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# Biodegradable mulch instead of polyethylene for weed control of processing tomato production

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**Abstract** Black polyethylene (PE) film is used for mulching in processing tomato (*Lycopersicon esculentum* P. Mill.) in Spain achieving a generally high weed control but causing a serious waste problem. Few herbicides are available for tomato, so that a biodegradable mulching is the desired solution which should provide high yield, high weed control and be economically available. For 3 years, the same field trial was carried out in four areas of Spain using the following mulch materials in processing tomatoes: (1) untreated control, (2) manual weeding, (3) PE, black, 15  $\mu\text{m}$  thick, (4) and (5) two types of biodegradable plastic mulch, black, 15  $\mu\text{m}$ , (6) oxo-degradable plastic mulch, black, 15  $\mu\text{m}$ , (7) paper mulch, black, 85  $\text{g m}^{-2}$ , (8) kraft paper mulch, brown, 140  $\text{g m}^{-2}$  and (9) barley straw, 1  $\text{kg m}^{-2}$ . Weed control, yield and economic aspects were analysed. Most frequent

weed species were *Convolvulus arvensis*, *Chenopodium album* and *Amaranthus* spp. Here, we showed that despite differences in weed species, soil type and years, weed competition caused a similar yield decrease in all locations. A common regression coefficient could be estimated indicating that weed competition was responsible for a yield decrease of 3.3 to 4.4  $\text{t ha}^{-1}$  for each 10% of efficacy loss. Weed control was high for biodegradable plastics, paper mulches and PE ranging between 80% and 100% for all of them; also, yield was similar for all plastic and paper mulching treatments ranging between 72% and 108% of the yield achieved by PE. Here, we demonstrate that technically viable biodegradable alternatives exist for all four locations. From the economic point of view, PE gave highest benefits, mainly due to its low market price and to high yields despite

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removal costs, showing that its substitution will depend on prohibition. For locations with low-density weed infestations, manual weeding can be an alternative.

**Keywords** Polyethylene · Biodegradable mulch · Paper · Barley straw

## 1 Introduction

Weeds are responsible of the highest potential loss in the most important crops worldwide (34%; Oerke 2006) and diminish processing tomato production (*Lycopersicon esculentum* P. Mill.) due to competition with water, nutrients and light (Weaver and Tan 1983; Patrap et al. 1997). Most damaging species are *Solanum nigrum* with infestation thresholds of only one plant per lineal meter in transplanted tomato (Maillet and Abdel Fatah 1983). High infestations of *Cyperus rotundus* (166 plants per lineal meter), a common perennial sedge in Mediterranean irrigated lands, can cause losses of 53% (William and Warren 1975). Main available tools for weed control are preventive cultural methods, mechanical weed control and herbicides; but the combination of these methods is usually the most effective strategy (Anderson 2007). In Spain, few herbicides are available for processing tomato and farmers' alternate herbicide use with black polyethylene mulch (PE). Besides environmental problems (Tabaglio et al. 2008), the main drawback of herbicide use is the need of combining it with other techniques because some weed species like *S. nigrum*, *C. rotundus* and *Orobanche ramosa* are poorly controlled (Tei 2001) while the main disadvantage of mulching is the waste generation. Mechanized harvest breaks the PE mulch which makes difficult to remove the plastic pieces completely. The European Directive 2006/12/EC encourages reduction in the production of waste by promoting clean technologies and products that can be recycled and reused and which has been adopted by the First Spanish National Plan on Residues of Plastics Used in Agriculture in 2006 (MARM 2011a, b). The presence of plastic debris in the fields also has a negative influence on subsequent crops such as spinach (*Spinacia oleracea* L.) or peas (*Pisum sativum* L.) for canning because plastic residues could contaminate packaging during the harvest process.

The easiest alternative for farmers to PE mulching are biodegradable plastics because the same mechanized process designed for PE can be used. However, high prices and lack of *Cyperus* spp. control with these materials (Anzalone et al. 2010) led us to investigate the effect of other mulch types on weed control and crop yield in processing tomatoes. Other available alternatives are oxo-degradable plastic, paper mulch and barley straw. The main advantage of oxo-degradable plastic is the low cost and the easy installation

but the main inconvenience is that the buried part does not suffer degradation and needs to be exposed to light and air to degrade because the degradation of oxo-degradable plastics is a result of oxidative and cell-mediated phenomena, either simultaneously or successively (Scott 2005). The use of paper mulch started already in the 1970s (Vandenberg and Tiessen 1972) but was replaced by PE because of its better mechanical properties in elasticity and avoiding water evaporation. The disadvantages of PE caused a new interest in paper mulch and at present, the most recent research in Italy focus on paper coated with other materials as blends based on polyhydroxyalkanoates (Salemi et al. 2008). The main disadvantages of using paper mulch are the heavier coils, slower mulching speed and the need of a careful installation to avoid fractures (Harrington and Bedford 2004). However, an interesting property of paper mulch is the ability to control *C. rotundus* (Shogren and Hochmuth 2004; Anzalone et al. 2010).

Barley is the main winter cereal in Spain, accounting for a planted area of 3,500,000 ha (MARM 2011a, b), so barley straw is the most commonly used product for organic mulch. In most of the found research work, the general trend is that straw mulch has positive effects on crops due to increased soil moisture and increased weed control but achieves a not-so-high yield improvement compared to black plastic mulch (Woldetsadik et al. 2003; Alcántara et al. 2007; Anzalone et al. 2010). In most cases, weed control with straw is also lower than with PE, which probably causes, in many cases, the lower yield.

Processing tomatoes occupied 34.951 ha in 2008 in Spain (MARM 2011a, b). Climatic characteristics as well as soil types vary within the different production areas and biodegradable mulches may have different agronomic behaviour depending on the area. Therefore, field trials were established in four different locations where processing tomato is grown.

The objective of this work was to evaluate the effect of several biodegradable mulches on weed control and yield of processing tomato in different areas of Spain (Fig. 1) to find an alternative to standard black PE mulch in order to reduce the waste problem.

## 2 Materials and methods

### 2.1 Field trials

The same field trial was established at four locations in Spain during 2006, 2007 and 2008 (Table 1). The experimental design was a randomized block design with at least three replicates of nine treatments: (1) untreated control, (2) manual weeding (three times along the crop cycle), (3) conventional plastic mulch (black PE, 15 µm thick), (4) biodegradable plastic mulch (black Mater-Bi©, 15 µm thick), (5)



**Fig. 1** View of one of the field trials where different biodegradable mulching materials were tested at Almodévar, Aragón, in 2007

biodegradable plastic mulch (black Biofilm©, 17  $\mu\text{m}$  thick), (6) oxo-degradable plastic mulch (black Enviroplast©, 15  $\mu\text{m}$  thick), (7) paper mulch (black MimGreen©, 85  $\text{g m}^{-2}$ ), (8) paper mulch (brown Saikraft©, 140  $\text{g m}^{-2}$ ), (9) barley straw (1  $\text{kg m}^{-2}$ ). Barley straw was provided locally and the dose was determined in previous experiments (Anzalone et al. 2010). Straw was applied 10 days after transplanting.

Soil preparation included soil tillage and formation of 0.8-m-wide raised beds with a distance of 1.5 m between the centre of the beds. Seeds of the processing tomato

variety ‘Perfect Peel’ were used and plants transplanted at 0.2 m plant spacing. Each experimental plot consisted in a crop row of 20 m long. Weed assessments were recorded in four fixed areas per plot, tomato yield was determined outside these areas to avoid any influence. Planting date, mulching date and type of fertilization were different depending on the location (Table 1) and the crop was conducted fully organically at Lleida. The crop was drip irrigated with a 16 mm diameter pipe per bed with 20 cm spacing between emitters. The irrigation system was configured so that different treatments could be irrigated separately. The moisture values obtained by dielectric sensors (Aquamer ECH2O, Decagon or Diviner, Sentek) were used to determine the appropriate amount of irrigation required to avoid moisture stress and to maintain the same soil moisture level at each treatment.

Weeds were counted at 21, 42 and 63 days after transplanting (DAT) in each plot in 20×100 cm frames next to the tomato plants avoiding the planting holes. Weed soil cover was also assessed at the same moments. In the manually weeded plots, weeds were removed, when necessary, three times during the cropping cycle. Weed biomass of the plants growing in the counting frame was collected at 63 DAT and dried until constant weight at 60°C.

Tomato was harvested when ripe fruits accounted for more than 80% of total fruits in each treatment. A minimum of five plants per plot were harvested, fruits classified in red commercial fruits, green fruits with a diameter greater than

**Table 1** Location of the fields, year of experiment, soil and fertilization characteristics, mulching, planting and harvest dates at the different locations

Location	Latitude	Longitude	Year	Soil type	Mulching date	Planting date	Harvest date	Harvest (DAT)
Aragón (Almodévar)	42°1'50.48"N	0°35'5.73"W	2006	Silty clay	22/05/06	25/05/06	17/09/06	116
Almodévar	42°1'50.48"N	0°35'5.73"W	2007	Silty clay	01/06/07	04/06/07	18/09/07 01/10/07	106, 122
Montañana	41°43'50.16"N	0°48'24.15"W	2008	Clay loam	22/05/08 <sup>a</sup>	18/06/08	06/10/08	109
Logroño (Agoncillo)	42°28'8.654"N	2°17'39.276"W	2006	Silty clay	02/05/06	10/05/06	22/08/06–04/09/06	104–117
Agoncillo	42°28'8.654"N	2°17'39.276"W	2007	Silty clay	08/05/07	11/05/07	30/08/07–03/09/07	111–115
Agoncillo	42°27'56.594"N	2°17'39.411"W	2008	Loam	07/05/08	13/05/08	01/09/08–03/09/08	111–113
Lleida (Vilanova de Bellpuig)	41°36'38"N	0°57'36"E	2006	Silty clay	06/05/06	08/05/06	25/08/06	109
Vilanova de Bellpuig	41°36'38"N	0°57'36"E	2007	Silty clay loam	28/05/07	30/05/07	10/09/07	105
Vilanova de Bellpuig	41°36'38"N	0°57'36"E	2008	Silty clay	12/06/08	13/06/08	02/10/08	111
Ciudad Real (Ciudad Real)	39°0'N	3°56' W	2006	Sandy clay loam	17/05/06	18/05/06	06/09/06–14/09/06	111–119
Ciudad Real	39°0'N	3°56' W	2007	Loam	16/05/07	18/05/07	27/08/07–03/09/07	101–108
Ciudad Real	39°0'N	3°56' W	2008	Loam	27/05/08	04/06/08	15/09/08–17/09/08	103–105

DAT days after transplanting

<sup>a</sup> 18/06/08 Saikraft® and Mater-Bi®

25 mm and non-commercial fruits (green fruits with diameter lower than 25 mm and rotten or damaged fruits) and weighed separately. The sum of red and big green fruits was considered for yield calculations.

## 2.2 Data analysis

Mean efficacy of weed control was calculated as % efficacy =  $100 - [(T_t/T_u) \times 100]$  where  $T_t$  is the weed cover in each treatment and  $T_u$  is the weed cover in the untreated control plots.

Efficacy was  $a \sin(\sqrt{(x/100)})$  transformed, weed biomass needed  $\sqrt{x}$  transformation and yield needed in some cases  $(x)^2$  transformation to satisfy normality and variance homogeneity following the indications of the Box–Cox transformation (Bowley 1999). Block was nested with year, which was taken into account in the ANOVA model using the statistic package SAS (SAS Institute, 1991).

## 2.3 Weed competition

The weed-free plots established by manual weeding allowed to assess the relevance of weed competition in reducing tomato yield. Yield loss was calculated following: % yield loss =  $100 - (Y_u/Y_m \times 100)$ , where  $Y_m$  is tomato yield in the manually weeded plots and  $Y_u$  is the yield in the untreated control plots.

Regression was used to describe the relationship between tomato yield and weed control. A linear regression analysis of yield on weed control efficacy was performed in each experiment with Systat©12 linear regression module. To test the homogeneity of the obtained regression coefficients, the method described by Dagnelie (1975) was applied to determine whether or not they can be considered to be estimates of a common coefficient.

## 2.4 Economic study

### 2.4.1 Costs and incomes

General costs including plantation, fertilization, irrigation etc., accounted for 6,278 € ha<sup>-1</sup> for all treatments (Gutiérrez et al. 2005; updated with Consumer Price Index through [www.ine.es/calcula](http://www.ine.es/calcula)). Costs of mulching material were obtained in the Spanish market from Zaragoza suppliers in 2010 considering covering 60% of the surface: 181 € ha<sup>-1</sup> for PE, 966 € ha<sup>-1</sup> for Mater-Bi®, 818 € ha<sup>-1</sup> for Biofilm®, 296 € ha<sup>-1</sup> for Enviroplast®, 843 € ha<sup>-1</sup> for MimGreen®, 429 € ha<sup>-1</sup> for Saikraft® and 200 € ha<sup>-1</sup> for barley straw (considering 36 € t<sup>-1</sup>, application dose 1 kg m<sup>-2</sup>). Mulch installation costs with machinery were 65 € ha<sup>-1</sup> for the plastics, which was increased additionally by 20 € ha<sup>-1</sup> for MimGreen® and 30 € ha<sup>-1</sup> for Saikraft® due to the slower

installation process. Barley straw mulching accounted for 200 € ha<sup>-1</sup> considering 20 h needed ha<sup>-1</sup> mulch installation, 10 € h<sup>-1</sup> of labour. Removal and retiring costs were considered 115 € ha<sup>-1</sup> for PE and half of that cost for Enviroplast® (58 € ha<sup>-1</sup>). Weeding costs were 600 € ha<sup>-1</sup> for the hand-weeded plots (considering 20 h ha<sup>-1</sup>, 10 € h<sup>-1</sup> of labour, and three times weeding). The total costs for each treatment are summarized in Table 5.

Costs were considered the same for conventional and organic production (at Lleida) because differences were minimal. Irrigation costs were also considered the same for all mulching treatments despite around 15% of water was saved in the untreated control plots in several trials (Vázquez et al. 2011) because the cost of the water itself was only 6% of the total irrigation costs (Gutiérrez et al. 2005).

The considered commercial tomato fruit price to calculate incomes was 80 € t<sup>-1</sup> for conventional farming and 151.5 € t<sup>-1</sup> for organic farming at Lleida in 2010.

## 3 Results and discussion

Installation of the paper mulches in field had some constraints especially on windy days. MimGreen® suffered less fractures than Saikraft® but a correct soil preparation with few clods, a slight adaptation of the mulching machine and a slower installation reduces fracture risk. Installation of barley straw should be done mechanically but the bad results in weed control and yield did not motivate studying it further. During the cropping season we only observed problems in windy areas where paper could be torn off.

### 3.1 Weed composition

Weed composition changed within locations and years but the most frequent weed species found were the dicotyledonous species *Convolvulus arvensis*, *Chenopodium album* and *Amaranthus* spp. (Table 2). The competitive weed *C. rotundus* was the most frequent at Aragón in 2008 and was able to pierce plastic mulches. Total weed density varied between 11 and 171 plants m<sup>-2</sup> in the untreated control plots at 63 DAT and was especially high at Aragón all 3 years (95 ± 11.6, 102 ± 14.0, and 84 ± 14.6 plants m<sup>-2</sup> in 2006, 2007 and 2008 respectively), at Ciudad Real in 2007 (171 ± 36.0 plants m<sup>-2</sup>) and at Logroño in 2008 (106 ± 33.8 plants m<sup>-2</sup>).

### 3.2 Weed control efficacy

As some mulching materials became damaged in time, weed control efficacy only at the latest assessment date was provided (i.e., 63 DAT) showing control efficacy at the most disadvantageous moment. Weed control efficacy at 21 and 42 DAT was always similar or higher than at 63 DAT. In the

**Table 2** Weed density of the main weed species found in the different years and locations in the untreated control plots 63 days after transplanting (plants m<sup>-2</sup>)

	2006		2007		2008	
Aragón	<i>Amaranthus blitoides</i>	33±5.4	<i>Amaranthus retroflexus</i>	48±8.6	<i>Cyperus rotundus</i>	44±16.8
	<i>Setaria verticillata</i>	29±4.0	<i>Xanthium spinosum</i>	18±2.9	<i>Convolvulus arvensis</i>	15±2.4
	<i>Chenopodium album</i>	27±3.8	<i>Echinochloa crus-galli</i>	14±2.8	<i>Portulaca oleracea</i>	14±4.7
	Total weeds	95 ±11.6	Total weeds	102±14.0	Total weeds	84±14.6
Logroño	<i>Beta vulgaris</i>	9±0.8	<i>Beta vulgaris</i>	7±2.6	<i>Sinapis arvensis</i>	24±12.0
	<i>Convolvulus arvensis</i>	7±2.2	<i>Convolvulus arvensis</i>	1±0.8	<i>Veronica persica</i>	22±17.0
	<i>Borago officinalis</i>	6±3.0	<i>Sonchus arvensis</i>	1±0.3	<i>Polygonum aviculare</i>	13±5.3
	Total weeds	33±5.2	Total weeds	11±1.9	Total weeds	106±33.8
Lleida	<i>Amaranthus retroflexus</i>	44±17.7 <sup>a</sup>	<i>Amaranthus retroflexus</i>	32±10.0 <sup>a</sup>	<i>Amaranthus retroflexus</i>	83±3.6 <sup>a</sup>
	<i>Chenopodium album</i>	9±3.8 <sup>a</sup>	<i>Chenopodium album</i>	7±3.6 <sup>a</sup>	<i>Chenopodium album</i>	9±2.3 <sup>a</sup>
	<i>Convolvulus arvensis</i>	2±1.3 <sup>a</sup>	<i>Convolvulus arvensis</i>	8±4.0 <sup>a</sup>	<i>Convolvulus arvensis</i>	7±2.4 <sup>a</sup>
	Total weeds	52±14.7 <sup>a</sup>	Total weeds	51±15.8 <sup>a</sup>	Total weeds	91±3.0 <sup>a</sup>
Ciudad Real	<i>Anthemis arvensis</i>	12±3.4	<i>Amaranthus albus</i>	106±36.3	<i>Convolvulus arvensis</i>	12±7.3
	<i>Convolvulus arvensis</i>	6±3.6	<i>Chenopodium album</i>	23±19.0	<i>Matricaria chamomila</i>	9±8.1
	<i>Amaranthus albus</i>	6±2.7	<i>Diplotaxis virgata</i>	18±5.3	<i>Amaranthus albus</i>	5±3.4
	Total weeds	44±4.1	Total weeds	171±36.0	Total weeds	35±15.8

Mean±SE

<sup>a</sup> Weed cover (%)

tested semi-arid conditions, the biodegradable plastic mulches as well as the tested paper mulches were generally capable to reduce weed biomass as much as PE, as found by Radics et al. (2006) and Harrington and Bedford (2004) in other climatic conditions, except in the case of *C. rotundus*, which was only controlled with paper mulch as also found by Shogren and Hochmuth (2004) and Anzalone et al. (2010). An exception to these trends was the bad weed control achieved in 2008 by several materials at Aragón because persistent rainfall after mulching caused a delayed planting, so that several materials were already damaged when the crop was planted.

The main factor causing significant interactions *year* × *treatment* was the irregular weed control efficacy of barley straw mulch. In some locations, barley seeds were carried with the straw, germinated and caused an additional weed problem while in other cases straw mulch reduced weed emergence effectively (Table 3). The medium or irregular weed control effect of barley straw has been reported for other crops (Alcántara et al. 2007; Woldetsadik et al. 2003). The effective use of barley straw for weed control needs more research, e.g. checking the effect of different qualities of straw considering its length or finding the way to hinder the wind to blow it away.

**Table 3** Weed control 63 days after transplanting depending on the treatment for the different locations and years

Efficacy (%)	Aragón			Logroño	Lleida			Ciudad Real		
	2006	2007	2008		2006	2007	2008	2006	2007	2008
Manual weeding	85 b	89 c	39 bc	74 c	82 a	77 bc	80 c	100 ab	99 a	89 bc
Polyethylene	100 a	100 a	71 ab	100 a	97 a	99 a	100 a	100 a	100 a	100 a
Mater-Bi®	99 a	99 ab	44 bc	91 b	93 a	96 ab	100 ab	100 ab	99 a	97 ab
Biofilm®	98 a	96 bc	5 c	87 bc	85 a	91 ab	99 b	100 ab	99 a	98 ab
Enviroplast®	99 a	99 ab	69 ab	–	–	–	–	100 a	99 a	100 a
MimGreen®	100 a	93 bc	87 ab	90 bc	93 a	96 ab	100 a	100 ab	100 a	100 a
Saikraft®	96 ab	93 bc	94 a	78 bc	84 a	94 ab	99 ab	99 b	100 a	84 c
Barley straw	34 c	42 d	71 ab	16 d	91 a	61 c	54 d	97 c	96 a	92 bc

Data are back-transformed ls means from  $a \sin(\sqrt{(x/100)})$  after analysis. Means are only shown for the locations without significant interaction *year* × *treatment*. Different letters within each location and year refer to statistically significant differences according to Duncan's mean separation test at  $P < 0.05$

### 3.3 Weed biomass

The interaction  $year \times treatment$  was significant for weed biomass in all locations except Ciudad Real. Despite the interaction, all mulching treatments drastically reduced weed biomass except barley straw and Biofilm®, Mater-Bi® and PE in Aragón in 2008 due to the mentioned problems in timing and to the massive presence of *C. rotundus* capable to pierce the plastics. Plastic mulches reduced weed biomass 87–100% compared to the biomass found in the untreated plots (data not shown). The paper mulches generally reduced weed biomass efficiently but were irregular depending on the year (80–99% weed biomass reduction); barley straw achieved the lowest biomass reduction from 40% to 97%. Thus, the biodegradable plastic mulches as well as the tested paper mulches were generally capable of reducing weed biomass as much as PE.

### 3.4 Yield

Weed control is absolutely necessary for this crop in the tested conditions because a yield decrease of 24 to 68% was found in the untreated control (Table 4). Yield achieved in the plastic and paper mulched plots was similar to plots mulched with PE (Table 4) as found also by for paper mulch in tomato, lettuce and summer squash by Anderson et al. (1995), Toth et al. (2008) and Coolong (2010), respectively, as well as by Martín-Closas et al. (2003) for biodegradable plastic mulches in tomato.

Barley straw achieved irregular yield, usually lower than with other mulching treatments as reported for different crops (Woldetsadik et al. 2003; Alcántara et al. 2007; Anzalone et al. 2010).

Higher yield in the mulched plots compared to the untreated control plots was probably not caused by the combination of

weed control and other advantages of mulching (temperature, moisture retention, etc.) because yield in the manually weeded plots was within the highest in all cases excepting Lleida (Table 4). Thus, elimination of weed competition either by mulch or manually was probably the main cause for high yield. This was probably due to the rapid soil coverage achieved by this crop as found also for cabbage (Tiwari et al. 2003) opposite to other crops as okra, where mulching itself increases yield significantly (Tiwari et al. 1998).

Yield obtained each year differed considerably between locations: highest yield was obtained in 2006 and 2007 in Lleida and 2006 in Logroño, while 2008 was the year with highest yield in Aragón and 2006 and 2008 in Ciudad Real (Fig. 2).

These differences were probably caused by edaphic and climatic differences between locations and years. Regressions of yield related to efficacy were significant for all locations and years excepting Logroño 2007 which means that decreasing in yield correlates with control efficacy decrease and is caused only by weeds (Fig. 2). The homogeneity of regression coefficient tests showed that lines were parallel all 3 years in each location so that the test was performed in all cases. The results indicate that a common regression coefficient value for the equation  $f(x) = y_0 + ax$  of  $a=0.387 \pm 0.056$  could be estimated. This value indicates that weed competition was responsible for a yield decrease of 3.3 to 4.4  $\text{tha}^{-1}$  for each 10% of efficacy loss. The  $r^2$  values of the regressions comprised between 13% and 77% means that 13% and 77% of the yield variance was explained by efficacy (data not shown) demonstrating that weeds are still an important issue for crop production (Oerke 2006).

The mean percent of maximum yield reduction comparing maximum and minimum yields each year in the trials varied between 26.8% and 71.8%. A direct measure of weed

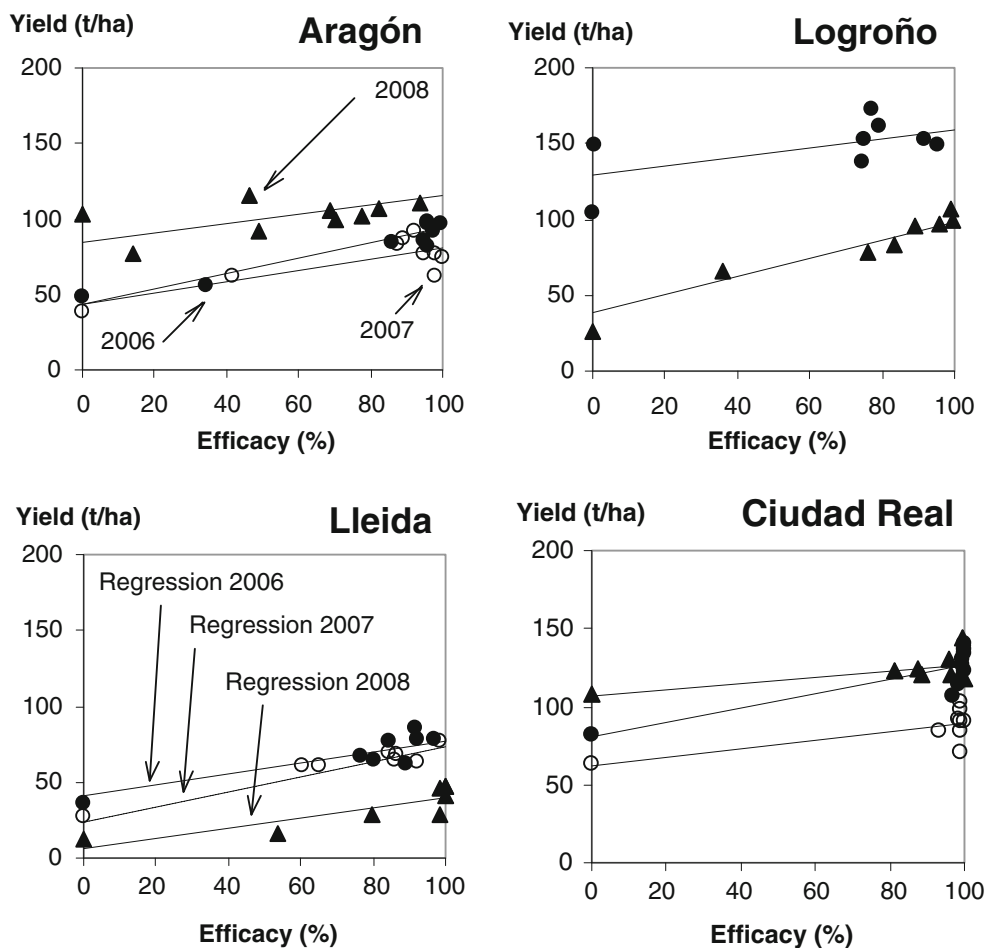
**Table 4** Tomato yield ( $\text{t ha}^{-1}$ )

Treatment/tomato yield ( $\text{t ha}^{-1}$ )	Aragón	Logroño <sup>a</sup>			Lleida <sup>a</sup>	Ciudad Real <sup>a</sup>
	Mean	2006	2007	2008	Mean	Mean
Untreated control	64 (71) c	104 (70) e	97 (78) c	30 (28) d	30 (42) d	88 (75) c
Manual weeding	96 (107) a	172 (115) a	133 (106) a	96 (89) ab	56 (79) bc	116 (98) ab
Polyethylene	90 (100) ab	149 (100) cd	125 (100) ab	108 (100) a	71 (100) a	118 (100) ab
Mater-Bi®	89 (99) ab	153 (103) bc	113 (90) bc	100 (93) a	71 (100) a	124 (105) a
Biofilm®	83 (92) ab	138 (93) d	112 (90) bc	99 (92) a	68 (96) a	119 (101) ab
Enviroplast®	82 (91) ab	–	–	–	–	123 (104) a
MimGreen®	97 (108) a	153 (103) bc	125 (100) ab	83 (77) bc	65 (92) ab	115 (97) ab
Saikraft®	95 (106) a	161 (108) b	113 (90) bc	78 (72) c	58 (82) bc	106 (90) b
Barley straw	75 (83) bc	150 (101) cd	123 (98) ab	67 (62) c	54 (76) c	109 (92) ab

Means are only shown for the locations without significant interaction  $year \times treatment$ . In parentheses, relative value compared to polyethylene. Different letters within each location refer to statistically significant differences according to Duncan's mean separation test at  $P < 0.05$

<sup>a</sup> Back-transformed from  $(x)^2$

**Fig. 2** Yearly linear regression between weed control efficacy (%) 63 days after transplanting and tomato yield in Aragón, Logroño, Lleida and Ciudad Real following the equation  $f(x) = y_0 + ax$ . Mean values of all mulching materials are shown



competition was calculated by comparing yield of untreated and manually weeded plots resulting in yield losses of 34%, 39%, 27%, 68%, 46% and 24% for Aragón, Logroño 2006, Logroño 2007, Logroño 2008, Lleida and Ciudad Real, respectively (based on data of Table 4).

3.5 Economic study

The cost of the mulching materials had the highest influence on final costs and Mater-Bi®, Biofilm® and MimGreen® had the highest global cost (Table 5). However, high yield was

**Table 5** Costs, income and benefit (€ ha<sup>-1</sup>)

Treatment	Costs Total cost (% of polyethylene mulching)	Income				Benefit					
		Aragón	Logroño	Lleida	Ciudad Real	Aragón	Logroño	Lleida	Ciudad Real	Mean	% compared to polyethylene
Untreated control	6,278 (95)	5,088	6,192	4,514	7,040	-1,190	-83	-2,836	762	-837	-30
Manual weeding	6,878 (104)	7,688	10,688	8,423	9,280	861	3,861	1,545	2,453	2,180	79
Polyethylene	6,639 (100)	7,224	10,200	10,787	9,440	585	3,561	4,148	2,761	2,764	100
Mater-Bi®	7,309 (110)	7,144	9,752	10,787	9,920	-165	2,443	3,478	2,611	2,092	76
Biofilm®	7,161 (108)	6,672	9,304	10,257	9,520	-489	2,143	3,096	2,359	1,777	64
Enviroplast®	6,697 (101)	6,432	-	-	9,840	-247	-	-	3,143	1,448	52
MimGreen®	7,209 (109)	7,656	9,624	9,787	9,200	447	2,199	2,578	1,991	1,804	65
Saikraft®	6,802 (102)	7,576	9,408	8,817	8,480	771	2,603	2,015	1,675	1,766	64
Barley straw	6,678 (101)	5,976	9,056	8,242	8,720	-702	2,378	1,564	2,042	1,321	48

Marketable price of 80 € t<sup>-1</sup> for conventional farming and of 151.5 € t<sup>-1</sup> for organic farming at Lleida



generally also achieved in these treatments. At Lleida, the sensibly higher price of the organic marketable tomato increased the benefit of most mulching treatments considerably, compensating lower yields and provoking higher benefit of most mulching materials compared to other locations (Table 5).

As it happened with weed control and yield, also from the economic point of view, PE mulching was difficult to improve despite environmental costs of PE removal and retiring were included in this study. However, paper mulches and biodegradable mulching materials gave within highest benefits in both the high-yield locations of Logroño and Ciudad Real and in the lower-yield locations of Aragón and Lleida. High benefit found in manually weeded plots shows that this weed control method might be appropriate for fields with low weed density. However, labour in Western Europe is scarce and increasingly expensive.

The percentage of weed management cost on total costs considered as mulching material, removal and retiring costs, mulching installation and other weeding costs ranged between 6% (for PE) and 16% (for Mater-Bi®; Table 5), which was lower than found by Clark et al. (1998), who estimated weeding costs of 22–25% for different tomato management systems.

#### 4 Conclusion

Weed control was necessary in the transplanted tomato crop to obtain benefits. Good weed control and high yield found for biodegradable plastics demonstrate that they are technically viable alternatives to PE. Also the results of paper mulches, which were slightly worse, were still similar to PE and were the only materials able to control purple nutsedge emergence, although they are more difficult to place in the field and can suffer fractures. From the economic point of view, the biodegradable materials gave benefits, though lower than PE. However, market price of the mulching materials is the most determining economic factor, so that PE will probably still be the most common mulching material despite its waste problem unless it was forbidden or the other materials were sold at lower cost. Manual weeding is also found to be an interesting alternative from the economic point of view, provided that weed density was low and labour costs do not increase.

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