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Non-chemical weed management for sustainable rice production in the Ebro Delta

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Abstract

Weed control is one of the major challenges in rice cultivation, and the use of agrochemicals for this crop is severely restricted under the new European agricultural policy. Therefore, new effective non-chemical weed control techniques are the key to sustain European rice production. We investigated four non-chemical weed management strategies in the Ebro Delta in north-eastern Spain, two in dry-seeded rice fields and two in water-seeded rice fields. In addition, two controls per sowing condition were included: a positive control consisting of chemical herbicides treatment and a negative control consisting of no weeding and no seeding. Mechanical weeding using a rotary harrow placed in front of the seeder was the best weeding technique for dry seeding, while 'stale seed bed' and transplanting was the best performing technique for wet seeding. Both techniques were as effective as the chemical weeding control, reducing the density of weeds and the supplementary manual weeding time needed for those weed species more abundant in Ebro Delta rice fields (i.e., *Echinochloa oryzoides*, *Echinochloa crus-galli*, *Bolboschoenus maritimus* and *Heteranthera reniformis*). Thus, non-chemical weeding alternatives have been proven effective for both, transplanting and dry seeding field management strategies.

KEYWORDS
barnyard grass, herbicides, integrated management, rice farming, weeds

1 | INTRODUCTION

Rice is the most important staple food for more than half of the world's population, providing up to 20% of total caloric intake (Das, 2017; Dass et al., 2017). In Europe, it is an important crop with a cultivated area of 637 872 ha and an average annual production of over 4 million tonnes of paddy rice (FAOSTAT, 2022). Spain is the second largest European rice producer next to Italy. In 2021, Spain produced 617 180 tonnes of paddy rice on more than 84 680 ha, representing about 20% of European production (FAOSTAT, 2022). Italy is the largest rice-producing country in Europe (227 000 hectares of cultivation area and 1.46 million tons of total grain production in 2021) (FAOSTAT, 2023).

The main rice-producing area in Spain is Andalusia, followed by Extremadura, Catalonia, Valencia, and Aragón (MAPAMA, 2018; Morillo, 2023; Rodrigo & Ribeiro, 2023). Spain is the leading European country in terms of cultivated area for organic food production (2 246 475 ha). However, only 1300 ha of organic rice are grown in Spain (less than 1.3% of the rice area), and only 0.8% of Spanish rice is marketed under organic certification. Thus, the current demand for organic rice in Spain (and all of Europe) is met by Italy. Spanish farmers generally avoid organic rice production because of difficulty in managing weeds (Mañosa et al., 2001). In fact, weed control is one of the major challenges in organic rice production (Hoosain et al., 2013).

Agrochemical inputs are used in conventional agricultural production systems to achieve high yields. Unfortunately, this practice leads to an increase in production costs, dependence on non-renewable resources, biodiversity loss, water pollution, chemically contaminated food, soil degradation, and risks to farmers' health (Dash et al., 2017; Katayama et al., 2019; Liu et al., 2020; Sihi et al., 2017; Wood et al., 2010). To address these concerns, the European Commission is imposing a substantial reduction in pesticide use by 2030 (Silva et al., 2022) which underscores the significance of this study.

Weed competition is the main factor affecting yield in both conventional and organic systems (Delmotte et al., 2011; Reddy et al., 2023). Weed proliferation during rice cultivation is determined by climatic and edaphic conditions, as well as the quality of the irrigation water which is one of the ways in which seeds are introduced in paddy fields (Kendig et al., 2003; Labrada et al., 1996; Scott et al., 2013). *Echinochloa* spp., *Leptochloa* spp., *Oryza sativa* (weedy rice), *Cyperus* spp., *Heteranthera* spp. and *Alisma plantago-aquatica* are the main weeds found in Spanish rice fields (Kraehmer et al., 2017; Osuna et al., 2012). In addition, *E. crus-galli* and *E. oryzoides* are the most problematic weeds in the Ebro Delta, (Gómez de Barreda et al., 2021; Lillebø et al., 2003) as spontaneous herbicide-resistant populations have emerged due to repeated applications of herbicides with the same modes of action (Gómez de Barreda et al., 2021). In fact, misuse of herbicide treatments and a reduction in the chemical modes of action targeted by commercially available herbicides have led to increased diversification of herbicide-resistant weeds (Osuna et al., 2012).

Manual weeding in direct-seeded rice fields is not economically viable, and qualified weeding personnel are scarce because the work is physically demanding. Water control is another important weed management tool that reduces the diversity and density of weed species and affects rice crop yields (Zhang et al., 2021). Farmers flood the fields prior to sowing after performing the stale seed bed technique. This involves flooding the rice field to induce the emergence of the first generation of weeds, which are then eliminated by mechanical puddling with a rotovator or herbicide treatment before rice sowing (Català, 1995). This technique implies a delay in rice sowing, which jeopardises the production of long-cycle varieties due to low temperatures during rice maturation. In addition, the stale seedbed technique increases the risk of rice seed loss due to chironomids (Dale, 1994).

Maintaining weed density at a level sufficiently low to avoid the threshold for herbicide treatment is difficult, even in conventional rice production. Therefore, new weed control methods need to be developed, not only for conventional rice production, but especially for organic rice production, where the use of synthetic herbicides is explicitly prohibited. Innovations in seeding, transplanting and mechanical weed control represent opportunities for both organic and conventional rice production. In addition, organic agrochemical products and organic farming technologies are more sustainable, even though they require greater inputs, knowledge, and skills (Hoosain et al., 2013).

Dry seeding is another strategy that can help in weed management. However, because rice is the most salt-sensitive cereal crop (Negrão et al., 2011), dry seeding hasn't been traditionally practiced in the highly salinized Ebro Delta. However, since 2009, apple snail invasion has prompted farmers to adopt dry seeding as a preventive measure against damage caused by this pest (Català et al., 2010; Lopez et al., 2010; Pérez Pons, 2012). The traditional puddling during the stale seed bed flooding destroys the first emergence of weeds and delays the undesirable effects of chironomids (Català, 2011; Franquet Bernis, 2018). However, stale seed bed flooding and puddling do not prevent apple snail activity and do not control chironomids to the same extent as dry seeding does. Nowadays, dry seeding is applied to about 10% of the rice fields in the Ebro Delta (about 2000 ha). Furthermore, dry seeding allows seedlings to be sown in rows, which is not possible with water-seeded rice (Franquet Bernis, 2018). This row seeding permits, in turn, the mechanised weeding between rows.

Mechanical weeding provides an alternative to herbicides (Liu et al., 2023). Seedlings growing in rows create corridors where the first generation of weeds (mainly grassy weeds) can be mechanically or even manually removed. A harrow, rotovator or roller can be used for this purpose. Harrows can be easily adapted to dry seeding in rows, although the rotovator commonly used in the stale seed bed would be more difficult to work with. Roller weeders or power weeders are also useful weeding tools in transplanted (non-seeded) or in row-seeded crops whereas a grass harrow (with flexible tines) could also be useful after dry seeding, although it is useless when fields are flooded.

The objective of this work was to investigate the use of non-chemical strategies to control weeds in rice fields, both in dry-seeding and in water-seeding systems, by analysing the dynamics of weed species in different plots subjected to different weed control treatments in the rice fields in the Ebro delta.

2 | MATERIALS AND METHODS

2.1 | Experiment design

This study was conducted in a farmer's field in the Ebro Delta (Tarragona, Spain) with an average annual temperature of 18°C and an annual precipitation of 500 mm (Figure SM2 in supplementary material). The experimental field (40° 42′ 40″ N 0° 37′ 41″ E) was a loamy-textured rice field with pH 7.9, CEC 1.13 $dS{\cdot}m^{-1}$, 2.39% OM, 14.1 $N\text{-}NO_3$ $mg{\cdot}kg^{-1}$ and 23 mg $P{\cdot}kg^{-1}$. Seeds of the temperate japonica rice (*Oryza sativa*) variety *Argila* were provided by COPSEMAR (Valencia, Spain). The trials were carried out from May to October of both 2019 and 2020. The area of each of the plot was $8 \times 30\ m^2$ with independent water inlets and outlets and a 1.5 m wide land embankment surrounding each plot. The experimental design included one replicate per treatment and year.

The experimental fields had not been treated with herbicides in the previous 2 years, and there was no cross-contamination from other adjacent fields. In addition, the weeds from the seed bank were qualitatively and quantitatively representative of the Ebro delta field conditions.

2.2 | Experimental procedures

Eight different weed control treatments were tested, of which 4 were dry-seeded and 4 were water-seeded. For each of these 4 treatments, one treatment served as a no-seeding control (i.e., DSC dry-seeding control and WSC water-seeding control, respectively) in order to determine the maximum weed incidence and the weeds seed bank present in each plot. The two remaining control treatments consisted of standard dry seeding and water seeding using herbicides commonly used by farmers in conventional rice production in Spain (i.e., DSH and WSH, respectively). In dry seeding, the seeding rate was 205 kg·ha^{-1} and 25 cm row spacing, while in water-seeding it was 274 kg·ha^{-1} to achieve optimal plant density. The weed control methods were named as follows: (1) dry seed control (DSC), (2) simple dry seed (SDS), (3) dry seed with supplemental irrigation (DSI), (4) dry seed with herbicide (DSH), (5) water seed control (WSC), (6) stale seedbed and seeding (FSW), (7) stale seedbed and transplanting (FSP), (8) water seeding and herbicide (WSH).

DSC plots were managed in the same way as the following dry-seeded strategies, with the exception that this plot was neither seeded nor weeded and was therefore used as a control. SDS plots were dry-seeded and weeded with a rotary harrow placed in front of the seeder. DSI plots were irrigated twice before seeding and were dry-seeded with a rotary harrow placed in front of the seeder, being additionally weeded with a flexible tine harrow once the rice has emerged. DSH plots were dry seeded with a rotary harrow placed in front of the seeder and an herbicide treatment was applied before flooding. WSC plots were managed in the same way as the following water-seeded strategies, although the parcel was neither weeded nor seeded. FSW plots were flooded and puddled using a metallic roller before water seeding and were additionally weeded during the second year by using an experimental roller frame. FSP plots were flooded and puddled using a metallic cylinder like FSW, but in this treatment rice was transplanted instead of seeded. Additionally, in the second year, they were weeded twice by using a roller frame between rows. Finally, WSH plots were weeded using herbicides before water-seeding.

All plots were fertilised with 800 kg·ha^{-1} POLYSOL (2-6-10) as a basal dressing application. Dry-seeding plots were fertilised with 400 kg·ha^{-1} $(NH_4)_2SO_4$ 45 days after seeding (DAS), 400 kg·ha^{-1} $(NH_4)_2SO_4$ at 60 DAS, and 200 kg·ha^{-1} $(NH_4)_2SO_4$ at 75 DAS, for a combined total of 236 kg·ha^{-1} total N. In the case of the water-seeded rice, the basal fertilisation was supplemented with 400 kg·ha^{-1} $(NH_4)_2SO_4$ at 25 DAS (before flooding) and 250 kg·ha^{-1} $(NH_4)_2SO_4$ at 50 DAS, for a combined total of 250 kg·ha^{-1} total N.

2.3 | Data collection

Weeds were identified per species and the plant densities for both the dry and water seeding experiments. A total weed scoring was performed yearly by a worker who exhaustively recorded the number of plants per plot and species during a complete manual weeding in late July. In addition, the time required for manual weeding per surface was recorded for each treatment. The weeding time per surface was estimated based on the time necessary to remove all weeds in the treatments' plots.

Weed control efficacy was quantified as the percentage of weeds that did not emerge per treatment compared to the unseeded control plot with the following formula $R = ((C - E)/C) \times 100$, where R is the percentage of weed reduction, C is the number of emerged weeds in the control plot, and E is the number that emerged in the treatment plot (Abbott, 1925). When evaluating the occurrence of the aquatic weed *Heteranthera reniformis*, it was necessary to calculate the weed volume in litres per square metre (l m^{-2}) rather than the number of seedlings per area because of its biology. The volume was estimated by using 16 L buckets when weeding *H. reniformis* out of the fields.

For 2019, grain yield was estimated as follows: rice was manually mowed from three circular surfaces of 0.418 m^2 randomly sampled in each plot and the results were proportionally estimated to a plot size equivalent to 1 Ha based on the potential yield of the rice fields. The grains and straw were threshed using a Kubota SRM27 harvester (Osaka, Japan), and the weight was recorded using a scale.

2.4 | Statistical analysis

A three-factor design with double interactions was used to contrast the effects of treatment, species and year on the number of weeds per m^2 observed in the field. The Fisher-Snedecor (F) statistic was used for multiple comparisons of the levels of each factor. When significant differences were found for a factor, pairwise comparisons were performed using Tukey's test and overlapping confidence intervals. The robustness of the statistics used was ensured by checking the validity conditions of the model or by checking the unimodality of the residuals. In addition, the Durbin-Watson statistic was used to check the independence of the sample values. The study with this design was conducted for dry and water-seeding. The software used was Statgraphics Centurion XVIII software (Statistical Graphics Corp., Rockville, MD, USA).

3 | RESULTS

3.1 | Weed occurrence in dry-seeding

In dry seeding, statistical analysis of the results allowed the detection of significant differences between treatments ($p < 0.0001$), between weed species ($p < 0.0001$), in treatment-species interaction ($p = 0.0001$) and in treatment-year interaction ($p = 0.0440$). On the other hand, no significant differences were observed between years ($p = 0.7033$) and no significant differences were observed in the species-year interaction (in the complete design, $p = 0.9949$). This high p-value justifies the removal of the species-year interaction from the model. The comparison between treatment pairs showed that the average number of weeds per m^2 (plants/m^2), was significantly higher

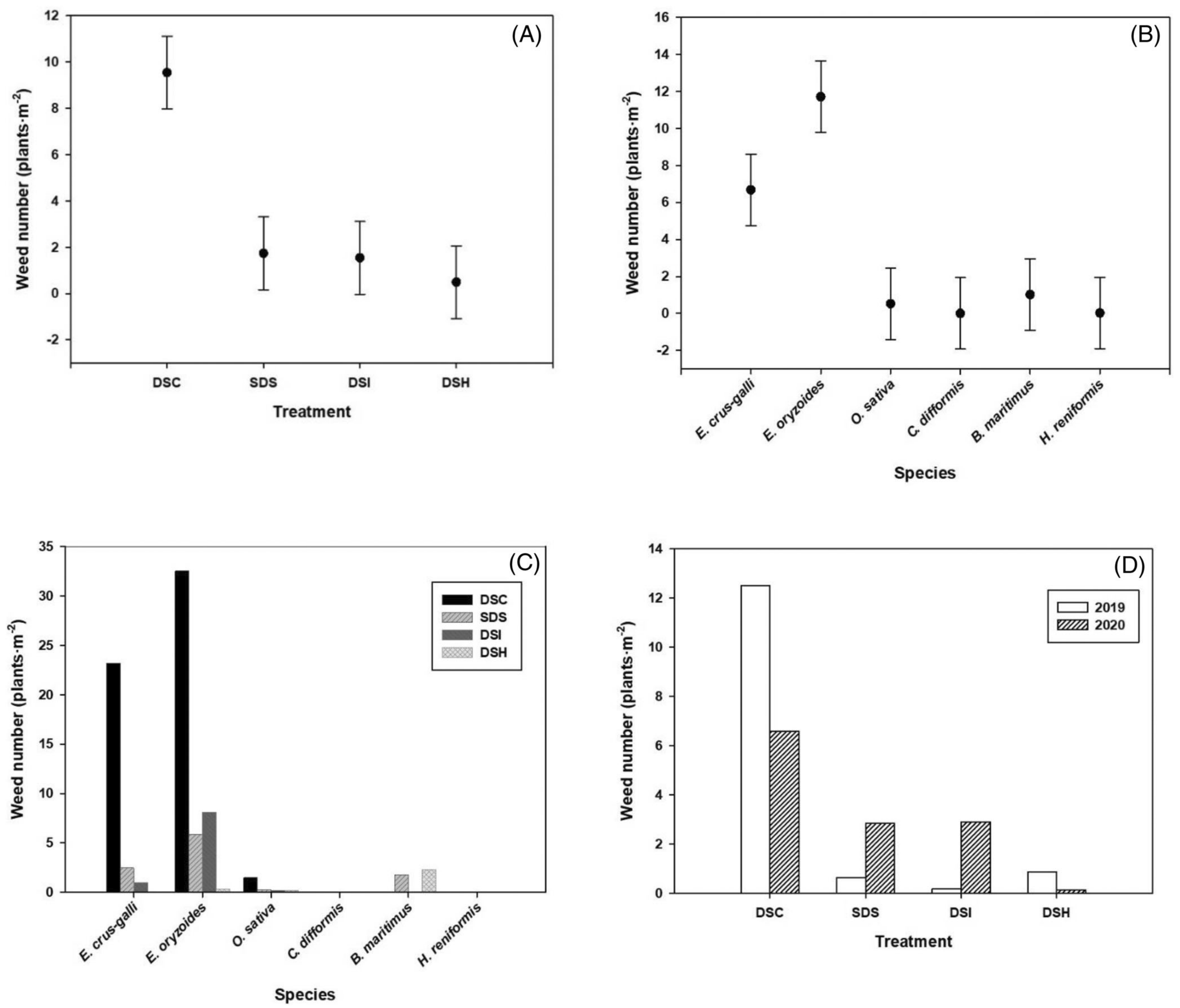

FIGURE 1 Results for the dry-seeding treatments (A) weed density of all species average of both years: Dry seeding control (DSC), simple dry seeding (SDS), dry seeding with supplemental irrigation (DSI) and dry seeding with herbicide (DSH). (B) weed density of all treatments average of both years: *Echinochloa crus-galli*, *Echinochloa oryzoides*, *Oryza sativa*. spp., *Cyperus difformis*, *Bolboschoenus maritimus* and *Heteranthera reniformis*. (C) weed density per treatment and specie average of both years: WSC (black), FSW (incrementing line), FSP (grey cross line) and WSH (decreasing line) (D) weed density in each treatment per year: 2019 (white) and 2020 (increasing line).

in the control treatment than in the other treatments (Figure 1A and Table 1):

$$\overline{N}_{\mathrm{DSC}}(9.54\,p/m^2) > \overline{N}_{\mathrm{SDS}}(1.73\,p/m^2) \approx \overline{N}_{\mathrm{DSI}}(1.54\,p/m^2) \approx \overline{N}_{\mathrm{DSH}}(0.49\,p/m^2) \quad (1)$$

On the other hand, the number of observed plants of the grassy weed species *Echinochloa oryzoides* (Ard.) Fritsch was significantly higher than that of the species *Echinochloa crus-galli* (L) Beauv. and the number of plants observed of the species *Oryza sativa* (L.) (weedy rice), *Cyperus difformis* (L.), *Bolboschoenus maritimus* (L.) and *Heteranthera reniformis* (Ruiz & Pavon) were almost residual in comparison with grassy weeds (Figure 1B and Table 1):

$$\overline{N}_{E.\ oryzoides}(11.71\,p/m^2) > \overline{N}_{E.\ crus-galli}(6.68\,p/m^2) > \overline{N}_{B.\ maritimus}(1.02\,p/m^2) \approx \overline{N}_{O.\ sativa}(0.52\,p/m^2) \approx \overline{N}_{H.\ reniformis}(0.02\,p/m^2) \approx \overline{N}_{C.\ difformis}(0.00\,p/m^2) \quad (2)$$

The interaction between treatments and species showed that the SDS, DSI and DSH treatments were effective in reducing the number of plants for those abundant weed species (i.e., *E. crus-galli* and *E. oryzoides*), while they had an almost irrelevant effect when the species were present at low density (i.e., weedy rice, *C. difformis*,

TABLE 1 Weed number observed per plot (plants/m^2) and weeding time (h/ha) per each combination of treatment in booth seeding systems: dry-seeding and water-seeding.

Response	System	T/S	*E. crus-galli*	*E. oryzoides*	Weedy rice	*C. difformis*	*B. maritimus*	*H. reniformis*	Plot (sum)	Mean
plants/m^2	Dry-seeding ($se_{T/S} = 2.70$)	DSC	23.20	32.53	1.50	0.00	0.00	0.00	57.23	9.54
		SDS	2.48	5.88	0.23	0.00	1.77	0.05	10.41	1.74
		DSI	0.98	8.10	0.17	0.00	0.00	0.00	9.25	1.54
		DSH	0.06	0.33	0.19	0.00	2.32	0.05	2.95	0.49
	Water-seeding ($se_{T/S} = 5.86$)	WSC	9.15	4.27	1.50	5.37	96.25	25.50	142.03	23.67
		FSW	0.03	0.08	0.20	0.05	9.10	20.58	30.02	5.00
		FSP	0.14	0.65	0.13	0.11	13.86	10.25	25.13	4.19
		WSH	0.16	0.65	0.00	0.00	1.51	0.59	2.90	0.48
hours/ha	Dry-seeding ($se_{T/S} = 22.17$)	DSC	211.20	341.01	8.52	0.00	0.00	0.00	560.73	93.45
		SDS	15.57	72.26	6.94	0.00	11.12	1.41	107.29	17.88
		DSI	13.55	57.18	20.99	0.00	0.00	0.00	91.71	15.28
		DSH	1.32	12.14	21.09	0.00	18.16	6.85	59.55	9.92
	Water-seeding ($se_{T/S} = 46.15$)	WSC	111.07	46.20	17.35	96.47	452.38	298.1	1021.56	170.26
		FSW	0.97	1.16	10.53	1.61	51.31	155.96	221.52	36.92
		FSP	1.02	14.88	5.755	3.88	52.90	208.07	286.50	47.75
		WSH	4.68	36.27	0.00	0	39.60	17.17	97.71	16.29

B. maritimus and *H. reniformis*). The differences in the number of weeds per species with respect to the DSC treatment (in absolute terms) fundamentally explain the significance of the treatment-species interaction (Figure 1C and Table 1). For the most abundant weed species in the field, the efficacy of the treatment relative to the control (i.e., percentage reduction of weeds) was evaluated as follows: 85.02% reduction for *E. crus-galli* in SDS; 94.34% for *E. crus-galli* in DSI; 99.65% for *E. crus-galli* in DSH; 77.48% for *E. oryzoides* in SDS; 65.39% for *E. oryzoides* in DSI; and 98.63% for *E. oryzoides* in DSH (Table SM1 in supplementary material). No significant differences were found in the interactions between species in both SDS DSI treatments (threshold: 7.48; $7.48 = 1.96 \cdot 2^{1/2} \cdot se_{T/S}$); the observed differences at a descriptive level can't sustain a possible differential incidence of the treatments with any species (Table 1). On the other hand, the interaction between treatment and year showed the different effect of climatic conditions on the efficiency attributable to the treatments (Figure 1D).

3.2 | Weeding time in dry-seeding

The statistical analysis of the experimental results for weeding time (hours/ha) highlighted the significance of the treatment ($p < 0.0001$), weed species ($p < 0.0001$) and the treatment-species interaction ($p = 0.0001$). On the other hand, no significant differences were observed neither between years ($p = 0.4663$) nor in the treatment-year interactions ($p = 0.1441$) and species-year interactions ($p = 0.2333$). The contrast between pairs in weeding time provided similar results to those obtained in the number of weeds. In treatments (Figure SM1a in supplementary material and Table 1),

$$\overline{T}_{DSC}(93.45\,h/ha) > \overline{T}_{SDS}(17.88\,h/ha) \approx \overline{T}_{DSI}(15.28\,h/ha) \approx \overline{T}_{DSH}(9.92\,h/ha) \quad (3)$$

and in species (Figure SM1b in supplementary material),

$$\begin{aligned} &\overline{T}_{E.\ oryzoides}(120.64\,h/ha) \\ &> \overline{T}_{E.\ crus-galli}(60.41\,h/ha) \\ &> \overline{T}_{O.\ sativa}(14.38\,h/ha) \\ &\approx \overline{T}_{B.\ maritimus}(7.32h/ha) \\ &\approx \overline{T}_{H.\ reniformis}(2.06h/ha) \\ &\approx \overline{T}_{C.\ difformis}(0.00h/ha) \end{aligned} \quad (4)$$

The treatment-species interaction also showed that the SDS, DSI and DSH treatments were effective in reducing weeding time for species with more presence in the field (i.e., *E. crus-galli* and *E. oryzoides*), but treatments had almost an irrelevant effect when the species were present at low density (i.e., *B. maritimus*, weedy rice, *H. reniformis* and *C. difformis*) (Figures SM1c in supplementary material and Table 1) The SDS and DSI treatments incidence shown non-significative differences in any of the species (treatment-species significance threshold = 61.45) (Table 1).

3.3 | Weed occurrence in water-seeding

For water seeding, significant differences were found between treatments ($p < 0.0001$), between weed species ($p < 0.0001$), between years ($p = 0.0214$) and in the treatment-species interaction ($p = 0.0001$) and the species-years interaction ($p = 0.0363$). On the other hand, no differences were observed in the treatment-year

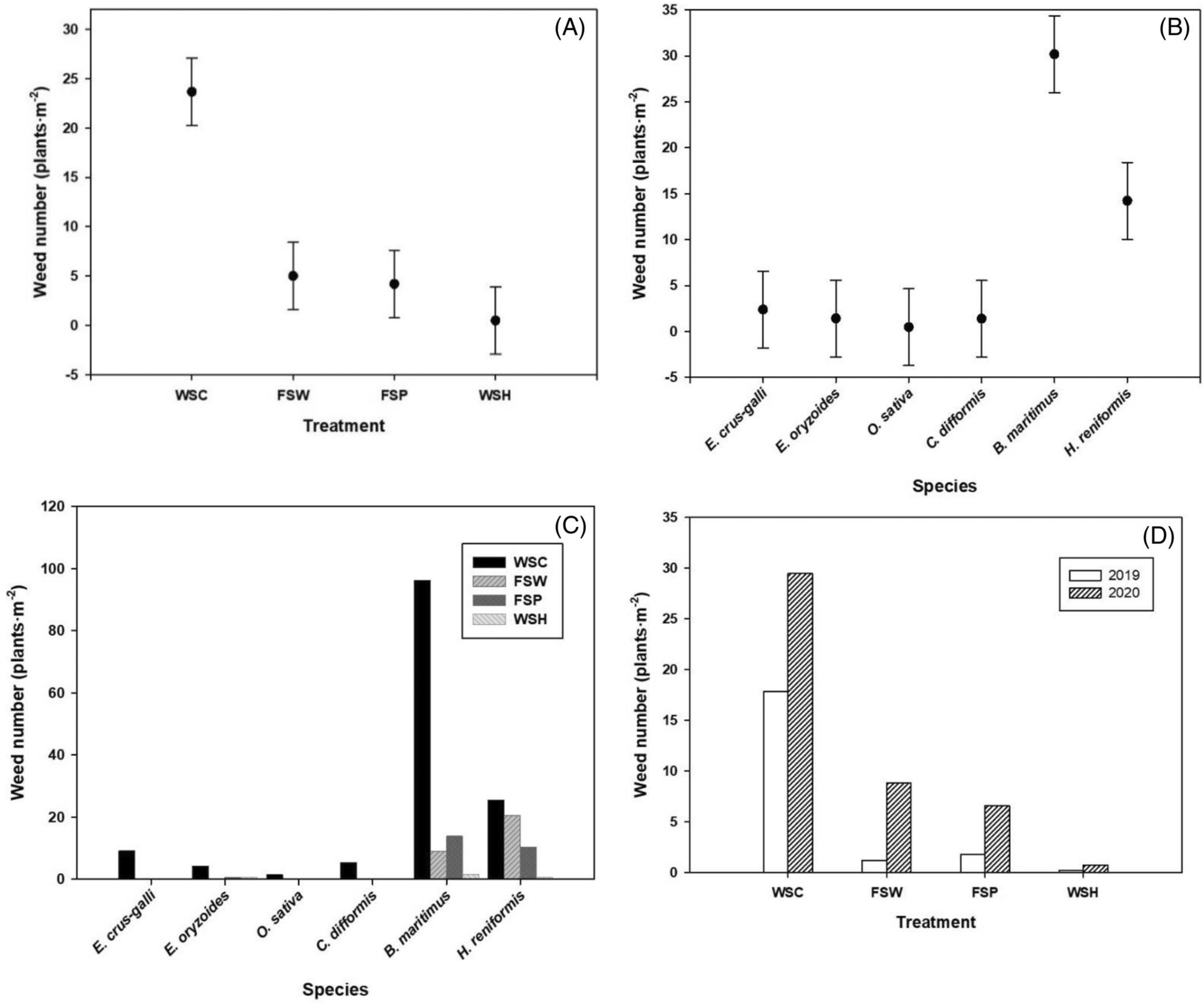

FIGURE 2 Results for the water-seeding treatments (A) weed density of all species average of both years: Water seeding control (WSC), stale seedbed followed and water seeding (FSW), stale seedbed and planting (FSP) and water seeding with herbicide (WSH). (B) weed density of all treatments average of both years: *Echinochloa crus-galli*, *Echinochloa oryzoides*, *Oryza sativa*. spp., *Cyperus difformis*, *Bolboschoenus maritimus* and *Heteranthera reniformis*. (C) weed density per treatment and specie average of both years: WSC (black), FSW (incrementing line), FSP (grey cross line) and WSH (decreasing line) (D) weed density in each treatment per year: 2019 (white) and 2020 (dashed line).

interaction ($p = 0.4389$). The contrast pairs of treatments showed that the average number of weeds observed per m^2 in the control treatment was significantly higher than the average observed in the other treatments (Figure 2A and Table 1):

$$\overline{N}_{\mathrm{WSC}}\left(23.67\,p/m^2\right) > \overline{N}_{\mathrm{FSW}}\left(5.00\,p/m^2\right) \approx \overline{N}_{\mathrm{FSP}}\left(4.19p/m^2\right) \approx \overline{N}_{\mathrm{WSH}}\left(0.48p/m^2\right) \tag{5}$$

The number of plants observed per m^2 of *B. maritimus* and *H. reniformis* species was significantly higher than that of the other species. For water-seeding, the differences between *B. maritimus* and *H. reniformis* species were statistically significant and the number of plants observed of *E. crus-galli*, *E. oryzoides*, weedy rice and *C. difformis* species were almost residual (Figure 2B and Table 1):

$$\begin{aligned} &\overline{N}_{B.\ maritimus}\left(30.18\,p/m^2\right) \\ &> \overline{N}_{H.\ reniformis}\left(14.23\,p/m^2\right) \\ &> \overline{N}_{E.\ crus-galli}\left(2.37\,p/m^2\right) \\ &\approx \overline{N}_{E.\ oryzoides}\left(1.41\,p/m^2\right) \\ &\approx \overline{N}_{B.\ maritimus}\left(1.38\,p/m^2\right) \\ &\approx \overline{N}_{O.\ sativa}\left(0.46\,p/m^2\right). \end{aligned} \tag{6}$$

Furthermore, the number of plants observed in 2020 was significantly higher than that observed in 2019 $\left(\overline{N}_{2020}\left(11.41\,p/m^2\right) > \overline{N}_{2019}\left(5.26\,p/m^2\right)\right)$ and this effect was observed in all the treatments (Figure 2D).

The treatment-species interaction showed that the treatments FSW, FSP and WSH were effective in reducing the number of plants of the majority species (i.e., *B. maritimus*) and reducing or stabilising the number of the *H. reniformis* species. For the species present with low density (i.e., *E. crus-galli*, *E. oryzoides*, weedy rice spp. and *C. difformis*), the effect was small in absolute (Figure 2C and Table 1). For the species most abundant in the field, the efficacy per treatment in relation to the control was evaluated as follows 91.62% for *B. maritimus* and FSW; 88.71% for *B. maritimus* and FSP; 98.47% for *B. maritimus* and WSH; 39.52% for *H. reniformis* and FSW; 53.08% for *H. reniformis* and FSP; and 98.37% for *H. reniformis* and WSH (Table SM2 in supplementary material). The difference between of the average of low density weed species per m^2 has decreased up to 0.35 (from 1.58 to 1.23 plants per m^2 in 2019 and 2020 respectively). In contrary, with those weed species present in high densities, the averaged plants per m^2 have increased up to 19.15 (12.63 and 31.78 plants per m^2 in 2019 and 2020 respectively). No significant differences were found in the incidence of FSW and FSP treatments for any of the species (treatment species significance threshold = 16.24), and the descriptive results indicated a possible stronger treatment effect in reducing *H. reniformis* in the case of FSP when compared to FSW (Table 1).

3.4 | Weeding time in water-seeding

The statistical treatment of the weeding time experimental results revealed the significance of the treatment ($p < 0.0001$), the weed species ($p < 0.0001$) and the treatment-species interaction ($p = 0.0097$). On the contrary, no significant differences were observed between the years ($p = 0.5263$). The interactions treatment-year ($p = 0.8056$) and species-year ($p = 0.9993$) have been removed from the statistic model. The contrast between pairs in weeding time provided results compatible with those obtained in the number of weeds. In treatments (Figure SM1d in supplementary material and Table 1).

$$\overline{T}_{\mathrm{WSC}}(170.26\,h/ha) > \overline{T}_{\mathrm{FSP}}(47.75\,h/ha) \approx \overline{T}_{\mathrm{FSW}}(36.92\,h/ha) \approx \overline{T}_{\mathrm{WSH}}(16.29\,h/ha) \quad (7)$$

and in species (Figure SM1e in supplementary material and Table 1),

$$\begin{aligned} &\overline{T}_{H.\ reniformis}(169.82\,h/ha) \\ &\approx \overline{T}_{S.\ maritimus}(149.05\,h/ha) \\ &> \overline{T}_{E.\ crus-galli}(29.43\,h/ha) \\ &\approx \overline{T}_{C.\ difformis}(25.49\,h/ha) \\ &\approx \overline{T}_{E.\ oryzoides}(24.63\,h/ha) \\ &\approx \overline{T}_{O.\ sativa}(8.41\,h/ha) \end{aligned} \quad (8)$$

The treatment-species interaction also showed that the FSW, FSP and WSH treatments were effective in reducing the number of plants of the majority species (*B. maritimus*) and reducing or stabilising the number of plants of the *H. reniformis* species (Figure SM1f in supplementary material and Table 1). No significant differences were found in the incidence of FSW and FSP treatments on any of the species (treatments-species significance threshold = 127.92) and the differences in the descriptive results with relation to the significance threshold were too small to be able to point any tendency (Table 1).

3.5 | Potential grain yield

For dry-seeding, the estimated yield in a commercial plot was evaluated as follows $(\overline{X} \pm s)$: 10586 ± 1741 kg·ha^{-1} for SDS; 7540 ± 537 kg·ha^{-1} for DSI; and 11 899 ± 780 kg·ha^{-1} for DSH. For water-seeding, the estimated (potential) yield was evaluated as follows: 11452 ± 750 kg·ha^{-1} for FSW; 11 163 ± 234 kg·ha^{-1} for FSP; and 10 801 ± 659 kg·ha^{-1} for WSH.

4 | DISCUSSION

The non-chemical treatments were very efficient in reducing the number of weeds and the weeding time. In dry-seeding and water-seeding conditions no significant differences were observed between the chemical and non-chemical control treatments (Figures 1A, 2A and SM1a,d in supplementary material). The negative controls gave not only an idea of the diversity and density of all weed species in the fields, but also provided a picture of the effects of the sowing strategy in the weed species proliferation. In detail, *E. crus-galli* and *E. oryzoides* were the most abundant weed species in dry-seeding (Figure 1B,C), while *B. maritimus* and *H. reniformis* were the most abundant weed species in the case of water-seeding (Figure 2B,C).

In dry-seeding, SDS and DSI non-chemical weeding treatments effectively reduced the weed densities and weeding time for the most abundant and problematic weed species *E. crus-galli* and *E. oryzoides*. Indeed, the species of the genus *Echinochloa* have high intra- and interspecific variability and prolific seed production and a rapid vegetative growth that make them highly problematic rice weeds (Masum et al., 2022). As expected, SDS and DSI treatments were less efficient for less abundant weed species (i.e., weedy rice, *C. difformis* *B. maritimus* and *H. reniformis*) (Figure 1C). One way to further improve weed control of both *Echinochloa* species could be to increase the rice seeding rate to increase competition, and carry out a mechanical control between the rice rows with a weeder adapted to the width of the rows.

Regarding the potential yield, differences between non-supplemental irrigation SDS (10 586 kg·ha^{-1}) and supplemental irrigation prior to dry seeding DSI (7540 kg·ha^{-1}) were detected. Irrigation before dry seeding could be a good option to increase weed emergence when the soil is too dry, to later kill the weeds chemically or mechanically (Català, 1995). In our case, the sudden solubilisation of crystalized salt patches strongly affected the rice seedlings germination and establishment. Thus, DSI better controlled the weeds, although the potential yield was clearly lower than that in SDS, due to an excess of salinity. This explains why SDS is a common practice for dry seeding in the Ebro Delta (Franquet Bernis, 2018). The economic thresholds defined in weed management models (Das et al., 2021) could explain the similar potential yields between SDS (10 586 kg·ha^{-1}) and DSH (11 899 kg·ha^{-1}) treatments. The yield is not affected under a certain weed pressure threshold as stated by many authors (Munnoli et al., 2023). In this current work, the rotatory harrow placed in front of the seeder tractor effectively reduced the number of emerged of weeds.

B. maritimus and *H. reniformis* were the most abundant weed species after water-seeding (Figure 2B,C). These species have been documented in rice fields in Europe (Carretero, 2004; Gussev et al., 2020), Southeast Asia (Caton, 2010; Pacanoski & Mehmeti, 2023) and America (Kraehmer et al., 2016). The high abundance of *B. maritimus* in the Ebro Delta flooded rice fields can be explained by its fast sprouting from tubers and its high salt-tolerance, both of which provide an initial advantage over rice and other weed species (Lillebø et al., 2003), although its tuber-based reproduction reduces its spatial dispersion (Charpentier et al., 2000). In contrast, *H. reniformis* competitivity can be explained by its propagation capacity based on high seed production with a staggered germination especially adapted to aquatic environments (Csurhes & Zhou, 2008; Ferrero, 1996; Zaidan et al., 2021). For those weed species that were more prevalent in the field, both chemical and non-chemical treatments had successfully reduced the weed densities. However, for the less abundant weed species, the effects of treatments were less effective. For the most abundant weed species, the efficacy of the FSW and FSP treatments was almost the same (Figure 2A–C).

Chemical (WSH) and non-chemical (FSW and FSP) weed control practices had negligible differences in water-seeded potential productions: 11452 kg·ha^{-1} (FSW), 11 163 kg·ha^{-1} (FSP) and 10 801 kg·ha^{-1} (WSH). Again, the weed density thresholds affecting the rice yield are high (Das et al., 2021), which can explain why there are no effects on production. In India, the yield reductions derived from weeds competition in fields managed following FSW are higher than those in FSP (Kumar et al., 2023). Mechanical transplanting permits mechanised weeding between rows and eases manual weeding (Pipeng et al., 2021), thereby reducing the need of herbicides (Liu et al., 2023). In contrast, small weeding rollers for small tractors have been widely used in Japan for years (Shibayama, 1994, 2001). Indeed, FSW was an old-fashioned standard water-seeding technique now replaced by pre-emergence herbicide treatments (Carreres, 2013).

Gloria extratropical cyclone in 2020 substantially increased the precipitation (Amores et al., 2020) during the second year of the study, flooding the fields in February, March and firsts April, and delaying all the fields preparation tasks and sowing (Figure SM2 in supplementary material). The delayed sowing affected rice production and favoured migratory birds rice predation at the end of the season. This exceptional event could partially explain the differences that have been observed between the years 2019 and 2020. Without significant differences between of the treatments (chemical and non-chemical), the number of weeds observed in crops with no chemical treatment was lower than or equal to that observed in crops with chemical treatment in 2019. In 2020, the result has been reversed (Figures 1D and 2D).

5 | CONCLUSIONS

All of the non-chemical treatments were quite effective at reducing the number of weeds and the amount of time spent weeding. In the Ebro Delta, simple dry seeding (SDS) was the best dry-seeding treatment and could compete with herbicide-based common weeding method (DSH). Stale seed bed and seeding (FSW) and stale seed bed and transplanting (FSP) approaches can compete with the herbicide-based chemical method (WSH) in water-seeding. Our findings demonstrate that dry seeding favoured grassland weeds such as *E. crus-galli*, *E. oryzoides*, while discouraging sedges and aquatic weeds. Contrary, cyperaceae and aquatic plants (*B. maritimus*, *C. difformis* and *H. reniformis*) were favoured in water-seeding treatments, while grasses were disfavoured. There are some encouraging outcomes, including the fact that non-chemical weed treatments increased control and produced results comparable to those of chemical treatments. The cost of adapting to non-chemical weed treatments in rice fields could be significant, but the yields are also substantial, and it could be an opportunity to diversify weed control in the face of increasing weed resistance to chemical methods. We are reporting on various non-chemical weeding techniques that can effectively control weeds at close levels of herbicide treatments. The proposed non-chemical weeding options represent better improvement over the chemical ones in the case of water-seeding than in the case of dry seeding. For weeding rice crops, new precision instruments are being developed. For sowing in rows and weeding between rows, all of them will require GPS-guided tractors. Smart farming for organic rice production is still being researched, and it will assist rice farmers in properly weeding their fields. These technological advancements will be critical in increasing organic rice output since they will assist both mechanised and human weeding and can be employed in either water or dry sowing. We improved non-chemical weed control through innovative seeding techniques and diversified cropping practises to contribute to the best integrated weed management.

The outcomes of this study will benefit both conventional and organic farming methods. We believe that these new and innovative strategies will help to efficiently reduce weed populations in sustainable rice cultivation.

AUTHOR CONTRIBUTIONS

A.P. and X.S. conceived the project and designed the experiments. A.P. and A.N. managed the field trial work, data collection and sample processing. M.S. and A.P analysed the results. A.P., M.S., X.S. and S.N. have interpreted the results. A.P., X.S and M.S. have written the manuscript. All authors reviewed the submitted manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All data used for analyses are available from the corresponding author upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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