, Ecovio® is the cheapest one and Arrosi® 69 and Arrosi® 240 are the cheapest paper mulches.

The costs of mechanical installation of paper mulches were calculated using data published by Cirujeda *et al.* (2012a) for the case of tomato crop adding an extra cost derived from the considered speed of the operation in the specific case of paper mulches, which need to be installed slower because they are not flexible and break easily at higher speed. Additionally, a PE roll usually contains 2400 linear meters and a paper roll approximately only 250 linear meters. The number of times that workers have to stop to change the roll in order to mulch a field of the same surface has been considered, too. 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 labour and machinery costs for soil preparation, crop installation, mulching installation and removal, application of fertilizers and herbicides, harvesting and final field conditioning.

Transplanting is a conducted manually in this area for pepper crop. The cost of this 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 personal cost of this action 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 when fruits are ripe.

Field conditioning involves manual removal of the irrigation system, crop rests removal (which is a combined mechanical and manual operation), 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.[1] However, they are not required to assume the cost of recycling hence farmers usually store their waste and transport it to an authorized recovery point. Although recycling is not mandatory for farmers in Spain, we consider the cost of plastic recycling in order to evaluate its effect on the final economic profitability. As a consequence, three different scenarios were considered in this work: 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. The consideration of the no waste treatment as a baseline scenario or benchmark 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 of the plastic waste from field to the recovery point (or the recycling plant) are included. An externalized task was considered so the cost includes plastic removal from the field with a specific rotatory machine and the transport of the residues with a tractor provided with a tow to the final destination. A distance of 30 km from the field to the recovery point or the recycling point has been considered for the calculations. For the scenario where farmers take the plastic to recycle, the cost of a local recycling plant was obtained which amount 62 € t^{-1}.[2] Usually, film mulches have impurities such as soil, debris, pesticides and 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 (Gartraud 2004). However, one local plant does not establish a limit for impurities.

Finally, cultivator tillage cost for soil preparation for the next season is included as well as the fuel consumption costs which are distributed proportionally among different operations. All these costs are included as field conditioning.

[1]Law 22/20[1]1 of Residues and Contaminated Soils (MAPAMA 2015)

[2] It is important to mention that recycling plants accepting this kind of residues are rare in the study area.

Incomes and Net margins. The calculation of incomes includes the market value for the crop yields. Although there were no statistical differences among materials (see Marí *et al.* (A) unpublished data, Chapter 2 of this document) 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}(MAPAMA 2018). Pepper is a delicate crop concerning water and humidity variations and in 2012 and 2013, technical problems in irrigation caused pepper seedlings mortality that could not be replaced. From May to October 2015, very strong winds and extremely high insolation were recorded. In that period, 71 more sunshine hours were recorded than the historical 30-year average (data not shown) interfering dramatically with the flower and fruit formation and thus, in low yield, too. 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. The “Lamuyo” pepper market price considered is 856 € t^{-1}, which is an average from the last three years from available data (MAPAMA 2017).

Additionally, farmers can obtain subsidies from the Spanish regional government (funded by the European Union) offering the possibility to receive 35% of the material costs when biodegradable mulching is used. Paper mulches do not receive any subsidy but they should perceive them included because these materials are also considered biodegradable but he lack of specific trials that support them do not allow to incorporate them. In such case, farmers must 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 (Gobierno de Aragón 2018). 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 public payments 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 yield with or without regional payments) and total costs (inputs, operations, labour, etc). Repayments for capital, taxes or insurance are not considered.

Results and Discussion

Costs. Table 4.3 shows the aggregated costs by operations calculated for fresh pepper crop in the experimental trials. The concept ‘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 ‘field conditioning’ includes irrigation system and crop removal, mulch removal and/or recycling or landfill for the non-biodegradable scenarios and, finally, a cultivator pass.

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 is attributed to crop season operations (mainly transplant and pepper seedlings costs) with 45.3% and the following is the harvest with 27% of the total costs because it is a manual task in the case of pepper crop for fresh consumption. 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 (from Table 4.3).

The analysis of field conditioning costs for PE scenarios 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 is obliged to transport the waste to the recycling point (landfill scenario) and up to 4.9% if the farmer has to take the plastic waste to recycle. By contrast, using biodegradable mulches allows a saving in field conditioning costs of a minimum of 54.7% and a maximum of 56.7% with respect to PE scenarios. These savings represents between 2% and 2.2% of the total cost.

Table 4.3. 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*	No waste management	408.5
	Landfill	418
	Recycling	424
Field conditioning biodegradable mulch scenario		232

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

Incomes. Table 4.4 shows the results obtained for yield and calculations of income including subsidies. No statistically differences are found among the mean yields under different mulching materials, PE obtained one of the lowest yields. Mater-Bi® and Arrosi®240 obtained amounts close to 30 t ha^{-1} which is similar to the average yields reported in Spain (29 t ha^{-1}).

These results indicate that all the used materials obtained similar yields to those of PE film, confirming some previous evidence such as that of Lahoz *et al*. (2014) who reported higher pepper yields with some of the biodegradable mulching materials used here compared to PE. Final incomes were calculated taking into account the subsidies available to cover the 35% of the cost of the biodegradable plastic films.

Table 4.4. Mean 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*	Subsidies	Total income
		t ha^{-1}	€	€
Non-degradable plastic film	**PE**	24.6 a	-	21549.6
Biodegradable plastic films	**Mater-Bi®**	29.2 a	407.4	25986.6
	Sphere®	25.8 a	270.2	22871.0
	Bioflex®	24.4 a	325.9	21700.3
	Ecovio®	23.3 a	176.8	20587.6
Paper mulches	**Mimgreen®**	26.7 a	-	23389.2
	Arrosi®69	25.3 a	-	22162.8
	Arrosi®G 1a	26.9 a	-	23564.4
	Arrosi®240	28.5 a	-	24966.0

*Same letters mean no statistical differences among treatments with SNK test at $p < 0.05$.

Net margins. Table 4.5 summarizes the main economic variables analyzed for the evaluated materials. Net margins are presented under the three waste management scenarios considered for PE and under the two scenarios considered for biodegradable materials (with and without subsidies). In addition, the percentage with respect to PE without waste management (benchmark scenario) is calculated in order to present a comparative analysis of different alternative materials.

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

When biodegradable materials are taken into account, the total costs are between 2.2 and 9.3% higher than for PE. The only exception is Ecovio®, which is cheaper than PE because the extra cost of the material is less than the costs of removing it. Regarding final profitability, two bio-degradable materials (Mater-Bi® and Sphere®) present higher net margins than PE (with and without subsidies) while Bioflex® and Ecovio® are the worse options, with reductions of 1.6% and 6.9% in margins with respect to the benchmark due to low yields obtained in the field trials. Mater-Bi® is the best biodegradable option, with an increase of 29.9% with respect to PE. However, given that there are no significant yield differences between materials it is important to emphasize that subsidies would be insufficient to compensate for the extra cost of the material if identical yields were obtained, with the exception of Ecovio® and Sphere®. This result is maintained even when considering the complete recycling of waste.

Therefore, the current level of subsidies (35%) does not seem to be a strong enough incentive for the majority of 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 aid 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 aid 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 result in higher net margins than the benchmark material, 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 obtained higher yields and this result changes when yield are considered the same as obtained by PE. As found for the biodegradable plastics, the over cost of paper materials are not compensated by the saving on waste management costs. In this case, the percentage of subsidies needed to make them as profitable as 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 been found to be more profitable, only two of them (Ecovio® and Sphere®) are good potential alternatives from the 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. Biodegradable plastics benefit from public aid to compensate for part of the higher market prices but the results show that the current aid system does not warrant 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, Cirujeda *et al.* (2012a) determined 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 PE, which probably comes from the low PE but the high market prices of biodegradable mulching materials. By contrast, our calculations show that biodegradable films can be better alternatives in the short-term even in the case of not waste management case. The net margins when using these biodegradable materials were even better when recycling is considered mandatory.

Table 4.5. Incomes, costs and net margin of different mulching materials (€ ha^{-1}).

Type of mulching	Mulching materials	Scenarios	Incomes	Costs	Net margin	% with respect to PE
					€ ha-1	
Non-degradable plastic film	**PE**	No waste management	21549.6	8675.3	12874.3	
		Landfill	21549.6	8684.8	12864.8	99.9
		Recycling	21549.6	8690.8	12858.8	99.9
Biodegradable plastic films	**Mater-Bi®**	No subsidies	25579.2	9258.8	16320.4	126.8
		With subsidies	**25986.6**		**16727.8**	**129.9**
	Sphere®	No subsidies	22600.8	8866.8	13734.0	106.7
		With subsidies	**22871.0**		**14004.2**	**108.8**
	Bioflex®	No subsidies	21374.4	9025.8	12348.6	95.9
		With subsidies	**21700.3**		**12674.5**	**98.4**
	Ecovio®	No subsidies	20410.8	8599.8	11811.0	91.7
		With subsidies	**20587.6**		**11987.8**	**93.1**
Paper mulches	**Mimgreen®**	No subsidies	23389.2	9214.8	14174.4	110.1
	Arrosi®69	No subsidies	22162.8	9152.8	13010.0	101.1
	Arrosi®G 1a	No subsidies	23564.4	9486.8	14077.6	109.3
	Arrosi®240	No subsidies	24966.0	9152.8	15813.2	122.8

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, Ramos *et al.* (2015) indicate that the presence of PE in horticultural soils in Argentina can represent around 10% of the soil and Zhao *et al.* (2014) affirm that the amount of plastic waste in an average vegetable field of China can 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, Zou *et al.* (2017) 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 by farmers mandatory, 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 Miles *et al*. (2017) 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% of yield decreased on the fifth year of using biodegradable films and tilling them at the end of the crop season. Unluckily, 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. Moreno *et al.* (2017) 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® the material presented the smallest fragments and surface after 200 DASI.

With regard to paper mulches, no waste management has to be implemented nor accumulation of waste in the soil is expected interfering with the crop so in principle, their effects are likely to be less harmful than plastics. However, papers are insufficiently explored until now to evaluate 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.

Conclusions

The extensive use of PE mulching materials is based on 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 the different options in the short-term. The inclusion of such costs under the current Spanish legislation only increases the costs in 9.5 €/ha with respect to no waste management scenario and 15.5 €/ha 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.

The consideration in the economic analysis of current Spanish public 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. Although 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 impeding their adoption in fields. An increase in aid 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, to consideration of effects on the quality of soil supports measures towards mandatory full recycling of waste and for the use of biodegradable and paper materials.

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General Discussion

Biodegradable mulches are gradually interest to replace polyethylene in vegetable crops. Some materials are sold in the market since several years ago and both plastic and paper are offered. However, more and more materials are developed by different companies and have to be tested because, unfortunately, the response in the field can be very variable. For that reason, it is very important to characterize these materials and compare them with LDPE in order to know which one adapts better to each particular situation and to take into account the economic aspect, which is a relevant factor for farmers.

In this study, the complete knowledge of paper mulching materials has been proposed as an important tool in controlling purple nutsedge and those materials would probably be the future for mulching technology if biodegradable plastic mulches do not fulfill with the new exigent zero-waste policies.

Physical properties of mulching materials. The grammage supplied by the manufacturer showed small differences with the laboratory results; in most cases the variation compared to the manufacturer weight was around 10% and the differences do not depend on whether the material is flexible as crepe papers or not. Paper mulches presented an average thickness of 0.3 mm, 2000% thicker than LDPE film, which measures 0.015 mm. Moreover, crepe papers are thicker than the non-flexible papers. The combination of grammage and thickness will determine the volume and weight of the roll, which is a very important factor to take into account when installing the material in the field. Rolls should weigh between 25 to 40 kg approximately to allow a practical handling and, in these conditions, a single plastic roll can mulch 2500 linear meters but in the case of paper, only 250 m. So, in this point we hypothesize that all materials with less than 100 g m^{-2} and values of thickness around 0.3 mm would fit with the most suitable options for an optimal field management, without exceeding 45 kg per roll to facilitate a one-person management.

The penetration strength (N) needed to pierce a sample was not dependent on whether the material was flexible or not. The crepe paper Walki® 2 got the highest rates in the LS (17.4 N) and Verso® paper the lowest (5.6 N), almost an opposite result to the traction test (Table 1.2). Maybe the creping process for the material limited the response of the sheet to only one direction. Deformation to penetration presented in the non-flexible materials only elongated around 1 mm in the longitudinal section (LS) while flexible papers showed a wider elongation even arriving to deform 4.2 mm in one material. Rates in the cross section (CS) were variable depending on the material and where not related to the flexibility. The practical application of these data is that materials with lower rates of deformation to penetration will break easily if a sharp stone touches them when laying the mulch in field and because of their non-flexible nature, once they break, the tear will extend until the machine does not stop as observed in the field (pers. comm.). From the point of view, the best materials were Arrosi® and Walki® papers.

In the traction test disparity of responses were found being the tensile strength on the LS needed to break the crepe papers very small (approx. 10 MPa) compared the non-flexible paper mulches, which required 86.2 MPa. Therefore, when materials with low rate of tensile strength in the LS are installed mechanically, breaks are expected easily. According to the UNE-EN 13655 (UNE-EN 13655, 2003) a minimal initial tensile stress at break of 16 MPa is required to keep the film integrity during the manipulation and mechanical installation of the material in the field, which corresponds to the rate for black LDPE. All tested crepe papers had a lower tensile strength than this rate none of them will be allowed to be commercialized. In the case of use, all of them will probably need a certain tension reduction by modifying of the laying-down machine to make mechanical installation possible.

The tensile strength of the CS was smaller than of the LS in all cases, which is a priori an inconvenient for the laying-down. These materials would present less capacity to expand if an extra pressure is applied for example from the wheels of the mulching machine. Some materials can elongate 35% of their initial sheet length which is positive (Arrosi® 130) while, on the other hand, the most non-flexible material Stora-Enso®, Verso® and Saica 140 only admit 2% of elongation. The literature shows that different coated papers had tensile strength rates between 45 to 85 MPa at the beginning of the season (Shogren 1999) which were in the same range of the non-flexible paper mulches rates. The flexible material, the crepe papers were lower than 15 MPa. Thus, the physical properties of the tested papers could be improved.

However, despite some results of the mechanical properties predict the limitation of these materials, in reality, when the mulch is installed mechanically in the field they could be mechanized (Chapter 2). In the case of LS, only an adjustment of the tension by guiding the film straight avoiding s-shaped patterns and speed reduction were sufficient to avoid breaks as also described by Vox *et al.* (2013) when testing novel biodegradable mulches. Moreover, diminishing the wheel pressure of the mulch laying machine when the sheet is buried contributed in a mechanized laying-down because these tensions affects the CS as also determined by Ghimire & Miles (2016) determined. Probably, materials with an intermediate combination of tensile strength and breakage deformation as, for example, Arrosi® 69_15 and Walki® 2, are those presenting the most successful mechanical installation. We thus consider that crepe papers have a good potential for biodegradable mulches from this point of view despite excessive they cause too thick rolls, as mentioned previously.

The tested paper materials can be separated in two different groups attending to the color of the sheet: i) the mulches with a color closer to black as PE and Mimgreen® and ii) the brownish papers. This characteristic has to be considered because, as Haapala *et al.* (2015) determined, paper mulches with dark color on the upper surface increase soil temperature more than the light-colored ones because dark color reflects and transmits less shortwave radiation. In addition, yield was higher and equally respectable comparing to biodegradable plastic film in the dark paper mulches rather than with the brown paper alone (Chapter 2).

Concerning translucency, the group of brown papers is more transparent than black papers. Compared to a non-mulched surface, from 2.5% to 12.5% of PAR is able to pass the films in the brown papers and from 0.03 % to 1 % in the black materials (Chapter 3).This aspect has been shown to be important for weed control, as explained later.

Mulches and translucency. Quezada-Martín *et al*. (2004) determined that in the beginning of the pepper cultivation, when the foliage of the plants is poorly developed, brown and black plastic mulch reflected around 8% of the total radiation incident while white mulch reflected 30%. This reduction of radiation compared to a non-mulched surface affects the growth and development of the crop. Brown plastic film raised soil temperature at the beginning of the season compared to bare ground but these differences diminished at the end of the season because of the shadow generated by the crop, as also validated by Haapala *et al*. (2015) in brown paper mulches. In the present trials one wax-coated material was evaluated and presented the highest transparency (35% PAR compared to a non-mulched soil) which will increase soil temperature and moisture as El-Nemr (2006) determined for a similar paper mulch compared to black polyethylene film. In our experiment, light-brown papers and wax- coated one have the disadvantage of allowing grass weeds to grow under them, which did not pierce the sheet but reached in the tillering stage and elongation of the stem at the end of the experiment hypothesizing a real competition would occur because these plants are consuming water and nutrients. This was also validated in the experiences of Shogren & Hochmuth (2004) and Haapala *et al*. (2015).

Cyperus rotundus ***control.*** Paper mulches, in general, effectively controlled purple nutsedge, as reported by Anzalone *et al*. (2010), Cirujeda *et al*. (2012b), and Shogren & Hochmuth (2004). In this last work, only 11 plants m^{-2} were found piercing in PE, by contrast, in our experience up to 120 plants m^{-2} emerged showing that the tested papers were able to withstand a very high nutsedge pressure. *C. rotundus* also sprouted under black paper mulches and the leaves were pressing against the mulch from below but without piercing it. At the end of the cycle crop and after the material had been removed, the leaves of this species were dry and brown-colored, confirming the findings of Shogren & Hochmuth (2004) and Webster (2005) under similar conditions. Therefore, it is reasonable to think that those nutsedge plants will not represent a real competition for the crop. This confirms the results of Lazo & Ascencio (2010) who found that sunlight has a positive effect on nutsedge tuber sprout number, dry tuber biomass production and dry root biomass. Also Bielinski *et al*. (1997) demonstrated a linear response to shading level of shoot and tuber dry biomass. The only concern was the fact the high nutsedge pressure caused tears in the separation between the paper and the soil in some paper mulches needed to be covered with soil again.

Plastic films were pierced easily by nutsedge leaves, as previously found by Cirujeda *et al.* (2012b), Marí (2013) and Webster (2005) who reported that nutsedges were capable of growing twice as much on PE as in the unweeded plot. Opposite to the expected results, in some essays (Marí *et al*. (A, B), unpublished data, Chapters 2, 3 of this document) PE was poorly pierced despite it is generally known that nutsedge perforates this film in field conditions. In the pot essays (Marí *et al*. (B) unpublished data, Chapter 3 of this document), it has already been explained that it is difficult to imitate the real field situation in a pot trial concerning the distance between the soil surface and the mulching materials; also in the meshes installed in the raised beds of the field trials a similar problem occurred as the meshes were placed in the center of the rows where the distance between the soil and the film is the highest; thus so sometimes the piercing of the plastic materials is different to imitate due to technical reasons. Biodegradable plastic films were pierced 2.5-fold by nutsedge compared to PE as also reported by Cirujeda *et al.* (2012a), Hershenhorn *et al*. (2015) and Moreno *et al*. (2017) probably due to their degradation and gradual loss of physical properties over time.

The number of tuber sprouts as well as the total dry biomass under the mulching material was found to be independent from the mulching material used or from the planting depth (Chapter 3), confirming the results of Roozkhosh *et al*. (2017) who found that 30 cm depth were necessary to reduce sprouting to 50% after 60 days of trials. These results are in consonance with the findings of Kawabata & Nishimoto (2003) who reported that during the first month the nutsedge sprouts are probably only influenced by the initial biomass of the tubers, which all weighed similarly in the present trial. Taking into account these results, it could be recommended to bury tubers deeper after harvesting a summer crop placing the remaining or newly-generated tubers in a deep non-favorable position.

Under biodegradable plastic mulch, tuber nutsedge generation ended in up to 2.6 tubers m^{-2} the initial amount of tubers. The plastic allowed nutsedge to grow and to develop across and under the film. Even if only a small amount of tubers would have been generated this would be enough to increase their density and producing yield losses (Horowitz, 1972). Fortunately, in some treatments, as black paper, reproduction rate was inferior to 1, which means that those mulching treatments not only impeded nutsedge emergence but also reduced the amount of viable tubers in the soil.

Degradation of the tested mulching materials. As expected, experimental materials showed a heterogeneous response within the years, with higher degradation values than marketed materials. Some biodegradable materials presented tears during the first month after transplant as Waterer (2010) and Zandstra *et al*. (2007) reported. The slow growth rate and the erect bearing of the pepper crop probably allowed a higher incidence of light onto the film than with other crops, thus, enhancing early film degradation. Indeed, Martín-Closas *et al*. (2016) and Moreno *et al.* (2017) indicated that the period elapsing between mulching, transplanting and maximum crop cover is the determining factor for mulch degradation, which supports the hypothesis.

In-soil degradation of paper mulches and plastic films was much faster than that of the aboveground part, probably due to the action of microorganisms. However, it was also quite variable as found in Martín-Closas *et al*. (2016) and Moreno *et al*. (2017) trials. The in-soil part of paper mulches already showed high degradation rates at 15 DAT, as Shogren (2000) also found for other papers. In the case of non-flexible Verso® paper, degradation at this time reached 80% of its surface. In paper mulches the edge between the buried part and the above-soil material generally degraded as early as 15 DAT and, on a windy day, the paper mulch can be lifted causing serious crop problems and losing their weed control effect in that area. Thus, a slight earthing-up before this occurs is highly recommended. This situation is common working with paper mulches and was observed in trials with tomato and pepper (Shogren & David 2006), lettuce and cabbage (Harrington & Bedford 2004) and strawberry (Weber 2003). The fastest biodegradable plastic film to be degraded was Sphere® 4, which reached 50% at 15 DAT in 2013 and at 45 DAT Sphere4® and Sphere6® biodegradable plastic films almost reached 60% degradation. At 30 DAT most materials remained fairly intact in the four-year experience with the exception of two paper mulches in 2013 which presented a 30% of the surface degraded and the biodegradable plastics Sphere® 4 and Sphere® 6 in 2014

At 45 DAT, degradation of some biodegradable plastic films was similar to that of paper mulches, reaching about 25%; only Bioflex® and Arrosi® 90/100 showed more than 50% of the mulch degraded at that stage in 2013. Therefore, the critical period of weed competition the soil will be covered by the mulch and avoid the reduction of competition.

Influence of the mulches on pepper yield. Despite pepper crop has a slow-rate growth and is a small canopy crop, all plastic and paper mulching treatments gave statistically similar pepper yield to that obtained on PE as found by Shogren & David (2006), Waterer (2010) and Zandstra *et al.* (2007). This reinforces the idea that these materials can be used in very variable horticultural crops such as tomato (Anzalone *et al.* 2010; Cirujeda *et al*. 2012a), lettuce (Brault & Stewart 2002) and cabbage (Coolong 2010). Concerning purple nutsedge, this species can cause up to 32% yield losses in the case of pepper

(Morales-Payan *et al.* 1997). Thus, the lack of yield differences in the present trials between highly infested plots with nutsedge and weed-free plots were probably due to other problems causing plant and fruit death such as meteorological factors and other agronomic difficulties ironing out the expected yield differences.

Economic assessment of the use of biodegradable mulches and environmental implications. As expected, mulching with PE represented a low fraction of the total pepper production costs (6.3%) what contributes in understanding the massive use of the mulching technique in some vegetable crops as processing tomato and pepper. Surprisingly, the costs for managing PE rests are very low, increasing only 0.11 or 0.18% of the total costs when the options are waste treatment or recycling. Due to this reason, it is reasonable to force farmers to manage PE waste in an appropriate way as explained in the State Plan Waste Management Framework. In practice, farmers are easily aware of the waste problem especially caused by wind when affecting neighbour farms or natural vegetation and some search for alternatives to PE on a volunteer basis. In some areas of Aragon a mid-term solution to avoid the use of PE has been including winter cereal and other vegetable crops as broccoli and onion in the crop rotation and to grow tomato or pepper without mulching anymore and using herbicide when necessary. However, in other cases, tomato or pepper remain the cash crops and in those situations, farmers are not willing to adopt this kind of agronomic solutions.

The higher prices and laying-down costs of the biodegradable mulches certainly push farmers away from choosing these materials as alternatives for PE. Also the fact that these materials have to be installed in a more careful way (slowing down speed and in some cases changing the rolls more often) suggest that solid arguments need to be given when proposing these materials as alternative. The good *C. rotundus* control by papers is a categorical reason for those areas with high nutsedge infestations (Chapter 2). In addition, the economic reasons are normally very convincing. Therefore, the finding that, at present, Mater-Bi® and Sphere® present higher net margins than PE both with or without subsidies is a very important fact. If farmers are capable to obtain higher yields with the other biodegradable materials than those obtained in the present trials, the net margins of some other of these materials could also be higher. So, all these materials should be considered by farmers also from an economic point of view and we suggest that it is worth to test them in the particular scenarios of each farmer.

Concerning the subsidies, it is important to highlight that in all cases the over costs of the tested biodegradable plastics and papers are higher than the savings on waste management costs. It would be very reasonable to compensate farmers with that real cost which would represent, following our calculations, increasing them from 35% to 50%. However, if the prohibition of using PE in agriculture arrives in a future, probably the costs of these materials would decrease with an increasing demand and the over costs would be lower.

In future work, it would be interesting to approach the problem of the environmental and economic situation of mulches by conducting a more complex measure with a live-cycle-assessment (LCA) or carbon footprint assessment. Maybe the results of these approaches would give us more arguments to impulse the use of biodegradable mulching materials in vegetable production.

Future research and considerations in this area:

1. In future trials, it should be confirmed if the freshly produced tubers under opaque mulches, which are sometimes very small, are viable. In addition, it should be determined if the nutsedge plants that grow under translucent paper mulches are capable of ending the life cycle and if that growth interferes with the yield.
2. Another interesting aspect would be to determine the maximum depth from which the nutsedge is capable of sprout and pierce using different biodegradable mulches.
3. There is the need to continue working with the companies that provide crepe papers in order to obtain an opaque and flexible material capable of diminishing the production of aerial biomass and tubers of purple nutsedge and to improve the mechanical installation.
4. Furthermore, the future new materials must be submitted to ecotoxicity test, among others, in order to know if the remaining components or materials once the papers are degraded represent a problem for the microfauna and to prove they degrade completely as observed in the field trials.
5. It would be interesting to conduct a life-cycle-assessment or carbon footprint assessment of the biodegradable mulches compared to PE. These analyses could probably deliver some more arguments to impulse the use of biodegradable mulching materials in vegetable production.

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General Conclusions

1. Physical characterization of biodegradable paper mulches

1.1 Paper mulches have variable grammage and thickness and the measures form the laboratory differ slightly from the information provided by the manufacturer.

1.2 The tested non-flexible dark papers are opaque, which is an interesting and important characteristic to avoid weeds growing below them and they probably influence on temperature and yield as found by other authors. The tested crepe papers are light brown, which allows light to pass through the mulch. Only one of the tested crepe material is black-greenish.

1.3. Crepe materials with intermediate rates of grammage and thickness showed higher values in the traction and punction tests than non-flexible papers. These characters confer them a certain resistance during the mechanical installation and more capacity of elongation when the material touches a sharp stone avoiding breakage.

1.4. Strength to breakage and capacity to elongate of the paper mulches were also very variable between materials even when comparing within longitudinal or the cross- section of each material. This wide range allows adjusting the choice of the material to the particular scenario of each farmer.

1.5. According to the standard EN 13655 (EN 13655, 2003) mulching films must have a tensile stress at break higher than 16 MPa that corresponds to the rate for low-density black polyethylene (PE). Rates of all tested creped papers were lower than this value so that all of them will probably need a certain tension reduction on the mulching machine to reduce the breaks during the mechanical installation.

1.6. Crepe papers are the optimal candidates to achieve an efficient mechanical installation in the field due to their mechanical properties but their high translucency need to be improved. The results should be taken into account aiming to find new paper mulches matching all the targeted mechanical properties.

2. Purple nutsedge (*Cyperus rotundus* L.) control with biodegradable mulches and its effect on fresh pepper (*Capsicum annuum* L.) production

2.1. Biodegradable plastic films efficiently controlled weeds except for purple nutsedge. However, as no other species emerged through the plastic films, using these materials are counterproductive because purple nutsedge grows without competition and its reproduction is, therefore, promoted.

2.2. Opaque paper mulches controlled efficiently purple nutsedge, so paper mulch must be recommended when serious nutsedge infestations exist.

2.3. Translucent paper allowed purple nutsedge and other species growing under the sheet but were not capable to pierce it.

2.4. Degradation of the in-soil part of paper mulches occurred in some cases as early as 15 days after transplant (DAT). This can become a problem in windy areas, because the mulch can be lifted before the crop is well established. Hilling shortly before 15 DAT can mitigate the problem. Biodegradable plastic films had a variable degradation of the in-soil part depending on the used base material and on the year.

2.5. Above-soil degradation did not occur in paper mulches so the sheets remained intact at least for the first 45 DAT. In contrast, biodegradable plastic films presented variable, in some cases, high above-soil degradation.

2.6. The yield obtained with biodegradable plastic films and paper mulches was equivalent to that obtained with PE, and even higher in the case of biodegradable plastic Mater- Bi®. Thus, any of the tested materials could be an alternative to PE for use with the erect and slow-growth rate vegetable crop such as pepper.

2.7. In the mesh trial a higher proportion of rotten tubers were found in all the mulching materials then in the unweeded control except for some translucent paper mulches.

3. Effect of translucency of mulching materials and burial depth on *Cyperus rotundus* L. growth and development

3.1. The degree of translucency of the mulching materials affected nutsedge biomass production, because when a high amount of photosynthetically active radiation (PAR) passes through the material, nutsedge grows and develops under the mulch films even as well as in the unmulched control growing without any other weeds. Moreover, although the most translucent materials were not pierced by *C. rotundus*, enough tubers were generated assuring the infestation of the field after removing the mulching material.

3.2. The observation of sprouting in time in the three growing chamber trials could not be related to higher growing degree-days gradient accumulation in the tubers.

3.3. Regardless of the tuber depth, biodegradable plastic was more intensively pierced than PE but paper mulch was not punctured by nutsedge.

3.4. The tubers buried along the first 10 cm of soil depth behaved similarly in their capacity of piercing PE and Mater-Bi® and in the number of sprouts 30 days after trial installing considering depth as factor.

3.5. The amount of biomass generated by nutsedge was independent of the type of mulch and, in addition, the tuber planting depth.

3.6. The bulk of the biomass weight produced was dedicated to produce underground biomass assuring new tubers for next season.

4. Economic and environmental evaluation of biodegradable plastic films and paper mulches used in open-air grown pepper (*Capsicum annuum* L.) crop

4.1. The inclusion of the costs of waste management and recycling is crucial for a proper evaluation of the economic profitability of the different options in the short-term. The inclusion of such costs under the current Spanish legislation only increases the costs for farmers in 9.5 €/ha with respect to the no waste management scenario and 15.5 €/ha if total recycling cost is considered. These increases only represent a reduction in the final net margin of 0.1%, which confirms that it would be reasonable to establish mandatory measures for farmers to assume the costs of waste management and recycling. Using the experimental yield data, benefits were obtained when using any of the tested biodegradable plastic films, translucent and opaque paper mulches in pepper compared to PE.

4.2. The inclusion of current Spanish public support of biodegradable mulching materials in the economic analysis allows us to affirm that only two materials (Ecovio® and Sphere®) are profitable alternatives to PE when the local average yield is considered.

4.3. Although there are saving in costs of field conditioning when using biodegradable mulching materials with regard to PE, the high market prices of biodegradable plastics and paper materials are not compensated with the current level of subsidies of 35% of acquisition price, slowing down their massive adoption in fields. An increase in aid rates up to 50.1% would allow all biodegradable films to be more used alternatives to PE.

Conclusiones Generales

1. Caracterización física de acolchados biodegradables de papel

1.1. Los acolchados de papel presentaron un gramaje y espesor variables y las medidas de laboratorio difieren ligeramente de la información proporcionada por el fabricante.

1.2. Los papeles negros no flexibles son de color negro lo cual es una interesante e importante característica para evitar el crecimiento de malas hierbas debajo del material y probablemente influye en la temperatura y la cosecha como otros autores han demostrado. Los papeles crepados son marrones claro lo que permite que la luz pase a través de los acolchados. Solo uno de los papeles crepado tenía un color negro-verdoso.

1.3. Los materiales crepados con unos valores intermedios de gramaje y espesor presentaron valores más elevados en las pruebas de tracción y punción que los materiales no flexibles o crepados. Estos caracteres les confieren cierta resistencia durante la instalación mecánica y mayor capacidad de elongación cuando el material toca una piedra afilada lo que evita la rotura de la lámina.

1.4. La fuerza a la rotura y la capacidad de elongación de los acolchados de papel fueron muy variables entre materiales incluso cuando se compararon las secciones longitudinal y transversal. Este amplio rango permite ajustar la elección del material al escenario particular de cada agricultor.

1.5. De acuerdo con la norma EN 13655 (EN 13655, 2003) los acolchados plásticos deben tener una resistencia a la tracción superior a 16 MPa que corresponde al valor para el polietileno de baja densidad negro. Los valores obtenidos para todos los papeles crepados fueron inferiores a este por lo que todos ellos probablemente necesiten una reducción en la tensión en la máquina de acolchado para reducir las roturas durante la instalación mecánica.

1.6. Los papeles crepados son los candidatos óptimos para conseguir una instalación mecánica eficiente debido a sus propiedades mecánicas, pero es necesario mejorar la translucidez. Los resultados obtenidos en las distintas propiedades mecánicas deben tomarse en cuenta cuando se pretende encontrar nuevos materiales de acolchado de papel.

2. Control de juncia (*Cyperus rotundus* L.) mediante acolchados biodegradables y su efecto sobre la producción de pimiento (*Capsicum annuum* L.) para fresco

2.1. Los plásticos biodegradables controlaron eficientemente las malas hierbas a excepción de la juncia. Sin embargo, como otras especies no atraviesan los acolchados plásticos, usar estos materiales sería contraproducente porque la juncia crece sin competencia y su reproducción se ve, por lo tanto, favorecida.

2.2. Los materiales de acolchado de papel opacos controlaron eficazmente la juncia por lo que los papeles deberían recomendarse cuando existan infestaciones elevadas de juncia.

2.3. Los materiales de acolchado de papel translúcidos permitieron el crecimiento de la juncia y de otras malas hierbas debajo de la lámina, pero no fueron capaces de perforarla.

2.4. La degradación de la parte enterrada de los acolchados de papel ocurrió en los primeros 15 días después del trasplante (DDT). Esto puede ser un problema en zonas ventosas porque el acolchado puede ser levantado antes de que el cultivo esté establecido. Aporcar tierra a los 15 días DDT puede mitigar el problema. Los plásticos biodegradables tuvieron una degradación variable de la parte enterrada dependiendo del material base y del año.

2.5. La parte no enterrada de los papeles no se degradó por lo que las láminas permanecieron intactas hasta al menos los 45 DDT. En cambio, los plásticos biodegradables presentaron degradación variable y, en algún caso, mayor degradación en la zona no enterrada.

2.6. La producción obtenida con los acolchados biodegradables plásticos y papeles fueron equivalentes a la obtenida con PE, incluso superior en el caso del plástico biodegradable Mater-Bi®. En consecuencia, cualquiera de los materiales ensayados puede ser una alternativa al PE usado en un cultivo hortícola de porte erecto y de crecimiento lento como es el pimiento.

2.7. En el ensayo de mallas se obtuvieron una proporción mayor de tubérculos podridos en todos los materiales de acolchados, seguido del testigo sin desherbar, exceptuando algunos papeles traslúcidos.

3. Efecto de la translucidez de materiales de acolchado y la profundidad del enterrado en el crecimiento y desarrollo de *Cyperus rotundus* L.

3.1. El grado de translucidez de los materiales de acolchado afectó a la producción de biomasa de la juncia porque, cuando una mayor cantidad de luz pasa a través de los materiales, la juncia crece y se desarrolla debajo del acolchado incluso tan bien como en el testigo sin acolchar sin otras malas hierbas. Por otra parte, a pesar de que los materiales más translucidos no fueron perforados por *C. rotundus* suficientes tubérculos se generaron asegurando así la infestación de la parcela después de retirar el acolchado.

3.2. Otro aspecto que ha dificultado el óptimo desarrollo de los ensayos de translucidez ha sido la imposibilidad de imitar el acolchado mecánico eficientemente en los contenedores. La tensión de los materiales cambió con el tiempo lo que hizo que la juncia no pudiera perforara la lámina, algo que no ocurre en el campo. Después de los diferentes ensayos realizados durante este periodo donde los tubérculos fueron usados en diferentes escenarios y condiciones, se puede afirmar que esta mala hierba perenne presenta dificultades para trabajar con ella porque la respuesta ha sido muy variable a pesar de que los tubérculos fueron elegidos por tamaño y aspecto. La variabilidad enla brotación y desarrollo probablemente pueden estar afectados por la edad del tubérculo, como otros autores ya lo determinaron, o por otros aspectos aún desconocidos. Este es un aspecto importante a tener en cuenta en próximos ensayos a pesar de que sea muy complicado saber la edad exacta de los tubérculos.

3.3. Las brotaciones en el tiempo en los tres ensayos de cámara de crecimiento no se pudieron relacionar con una mayor acumulación de los días-grado en los tubérculos.

3.4. Haciendo referencia a profundidad de los tubérculos, el plástico biodegradable fue perforado más intensamente que el PE pero los papeles no fueron atravesados por la juncia.

3.5. Los tubérculos enterrados a lo largo de los primeros 10 cm de profundidad se comportaron de manera similar en su capacidad para perforar el PE y el Mater-Bi® y en el número de brotaciones 30 días después de la instalación del ensayo considerando la profundidad como factor.

3.6. La cantidad de biomasa generada por la juncia fue independiente del tipo de acolchado y, además, de la profundidad de enterrado de los tubérculos.

3.7. El grueso de la biomasa generada por la juncia se dedicó a producir biomasa subterránea asegurando nuevos tubérculos para la siguiente temporada.

4. Evaluación económica y ambiental del uso de materiales biodegradables plásticos y papeles en cultivo de pimiento (*Capsicum annuum* L.) al aire libre

4.1. La inclusión de los costes de gestión de los residuos y de reciclaje de los plásticos es crucial para una evaluación correcta de la rentabilidad económica de las diferentes opciones a corto plazo. La inclusión de estos costes bajo la actual legislación española solo incrementa los costes al agricultor en 9,5 € ha^{-1} con respecto al escenario donde no gestionan los residuos y 15,5 € ha^{-1} si el total de los costes de reciclaje es considerado. Estos incrementos solo representan una reducción del 0,1 % del margen neto final, lo que confirma que sería razonable establecer medidas obligatorias para los agricultores para que asuman los costes de la gestión de residuos y de reciclaje. Si tenemos en cuenta los datos experimentales de cosecha, se obtuvieron beneficios usando cualquiera de los materiales biodegradables ensayados ya sean plásticos, papeles opacos o traslúcidos si comparamos con el PE.

4.2. La inclusión de las ayudas para asumir el coste de los materiales plásticos biodegradables en el análisis económico nos permite afirmar que solo dos materiales (Ecovio® y Sphere®) son económicamente viables comparados con el PE cuando se usa la producción media local.

4.3. A pesar de que haya ahorro en los costes de instalación del cultivo cuando usamos materiales biodegradables comparado con el PE, el alto precio de estos materiales no se compensa con la cantidad de subvención actual del 35% del precio de adquisición, lo que retrasa su uso. Un incremento de las subvenciones hasta el 50,1% permitiría que estos materiales biodegradables tanto plásticos como papeles fueran alternativas viables al PE

Conclusions Generals

1. Caracterització física d'encoixinats biodegradables de paper

1.1. Els encoixinats de paper presentaren un gramatge i espessor variables i les mesures de laboratori diferiren de la informació proporcionada per el fabricant.

1.2. Els papers negres no flexibles són de color negre el qual és una interessant i important característica per evitat el creixement de males herbes baix del material i probablement influeixi en al temperatura i la collita com altres autors han demostrat. Els papers crepats són marrons clar lo que permet que la llum passi a través dels encoixinats. Només un dels papers crepats tenia un color negre-verdós.

1.3. Els materials crepats amb uns valors intermedis de gramatge i espessor presentaren valors més elevats a les probes de tracció i punció que els materials no flexibles o crepats. Aquests caràcters els hi confereixen certa resistència durant la instal·lació mecànica i major capacitat d'elongació quan el materials toca alguna pedra afilada lo que evitar e trencament de la làmina.

1.4. La força al trencament i la capacitat d'elongació dels encoixinats de paper varen ser molt variables entre materials inclòs quan es compararen les secciones longitudinal i transversal. Aquest ampli rang permet ajustar l'elecció del material a l'escenari particular de cada agricultor.

1.5. D'acord amb la norma EN 13655 (EN 13655, 2003) els encoixinats plàstics han de tenir una resistència a la tracció superiora 16 MPa que correspon al valor del polietilè de baixa densitat negre. Els valors obtinguts per a tots els papers crepats varen ser inferiors a aquest valor per lo que tots ells probablement necessiten una reducció en la tensió en la màquina d'encoixinar per reduir els trencaments durant la instal·lació mecànica.

1.6. Els papers crepats són els candidats òptims per aconseguir una instal·lació mecànica eficient degut a les seves propietats mecàniques., però és necessari millorar la translucidesa. Els resultats obtinguts en les diferents propietats mecàniques s'han de prendre en compte quan es pretén trobar nous materials d'encoixinat de paper.

2. Control de castanyola (*Cyperus rotundus* L.) mitjançant l'ús d'encoixinats biodegradables i el seu efecte sobre la producció de pebrot (*Capsicum annuum* L.) per fresc

2.1. Els plàstics biodegradables varen controlar eficientment les males herbes a excepció de la castanyola. No obstant, com ninguna altre espècie travessa els encoixinats plàstics, utilitzar aquests materials seria contraproduent perquè la castanyola creix sense competència i la seva reproducció es veu, por tant, afavorida.

2.2. Els materials d'encoixinat de paper opacs controlaren eficientment la castanyola per lo que els papers tindrien que recomanar-se quan existeixen infestacions elevades de castanyola.

2.3. Els materials d'encoixinat de paper translúcid varen permetre el creixement de la castanyola i d'altres males herbes baix de la làmina, però no varen ser capaços de perforar-la.

2.4. La degradació de la part enterrada del encoixinats de paper va ocórrer en els primers 15 dies després del transplantament (DDT). Això pot ser un problema en zones ventoses perquè l'encoixinat pot ser aixecat abans de que el cultiu estigui establert. Aportar terra als 15 dies DDT pot mitigar el problema. Els plàstics biodegradables varen tenir una degradació variable de la part enterrada depenent del material base i de l'any.

2.5. La part no enterrada dels papers no es va degradar per lo que les làmines varen romandre intactes fins, al menys, els 45 DDT. En canvi, els plàstics biodegradables varen presentar una degradació variable i, en algun cas, major degradació a la zona enterrada.

2.6. La producció obtinguda amb els encoixinats biodegradables plàstics i de paper varen ser equivalents a l'obtinguda amb PE, inclús superior en el cas del plàstic biodegradable Mater-Bi®. En conseqüència, qualsevol del materials assajats poden ser una alternativa al PE usat en un cultiu hortícola de port erecte i de creixement lent com és el pebrot.

2.7. A l'assaig de malles es va trobar una major proporció de tubercles podrits en tots els materials d'encoixinat seguit del testimoni sense escardar, exceptuant alguns materials d'encoixinat de paper translúcids.

3. <u>Efecte de la translucidesa de materials d'encoixinat i la profunditat d'enterrament en el creixement i desenvolupament de *Cyperus rotundus* L.</u>

3.1. El grau de translucidesa del materials d'encoixinat va afectar a la producció de biomassa de castanyola perquè, quan una major quantitat de llum passa a través del materials, la castanyola creix i es desenvolupa baix l'encoixinat inclús tan bé como en el testimoni sense encoixinar sense presència d'altres males herbes D'altra banda, malgrat els materials més translúcids no varen ser perforats per *C. rotundus*, es varen generar suficients tubercles assegurant així la infestació de la parcel·la després de retirar el plàstic de l'encoixinat.

3.2. Un altre aspecte que compromet el desenvolupament del assajos de translucidesa ha set la dificultat per imitar de manera eficient l'encoixinat mecànic als contenidors. Va ser difícil mantenir la tensió al material por tant, al contrari a les observacions a l'assaig de camp, la castanyola no va se capaç de perforar les làmines en molts de casos. Després de tots els assajos diferents duts a terme durant aquest període on els tubercles es varen utilitzar en diferents escenaris i condicions, es pot afirmar que aquesta espècie de mala herba perenne presenta dificultats per ser manejada perquè la resposta ha set molt variable malgrat que els tubercles varen ser seleccionats per mida i aspecte. La variabilitat a les brotacions i desenvolupament es veuen probablement afectades per l'edat del tubercle, com alguns autors afirmen, o per altres aspectes no coneguts.

3.3. Les brotacions en el temps en els tres assajos de càmera de creixement no es poden relacionar amb una major acumulació del dies-grau en els tubercles.

3.4. Fent referència a la profunditat del tubercles, el plàstic biodegradable va ser perforat més intensament que el PE però els papers no varen ser travessats per la castanyola.

3.5. Els tubercles enterrats en els primers 10 cm de profunditat es comportaren de manera similar en la capacitat de perforar el PE i el Mater-Bi® i en el nombre de brotacions 30 dies després de la instal·lació de l'assaig considerant la profunditat com a factor.

3.6. La quantitat de biomassa generada per la castanyola va ser independent del tipus d'encoixinat i, a més, de la profunditat d'enterrament dels tubercles.

3.7. El gruix de la biomassa generada per la castanyola es va dedicar a produir biomassa subterrània assegurant així nous tubercles per la següent temporada.

4. Avaluació econòmica i ambiental de l'ús de materials biodegradables plàstics i papers en cultiu de pebrot (*Cpasicum annuum* L.) al aire lliure

4.1. La inclusió dels costos de gestió dels residus i de reciclatge dels plàstics es crucial per una avaluació correcta de la rendibilitat econòmica de les diferents opcions a curt termini. La inclusió d'aquests costos baix la actual legislació espanyola només incrementa els costos a l'agricultor en 9,5 € ha^{-1}comparat amb l'escenari on no es gestionen els residus i 15,5 € ha^{-1} si el total dels costos de reciclatge es considerat. Aquests increments només representen un 0,1 % del marge net final, lo que confirma que seria raonable establir mesures obligatòries per als agricultors per que assumeixin els costs de la gestió de residus i reciclatge. Si tenim en compte les dades experimentals de collita, es van obtenir beneficis usant qualsevol material biodegradable assajat ja siguin plàstics, papers opacs o translúcids si comparem amb PE.

4.2. La inclusió de les ajudes per assumir el cost del materials plàstics biodegradables a l'anàlisi econòmic ens permet afirmar que només dos materials (Ecovio® i Sphere®) són econòmicament viables comparats amb el PE quan s'usa la producció mitja local.

4.3. Tot i que hi hagi estalvi en els costos d'instal·lació del cultiu quan utilitzem materials biodegradables comparat amb el PE, l'alt preu d'aquests materials no compensa amb la quantitat subvencionada del 35% del preu d'adquisició, lo que retarda el seu ús. Un increment de les subvencions fins al 50,1% permetria que aquests materials biodegradables tant plàstics com papes fossin alternatives viables al PE.