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ORIGINAL ARTICLE

Shoot and biomass reduction of perennial weeds using hydromulches and physical changes in the mulches

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Abstract

Hydromulch, used primarily for erosion control, is now being studied as a weed control method in perennial crops and public gardens where weed control is especially difficult; the most challenging species are perennials having powerful shoots that emerge from subterranean propagules. In a previous article, we considered rhizome sprouting capacity through three experimental hydromulches based on wheat straw (WS), rice husk (RH) and used mushroom substrate (UMS). Here, we present data for the number of emerged shoots and their biomass to test whether the mulches were able to influence outcomes affecting weed-crop competition. In addition, the mechanical resistance of these hydromulches was characterized in terms of punching stress or resistance, considering two air humidity levels and applying an artificial ageing test (AAT) to simulate an average spring rainfall for Mediterranean areas. All three mulching types were effective in reducing the weed biomass (60–85%) and RH and UMS also the number of shoots (39–64%) of the four tested weed species compared to the non-mulched control. *Cyperus rotundus* was capable of generating the largest shoot number and biomass, regardless of the mulch treatment. In comparison, all three hydromulches provided a more effective control of *Cynodon dactylon*, *Sorghum halepense* and *Paspalum dilatatum*. Air humidity levels did not cause consistent changes in the physical properties of the hydromulches, while all three showed a weakening after the AAT, more pronounced in UMS than in WS or RH-based mulches, which could compromise the duration of effective weed control. Field trials are envisaged to confirm the duration of the perennial weed control associated with these hydromulches.

Keywords Rhizomes · Punching resistance · Weed shoot sprouting · Aboveground weed biomass

Introduction

Weed control in woody crops such as vineyards and minor crops such as horticultural or aromatic crops and city gardens are not easy, especially in the first years of establishment, because a limited number of herbicides are available for use in such situations, and moreover, they do not control all emerging weeds (for Spain, MAPA 2022). Mechanical weed control in these crops is risky until the trees attain a certain size and vigour because it can damage

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roots or trunks (Hussain et al. 2018). Organic mulches maintained in a layer at least 10 cm thick can control weeds but may reduce the nutrient availability for the plants due to high carbon content (Pérez-Álvarez et al. 2015). Moreover, such mulches require annual replacement, and transportation costs may be a concern unless the mulches are produced on the farm (Hammermeister 2016). In this context, weed control treatments other than herbicides, mechanical treatments, plastic mulches, and even living mulches or solid thick organic non-living mulches could worthwhile alternative. Innovative proposals have been made along these lines, such as the use of biodegradable pyrolysis liquid-amended mulch (Hagner et al. 2020) or the hydromulches, defined as a blend applied in liquid stage and that dries out later. In this specific case, the blends are made of recycled paper slurry, a lignocellulosic material and gypsum as an additive leaving a 1.5–2-cm-thick layer on the soil.

The first studies related to the use of hydromulches appeared in the 1970s as technologies used for soil revegetation in highly eroded areas requiring restoration. In these cases, the organic materials used were chopped pine bark, wood fibre and pulp, sawdust, paper fibre, straw, jute, milled recycled paper and mixtures of these materials with manure, municipal compost or sewage sludge and additives (Lee et al. 2018, Alegre et al. 2016). Warnick et al. (2006) specifically searched for a weed control technique for *Cyperus rotundus* L. (purple nutsedge) by means of different hydromulch formulations based on cotton waste, newsprint, gypsum and a proprietary adhesive. Their hydromulch remained intact in most situations and controlled effectively broadleaved and grass weeds but not *C. rotundus*, which was capable of piercing it. Among the control methods commonly tested on this species, the only effective control method at present other than herbicides is the use of paper sheets (Shogren and Hochmuth 2004; Cirujeda et al. 2012a, b), while plastic films regardless of polyethylene or biodegradable ones are often pierced (Marí et al. 2019).

Claramunt et al. (2020) tested the mechanical performance of 24 different hydromulch formulations based on paper pulp and also evaluated the capacity of the two best formulations, in reducing seedling emergence of four common annual weeds in a growth chamber. On average, the weed suppression capacity, either because the seeds went into secondary dormancy or because the seedlings did not pass through the mulch layer, ranged from 64.6 to 95.9%, depending on the species and the lignocellulosic component. Based on their results, the three most promising blends were fibre-enriched, thereby increasing punching shear strength (Micó et al. 2019). The composition of the resultant hydromulch and its potential weed control capacity have been described and are protected in a Spanish patent (P201930857, 11/01/2022). The mulching types have been tested in greenhouse trials (Mas et al. 2021), showing that they were capable of reducing to some extent the emergence of four perennial weed species by inhibiting rhizome sprouting (also called bud break), preventing aboveground sprout elongation, or trapping the elongated stems under the mulch layer. However, some rhizome fragments were capable of sprouting and had at least one stem that could elongate and had enough vigour to pierce the hydromulch layer to emerge as a first shoot. Information about the possible effect of the hydromulch on the number of aboveground shoots and biomass that can effectively develop from these rhizome fragments is still lacking, and data are presented in this paper.

Before putting substantial effort into field trials, experiments under controlled conditions can indicate the weed suppression capacity of the hydromulches, and therefore, trials of this sort are common in works that evaluate new materials and novel methodologies (e.g. França et al. 2018; Claramunt et al. 2020; Hagner et al. 2020). For the same reasons, data are necessary to predict how long the desired physical properties of the mulches may last after exposure to changing temperatures, sunlight, wetting and drying (after rain). Future climatic conditions are unforeseeable, but simulations can estimate the weed control potential of the mulches, although the suppressing effect of the mulches will depend apart from the climatic factors, also on the weed species and field growth conditions. Accelerated ageing tests (AATs) are commonly used to predict the durability of biodegradable mulches and evaluate their weather fastness (Wang et al. 2022). In some cases, UV radiation is the studied variable (Mosnackova et al. 2019), while in other cases the influence of rain and hot air is tested (Li et al. 2021). The most interesting physical characteristic for hydromulches designed for weed control is probably the mechanical resistance to piercing, which is targeted for improvement to hinder weeds getting through the mulch layer. As the hydromulch blends are hygroscopic, it is expected that successive periods of wetting and drying may affect their global toughness, in terms of physical integrity and durability of its weed control capacity; the potential influence of air humidity on these characteristics also remains unknown. This knowledge would give insight into the range of hydromulch response and impacts when used in various environmental conditions.

Taking into account the previous results of the research assessing the rhizome bud break inhibition capacity of the different hydromulch types of four perennial weeds (Mas et al. 2021), our aims here are complementary: (i) to analyse the potential capacity of three hydromulches in reducing the number of aboveground shoots and biomass of those weeds capable of emerging from rhizomes through the mulches, (ii) to study the punching resistance of these mulches after artificial ageing, and (iii) to compare hydromulch punching resistance (measured by punching stress) at two contrasted relative air humidity values.

Materials and methods

Three experiments were conducted to address each of the three objectives stated above. For all the experiments, the same three hydromulch formulations were used. To create all hydromulches, 16.7 l m^{-2} recycled paper pulp was used as the cellulosic base, with 209.6 g m^{-2} of *Pinus radiata* D. Don fibre (Capellades, Paper Mill Museum, Capellades, Spain) and also 1002 g m^{-2} of gypsum (Marfil ALGISS) added. The three mulches contained different cellulosic compounds originating from crop waste: wheat straw hydromulch (WS) contained 833 g m^{-2} of wheat straw milled with a 2.5-mm sieve, rice husk hydromulch (RH) contained 1250 g m^{-2} of rice husk, and mushroom substrate hydromulch (UMS) contained 3100 g m^{-2} of open-air dried used mushroom substrate. In this case, UMS was based on wheat straw and a layer of peat and milled limestone on the top. Different to WS, this substrate is already quite decomposed by the fungi and has a brown colour and much fines texture.

Greenhouse trials

Greenhouses used for experiments were situated at the facilities of the Universitat Politècnica de Catalunya (UPC) and of the Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), in two locations: in Viladecans (Barcelona, Spain) and in Montañana (Zaragoza, Spain). The experiments were conducted over three months twice at each location, in 2019 and in 2020, from February to May.

Rhizomes of *C. rotundus*, *Cynodon dactylon* (L.) Pers. (bermuda grass), *Paspalum dilatatum* Poiret in Lam. (dallis grass) and *Sorghum halepense* (L.) Pers. (johnson grass) were collected from natural populations and kept in vermiculite at 4°C until use, a few days later. Fragments and tubers without any visible sprouts were chosen. Fragments of *C. dactylon*, *P. dilatatum* and *S. halepense* rhizomes were cut at two nodes and at a minimum length of 1 cm. The medium-sized *C. rotundus* tubers had a mean length of 15.7 ± 0.16 mm. The mean lengths ± standard errors of the rhizomes of the other species were 27.4 ± 0.86 mm (*C. dactylon*), 16.6 ± 0.35 mm (*P. dilatatum*), and 32.4 ± 0.78 mm (*S. halepense*).

Individual rhizomes were confined in smaller pots (called hereafter rhizome boxes) inside a circular pot 28 cm in height and 39 cm in diameter. Ten of these boxes measuring 8 × 8 × 8 cm were placed in the circular plot with one rhizome in each of them. In preliminary trials, it had been observed that *C. rotundus* and *C. dactylon* plants were able to grow horizontally under the hydromulch layer for several cm until they reached the pot edge and emerged there without needing to pierce the hydromulch (data not shown). This design was thus chosen to hinder the rhizomes from sprouting without piercing the mulch, forcing them to grow vertically inside their 8 × 8 × 8 cm box. In field conditions, the mulches are wider than the pot diameter (at least 1 m) so that only a fraction of the rhizomes is expected to have the capacity of growing horizontally avoiding the mulches. Additionally, this design was chosen to facilitate the detection of which rhizomes/tubers were truly able to pierce the mulch and which were not.

The first 10 cm of the big pots was filled with lightweight expanded clay aggregate (8/16 mm Burés, Castelldefels, Barcelona), afterwards covered with 8 cm of substrate (J2 Ecológico Burés, Castelldefels, Barcelona, which is a mixture of vegetable compost, *Sphagnum* peat and perlite containing NPK 8-3-3). The ten boxes were placed on this substrate, and the gaps between the boxes were filled with more substrate. Once the rhizomes had been planted at a depth of 3–4 cm, they were covered with the same substrate and watered with 1 l of water. After that, the hydromulches were applied by pouring 16.7 l m^{-2} on top (2.3 l per pot). The dry weight of the mixtures was between 3.045 and 3.630 g m^{-2}. The resulting thickness of each applied hydromulch layer was 1.9 cm and remained the same once they hardened out. Within each trial, the four species and the four levels of hydromulch treatment (i.e. non-mulched control, WS, RH and UMS) were located randomly, with 64 pots containing 160 rhizomes of each species used in each trial. To test the ability of mulch to affect the plant growth once the plant has pierced it, two responses were assessed, both expressed per rhizome box that showed at least one emerged sprout as unit sample: (1) number of emerged shoots formed from the rhizome, emerging through the hydromulch after piecing it, or emerging in the substrate surface in the control treatment without mulch (NSHOOTS) and (2) dry biomass of these aboveground shoots (g), considering, as before, only those rhizome boxes with emerged shoots (BIOMASS). The hydromulch layer was lifted carefully 72–93 days after rhizome planting, and the emerged shoots were assigned to the corresponding rhizome boxes inside each big pot. This information is aimed as additional information to the data on the proportion of rhizomes whose sprouting was inhibited by the mulches, and about the proportion of sprouted rhizomes whose shoots were totally trapped or not by the mulch, obtained from the same trials, published in Mas et al. (2021). Concerning irrigation, in the Zaragoza trials pots were watered by immersion once during the trial, placing the pots in water allowing water absorption for 15 min. The trial was finished when no new emergences occurred in one week.

Response variables were analysed by means of generalized linear mixed models with (i) a Poisson distribution with a log-link function for NSHOOTS and (ii) a gamma distribution with a log-link function for BIOMASS. Parameters were estimated by maximum likelihood with Laplace approximation. Three fixed effects were considered: (i) 'hydromulch', with four levels of hydromulch type (non-mulched control, WS, RH and UMS), (ii) 'species', with four levels of weed species (*C. dactylon*, *C. rotundus*, *P. dilatatum* and *S. halepense*), and (iii) The interaction between them. Type III chi-square significance tests were performed for these three fixed effects. The random sources taken into account, all of them modelled with unstructured covariance matrices, were chosen seeking the best fitted model in two steps. In the first step of the analyses, the following random sources were considered as possible intercept terms of the linear predictor: 'locality', 'year', 'locality × year', 'replicate' nested within 'locality × year', 'pot', and the covariable 'mean rhizome length' per pot nested within 'species'. After that, in a second step, the random sources 'locality × year' and 'replicate' were removed from the model because the statistics Akaike's information criterion (AIC) and Pearson Chi-square/degrees of freedom indicated better fit without them; moreover, 'mean rhizome length' was considered for NSHOOTS and 'pot' for BIOMASS.

Thus, the mean of NSHOOTS on a link scale (log) of Poisson distribution is given by Eq. (1), where β_o is the overall mean, H_i is the ith 'hydromulch' fixed effect, S_j is the jth 'species' fixed effect, HS_{ij} is the 'hydromulch × species' interaction effect, L_k is the kth 'locality' random effect, Y_l is the lth 'year' random effect and is the β_{ijkl} overall mean of the mean rhizome length and R_{ijkl} is the ijkl mth mean rhizome length covariable.

$$H_{ijkl} = \beta_o + H_i + S_j + HS_{ij} + L_k + Y_l + \beta_{ijkl}R_{ijkl} \quad (1)$$

The mean of BIOMASS on a link scale (log) of gamma distribution is given by Eq. (2), where β_o is the overall mean, H_i is the ith 'hydromulch' fixed effect, S_j is the jth 'species' fixed effect, HS_{ij} is the 'hydromulch x species' interaction effect, L_k is the kth 'locality' random effect, Y_l is the lth 'year' random effect, P_m is the random 'pot' mth effect and ω_{ijklm} is the residual.

$$H_{ijkl} = \beta_o + H_i + S_j + HS_{ij} + L_k + Y_l + P_m + \omega_{ijklm} \quad (2)$$

The least-square means of the levels of the fixed effects ($P<0.05$) and its 95% confidence limits were computed using probability values from the Chi-square distribution. Multiple comparisons were made following the Tukey–Kramer procedure. The GLIMMIX procedure was used to perform the above-mentioned generalized mixed linear models and least-square means comparisons using SAS software version 9.4. (SAS 2013).

Percentage shoot and biomass reduction were calculated with the means of each species in the different treatments. Percentage reduction was determined compared to the data obtained of the non-mulched control pots.

Influence of air humidity

Five sheets of the three types of hydromulch used in the first trial at Viladecans were carefully separated from the substrate at the end of the experiment. Four circular subsamples (35 mm in diameter) were cut from each sheet: two of each were kept at 55% air moisture, the other two at 90% (in a MEMMERT HCP50 humidity chamber), in both cases at 25 °C for 7 days. In these conditions, the hydromulches retained on average 11.18% of the water when kept at 55% relative humidity, and 11.93% when kept at 90% relative humidity, according to the weights obtained before and after drying the sheets at 100 °C for 48 h.

Punching tests of the subsamples were performed with a texture analyser (Stable Micro Systems XT Plus) with a probe 7.86 mm in diameter. The cross head speed in the tests was 4 mm min^{-1}. The surface used to calculate the punching shear corresponds to the lateral surface of a cylinder of 7.86 mm diameter using a mean of three thickness values measured in the penetration section. The following characteristics were assessed: (a) the maximum breaking strength or modulus of rupture, named stress (MPa), which is obtained by dividing the maximum force registered by the area of the tangential section, and (b) the toughness or specific energy of the assay (J m^{-2}), that is, the ability of a material to absorb energy and plastically deform without fracturing, named specific energy. Both were obtained according to Claramunt et al. (2020).

The variables 'stress' and 'associated energy' were statistically analysed, and least-square means were compared by means of generalized linear models of gamma distribution with a log-link function considering three fixed effects: the type of hydromulch, with three levels (WS, RH and UMS), the treatment (55 and 90% relative humidity) and the interaction between them. Parameters were estimated using a complementary log-link function and Type III analysis options. Likelihood ratio statistics were used to compute the significance of each effect. Finally, least-square means of the levels of the effects were computed and compared using probability values from the Chi-square distribution. The GENMOD procedure (SAS 2013) was used to perform both generalized linear models and means comparisons.

Simulated ageing experiment on the hydromulches

The three types of hydromulch tested in the greenhouse trials were also prepared in the laboratory for their mechanical characterization using the same materials and proportions. Because of the limitation of a maximum resistance of 500 N in the load cell of the available texture analyser, the materials were produced at 66.6% of each of the components with respect to those of the greenhouse trials.

To prepare each sheet, the ingredients were mixed using a stirrer (Stirrer LH, Velp Scientifica) and the resultant paste was poured into a $300 \times 300 \times 40$ mm^3 mould, specially designed to apply uniform suction on the lower surface. The mould is made up of two removable elements: (a) An upper box with a lower base perforated with 1-mm-diameter holes evenly distributed on a 10×10 mm grid, on which a filter sheet is placed and (b) a lower vacuum box connected to a pump through a control gauge. In this case, the suction pressure was set to − 20 kPa. Once the required amount of paste had been deposited, the vacuum pump was activated and the excess water was retained in the vacuum box; the mixture was forced to lose water and to acquire a pasty consistency, and the loss of water reduced the plates to an approximate thickness of between 8 and 12 mm. This process had an approximate duration of 30 s. After that, each sheet was dried in an oven at 60 °C for 24 h and kept at room temperature and humidity until use.

Four sheets of each hydromulch type were prepared. Two sheets were left untreated and were kept at room temperature, while the other two underwent forced ageing (AAT) by means of twelve consecutive cycles of wetting and drying of 6 h of duration each in a CCI climatic chamber specially designed to age building materials. During each cycle, the following processes took place: 5 min of 24 mm water shower at maximum pressure at the outlet nozzle of 210 kPa, 55 min of temperature increase up to 60 °C and a gradual decrease of the relative air humidity until 20% was reached, and 5 h at 60 °C and 20% relative air humidity. The amount of rain received by the sheets in the 12 cycles was 288 mm. Considering that no standardized ageing test is available for hydromulches, the chosen cycles described were intended to simulate the amount of spring rainfall that can be expected in some Mediterranean viticultural-growing areas.

The variables stress and associated energy were statistically analysed using the GENMOD procedure (SAS 2013) by means of generalized linear models of gamma distribution with a log-link function as before considering three fixed effects: the type of hydromulch, with three levels (WS, RH and UMS), the treatment (ageing or not), and the interaction between them. Least-square means of the levels of the effects were computed and compared using probability values from the Chi-square distribution.

Results

Greenhouse trials

At least some plants from all four species were able to emerge through all three types of hydromulches as well as in the control treatment, demonstrating their vigour and viability (see Fig. 1 as an example).

Both NSHOOT and BIOMASS were significantly impacted by weed species and hydromulch type, with no significant interaction (Table 1). The random effect 'year' was associated with the greatest variability for NSHOOTS, and 'locality' was associated with the greatest variability for BIOMASS. Two hydromulches, RH and UMS, reduced mean shoot number by nearly 50% compared to

Fig. 1 First row: examples of non-mulched control pots; row 2: appearance of some pots covered by hydromulch where some weed shoots were able to pierce it. From left to right, *Cynodon dactylon* (row 2 through used mushroom substrate), *Cyperus rotundus* (row 2 through rice husk), *Paspalum dilatatum* (row 2 through wheat straw) and *Sorghum halepense* (row 2 through rice husk), all of them belonging to the 2020 greenhouse trial at Viladecans (Barcelona, Spain)

Table 1 Likelihood ratio statistics of fixed effects 'hydromulch', 'species', and 'hydromulch × species', covariance parameter estimates of the random effects, and model fit statistics in the analyses of number of shoots and aboveground biomass *per* rhizome box, according to generalized linear mixed models of Poisson distribution for NSHOOTS, and gamma distribution for BIOMASS

	NSHOOTS		BIOMASS (g)	
	d.f. num/d.f. den	*P* > chi- square	d.f. num/d.f. den	*P* > chi- square
Test of fixed effects				
Hydromulch H	3/151	< 0.0001	3/151	< 0.0001
Species S	3/151	< 0.0001	3/151	< 0.0001
H × S	9/151	< 0.8152	9/151	0.6344
Covariance parameter estimates of random effects				
Locality	0.2548		0.3319	
Year	1.6026		0.0143	
Pot	–		1.1E−12	
Mean rhizome length	5.2E−23		–	
Residual	–		0.5379	
Model fit statistics				
AIC	537.50		373.76	
Pearson chi-square/d.f	0.49		0.49	

NSHOOTS Number of emerged shoots *per* rhizome; *BIOMASS* Dry biomass of the emerged shoots *per* rhizome; *d.f.* Degrees of freedom; *num* Numerator; *den* Denominator

Table 2 Least-square means for the levels of the two main fixed effects, type of hydromulch and species, corresponding to the analyses of NSHOOTS and BIOMASS *per* rhizome box, according to generalized linear mixed models of Poisson distribution for the first variable, and gamma distribution for BIOMASS, the second. In each effect and variable, least-square means with the same letter are not considered significantly different at $P < 0.05$ (Tukey–Kramer test)

	NSHOOTS	BIOMASS (g)
Hydromulch		
Wheat straw (WS)	1.6800^{ab}	0.9641^{b}
Rice husk (RH)	1.5127^{b}	0.5576^{c}
Used mushroom substrate (UMS)	1.4887^{b}	1.2269^{b}
Non-mulched control	2.9539^{a}	2.2221^{a}
Species		
Cynodon dactylon	1.6986^{b}	0.5383^{c}
Cyperus rotundus	3.1821^{a}	0.9625^{b}
Paspalum dilatatum	1.4514^{b}	0.9351^{bc}
Sorghum halepense	1.4246^{b}	3.0251^{a}

NSHOOTS Number of emerged shoots *per* rhizome; *BIOMASS* Dry biomass of the emerged shoots

the control, whereas shoot numbers associated with WS did not differ from the control ($P = 0.05$). With respect to the mean aboveground weed biomass reduction (Table 2), they achieved 75% with RH, 57% with WS, and 45% with UMS.

C. rotundus produced more shoots than any of the other three species and generated around one-third of the biomass of *S. halepense* (Table 2). *C. dactylon* and *P. dilatatum* had intermediate shoot and biomass productions.

Considering only those rhizomes that produced some shoots able to grow above ground, the estimated mean shoot number per *C. rotundus* tubers was 3.18 ± 1.19. The mean of sprouts per tuber was 6.1 ± 2.3, 3.1 ± 1.2, 1.4 ± 0.9 and 2.3 ± 0.9 for the untreated control, WS, RH and UMS, respectively.

Influence of air humidity on punching resistance

None of the three hydromulch types differed with respect to mean stress or mean energy needed to pierce them relative to the 55% or 90% air relative humidity level (Table 3).

Regardless of the air moisture, the WS-based mulch exhibited the greatest stress, greater than both RH and UMS.

Simulated ageing experiment on the hydromulches (AAT)

Mean punching stress values for RH and WS hydromulches were reduced, but UMS hydromulch was not weakened by the ageing process; however, this type was weaker than the other types before ageing (Table 4, Fig. 2). The WS hydromulch exhibited higher mean stress values than the UMS hydromulch, with RH hydromulch having intermediate resistance. The energy needed to pierce the mulches was reduced for the aged materials regardless of the mulch type, although the mean energy needed to pierce the mulches was lower for UMS compared to RH and WS (Table 4).

Discussion

Greenhouse trials

The aim of an integrated weed management strategy (IWM) is to combine several control methods in order to

Table 3 Likelihood ratio statistics of different effects in analyses of punching stress and energy and least-square means of the levels of the main effects ‘type of hydromulch’ and ‘relative humidity’, according to generalized linear models of gamma distribution. Squares means with the same letter are not considered significantly different at $P<0.05$ (Tukey–Kramer test)

Variable	Effect	DF	Chi-square	*P* > chi-square	Levels	LS mean
Stress MPa	Type of hydromulch (H)	2	42.13	< 0.0001	RH	0.79[b]
					WS	1.38[a]
					UMS	0.49[c]
	Relative humidity (%rh)	1	1.08	0.2994	55%	0.86[a]
					90%	0.77[a]
	H × %rh	2	0.56	0.7576		
Energy (J/m^2)	Type of hydromulch (H)	2	32.56	> 0.0001	RH	5899[b]
					WS	9831[a]
					UMS	4209[c]
	Relative humidity (%rh)	1	0.84	0.3598	55%	6566[a]
					90%	5948[a]
	H × %rh	2	1.86	0.3946		

RH Rice husk, *UMS* Used mushroom substrate, *WS* Wheat straw

Table 4 Likelihood ratio statistics of different effects in analyses of punching stress and energy and least-square means of the levels of the main effects ‘type of hydromulch’ and ‘ageing’, according to generalized linear models of gamma distribution. In each effect and variable, least-square means with the same letter are not considered significantly different at $P<0.05$ (Tukey–Kramer test)

Variable	Effect	DF	Chi-square	*P* > chi-square	Levels	LS mean
Stress MPa	Type of hydromulch (H)	2	4.75	0.0931	RH	1.75[ab]
					WS	1.86[a]
					UMS	1.51[b]
	Ageing (A)	1	14.35	0.0002	Non-aged	1.99[a]
					Aged	1.45[b]
	H × A	2	5.97	0.0505		
Energy (J/m^2)	Type of hydromulch (H)	2	16.19	0.0003	RH	4391[a]
					WS	4280[a]
					UMS	2758[b]
	Ageing (A)	1	13.18	0.0003	Non-aged	4504[a]
					Aged	3087[b]
	H × A	2	2.4	0.3019		

RH Rice husk, *UMS* Used mushroom substrate, *WS* Wheat straw

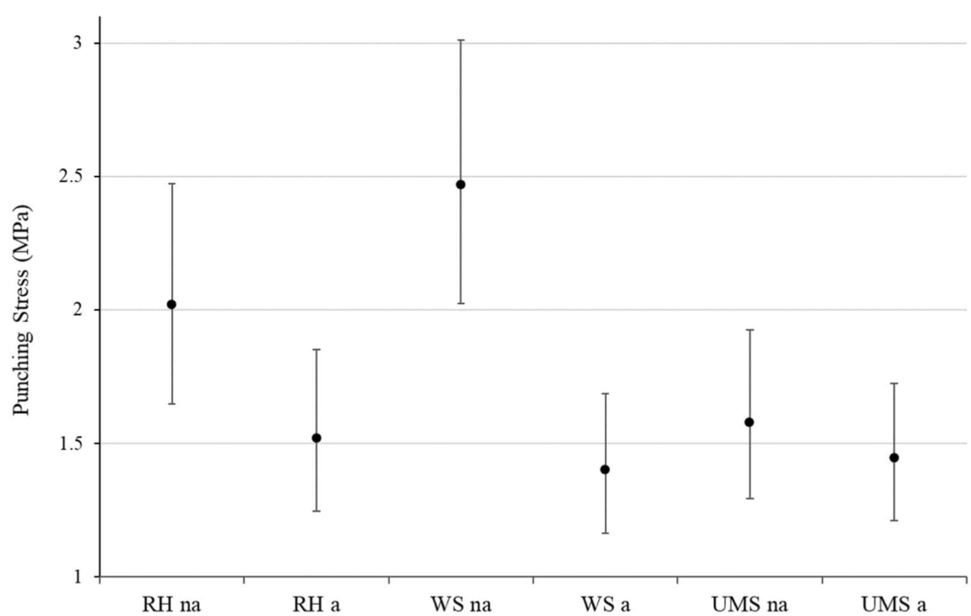

Fig. 2 Least-square means and their 95% confidence limits of the levels of the interaction effect ‘type of hydromulch × ageing’ for the variable punching stress (MPa) in which, analysed by means of generalized linear models of gamma distribution, the interaction was significant at $P=0.05$. RH: rice husk, WS: wheat straw, UMS: used mushroom substrate, na: non-aged, a: aged

achieve sufficient and sustainable weed control (Hussain et al 2021). Weed rhizomes sprouting from the existing propagule bank is one step of governing weed population dynamics (Gerowitt and Baraibar 2022), and reducing this capacity could be considered as "one little hammer", following Liebman and Gallandt (1997). An effective mulch should have the ability reducing weed emergence, but an additional control effect could be that the emerging plants would be weaker than in the non-mulched treatment, representing less competition for the crop.

The three mulch types were capable of hindering rhizomes of the four weed species to pierce them, meaning that they sprouted under the mulch layer but were not able to pierce it (Mas et al. 2021). Despite the effect of 'trapping' was not affected by the interaction 'species × mulch', it is interesting to know that the highest reduction value was achieved for *P. dilatatum* (87.5%) and the lowest for *C. rotundus* (13.6%) (Mas et al. 2021). The present results show that all three mulches were additionally capable of reducing shoot number and reducing biomass of the emerged shoots in all four species.

The chosen weed species are problem species worldwide (Holm et al. 1977) and also frequent in irrigated crops in north-eastern Spain. However, it is not common that all four species grow at high density in the same crops.

C. rotundus is especially insidious in irrigated areas established decades ago, affecting all type of crops including gardens. Despite being reduced unfortunately the lowest bud break and emergence reductions were found for this species (Mas et al. 2021) and the present data show that *C. rotundus* also had the lowest mean shoot number reduction within the four tested species, in this case probably due to its sharp leaves (Holm et al. 1977) capable of piercing plastic mulches as well (Cirujeda et al. 2012a). This species exhibited a different biological strategy compared to the other ones tested here, producing more stems in all of the treatments (Fig. 2) but lower biomass (Table 2). When growing under maize in different maize plant arrangements, this species is found to emit between 2 and 8.7 shoots per plant (Rambakudzibga 1999), while Muzik and Cruzado (1953) observed an average of 5 shoots per tuber; the present results in the untreated control were in the range of these results and lower in the mulched treatments. Taking into account that *C. rotundus* is susceptible to competition (Patterson 1982; Nesser et al. 1997; Santos et al. 2015), a possible strategy to control this weed could be combining the emergence and biomass reduction with hydromulch and planting a fast-growing crop weakening the emerged weed afterwards.

C. dactylon is common in irrigated and dryland summer crops and is difficult to control even in rainfed vineyards due to its high tolerance to drought (Valencia-Gredilla 2020). This weed sprouts both in the lines of the crops and in the interrows. A possible IWM strategy could be combining cover crops in the interrow with the use of hydromulch in the remaining areas. Despite mulches achieved a mean high emergence reduction (Mas et al. 2021) and also on the biomass, still some shoots were capable to grow through the mulches, so that the remaining plants might be necessarily controlled, e.g. with herbicides to avoid regrowth of the stand.

S. halepense is a major weed in maize, in fruit orchards and in gardens. A widespread resistance to ALS-inhibiting herbicides in maize in the area (Torra et al. 2022; Montull and Torra 2023) is forcing to substitute maize with other crops. A common control strategy for these populations in the area is combining tillage in early summer to dry out rhizomes (as described, e.g. in Ceseski et al 2017 and Travlos et al. 2019) with establishing alfalfa in autumn during 4–5 years (Arle and Everson 1955); however, if a perennial crop is chosen for crop rotation, applying hydromulch could be a IWM proposal, too. However, it needs to be taken into consideration that this species showed the capacity to generate a considerable biomass from a low number of stems (Table 2) so that it might be necessary to combine other methods such as mowing, too.

Finally, *P. dilatatum* is present in gardens, roadsides, agricultural land and other disturbed sites; moreover, it is a troublesome weed in savannas, moist grasslands, wetlands, riparian habitats, and forests of tropical and subtropical areas (Vélez-Gavilán 2017). This species showed the highest proportion of trapped *versus* sprouted rhizomes (Mas et al. 2021); additionally, mean number of shoots and biomass were notably reduced with the hydromulches, which is a good starting point. Which specific method should be combined with hydromulch use to control this weed will depend on each situation.

The hard and rigid hydromulches thus possibly hindered weed growth by constricting the stems from below. This effect might be an additional positive aspect for weed control compared to other mulches: plastic mulches are more flexible and once they are pierced they offer little mechanical resistance, allowing plant enlargement; loose organic materials such as bark or straw can more easily be physically avoided by the plants as they offer non-continuous resistance since the fragments are not joined; only rigid paper sheets might also cause some constriction on the plant stems from below (Marí, 2019). The mean shoot number and weed biomass reductions thus demonstrate the potential of these hydromulch types to reduce weed competition with a crop (Tables 1 and 2).

Our results, though obtained from pot experiments, are similar to those obtained by Hagner et al. (2020), who, after 12 weeks of applying biodegradable pyrolysis liquid-amended mulches in a city park experiment including perennials such as *Poa pratensis* L., *Festuca rubra* L., *Trifolium* *repens* L., and *Taraxacum officinale* Weber in Wiggers, reached weed cover reductions of 85%. The high level of shoot and biomass reduction of *P. dilatatum* achieved by the three types of hydromulches make them worth to be considered for further research as a potential an alternative to herbicides, especially suitable for using also in gardens and other non-cropped areas where it is a troublesome weed (Vélez-Gavilán 2017).

Concerning the hydromulch type, RH was able to reduce weed biomass to a greater extent than the other two mulches (Table 2) but from the shoot number control effect, all three had similar performance. The similar shoot and biomass reduction capacity in these trials do thus not contribute to facilitate the election of the most appropriate mulch for weed control.

Punching resistance of the mulching materials and AAT

The balance between the moisture in the tested hydromulch types and the relative humidity of the air showed a different pattern to that observed for other materials. For example, wheat straw pellets and sorghum stalk contained 13% moisture at 55% relative humidity and up to 20% with 90% air humidity (Theerarattananoon et al 2011). Thus, the tested hydromulch types were less influenced by the environmental humidity than expected, despite containing wheat straw and other similar materials. Possibly the content in other components had an influence on this behaviour. However, this finding is consistent with the fact that little water (0.75%) was retained by those mulches. Results of the AAT demonstrate that rainfall has more impact than air humidity in the degradation of the tested materials. The results of the air moisture and AAT trials show that potentially the tested hydromulch materials can be useful in reducing weed rhizome sprouting and shoot emergence in environments with lower and with higher air humidity, provided that rainfall is not very frequent and persistent.

At present, it is not possible to compare these results with other AATs on hydromulches as no other similar studies are available. However, Lanini et al. (2011) found that organic mulches generally require annual replacement, probably because they lack a matrix capable of binding the loose elements, while the objective is that hydromulches have a weed control capacity during a longer time. In other studies, the duration of such mulches has not yet been analysed (López-Urrea et al. 2020). It is possible to state, however, that the mean stress values obtained in the punching tests of the same types of hydromulches "aged" in the three-month greenhouse trial presented above were about half those obtained after the artificial ageing process, while the energy values were higher (Table 3, Table 4). So, it is possible that solar radiation plays an important role in their mechanical resistance as it occurs in some biodegradable mulch films (Kijchavengkul et al. 2008; Immirzi et al. (2009). In any case, the 1.99 MPa obtained as the mean stress value of non-aged hydromulches (Table 4) is still far from the 3.87 MPa achieved by some black polyethylene plastics employed as agricultural mulches (Hosseinabadi et al. 2011).

One important advantage of the hydromulches is that they potentially last longer and are less susceptible to wind or animal-driven dispersion than other less rigid and non-continuous mulches such as bark or pruning waste. Unfortunately, the present results suggest that punching resistance decreased over time after an average spring rainfall so that the shoot number and weed biomass reductions will probably be less and a re-application might be necessary if the mulch does not resist the punching capacity of the weeds when losing its resistance with time. However, further field studies are needed to confirm it in on-farm conditions and to find out the successful duration of the materials in each situation.

Conclusions

Although some plants were capable of growing through the hydromulch layers, the mean biomass were significantly lower for all of the hydromulch types compared to the non-mulched control and the mean number of shoots for RH and UMS. Additionally to the capacity of bud break inhibition (Mas et al. 2021), all of the mulches were thus able to reduce the potential competitiveness of the four weed species by reducing the aboveground biomass: less rhizomes buds sprout, and those which are able to pierce the mulches end up with lower biomass. These results encourage doing field trials considering hydromulch as one more weed control method to be considered in IWM programmes.

It would be interesting to find out if besides the tested parameters also the reproductive capacity of the weeds can be reduced with these mulches.

After the AAT, and also after the duration of the greenhouse experiment, all three hydromulch types showed a decrease in their physical properties, being more susceptible to piercing by weeds, although they were not affected by the relative air humidity. This finding opens the possibility for using the mulches in situations with high air humidity, such as near the seashore.

Our results suggest that rain and the resulting wetting and drying periods are environmental factors that can potentially diminish the weed control capacity of the tested hydromulch types. To extend the efficacy of these hydromulches, further work could use a thicker layer than was tested in this experiment, focusing on RH and WS-based mulches and attempting to lengthen the weed control period by improving these formulation probably by adding a hydrophobic substance that would allow the mulch to dry our faster and to get less wet after a rainfall. The difficulty of finding biodegradable products that are both suitable for hydromulch formulation and cost-effective needs to be considered as well.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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