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Safety of Oilseed Rape Straw Mulch of Different Lengths to Rice and Its Suppressive Effects on Weeds

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Abstract: Rice is widely grown after harvesting of oilseed rape (*Brassica napus* L.) in many countries. Experiments were carried out under greenhouse and field conditions to assess the impact of oilseed rape straw mulch on rice and paddy weeds. Oilseed rape mulch (900 g m^{-2}) from straw 1-to-7 cm long was found to be safe for rice, when applied four days after sowing (DAS) in direct-seeded rice or four days after transplanting (DAT). In the meantime, the biomass of *Echinochloa crus-galli* (L.) P. Beauv. was reduced 65.74%, 80.18%, 81.15%, 70.99%, 55.65%, and 27.22%, respectively, when mulched with powder, and 1, 3, 5, 7, and 9-cm long oilseed rape straw, respectively, and the biomass reductions in *Leptochloa chinensis* (L.) Nees., *Ludwigia prostrata* Roxb., *Ammannia auriculata* Willd., and *Cyperus difformis* L. were all above 97% when mulched with 1 cm-length straw. The results of a field trial confirmed that oilseed rape straw mulch (900 g m^{-2}) of 1 cm length was safe for rice. Moreover, weed suppression was as effective as the standard herbicide (oxadiargyl + butachlor 525 g ai ha^{-1}) treatment. These findings demonstrate the potential to manage paddy rice weeds in an effective and environmentally sound manner by mulching with the straw of a preceding crop, oilseed rape.

Keywords: crop safety; *Brassica napus* L.; *Oryza sativa* L.; straw mulch; weed suppression

1. Introduction

Rice (*Oryza sativa* L.) is the main cereal grain crop grown in the world and is the staple food for more than half of the world's population, including 65% of the Chinese population [1]. In 2017, 214 million tons of rice were produced on more than 31 million hectares (ha) in China, accounting for 27.9% of global rice production [2]. The traditional method of paddy farming in China is through manual transplanting of rice seedlings in fields. However, the proportion of direct-seeded rice increased from 2% of the total rice area in 2000 to about 11% in 2009; and during this same period, mechanical transplanting increased from 2% to nearly 13% of the total rice area in China [3].

Weeds can compete with crops for nutrients, light, moisture, and space, resulting in reduced crop quality and yield [4]. In China, weeds threaten more than 15 million ha planted to rice, accounting for 45% of the total rice planting area [5]. Globally, rice yield losses due to weeds are estimated at

~37% of total production, suggesting that optimum crop yields can only be attained under weed-free conditions [6]. In the past 30 years, chemical weed control has become the preferred method of weed control because it is less laborious, cost-effective, and highly efficient, thus ensuring high and stable grain yields [7]. However, because of the long-term, widespread and repetitive use of relatively few herbicides in China, the incidences of weed resistance to them have increased rapidly in the past decade. To date, ten weed species have developed resistant populations to herbicides in paddy rice systems [8]. Weeds such as *Echinochloa crus-galli* (barnyardgrass) [8], *Monochoria korsakowii* Regel et Maack (false pickerelweed) [9], *Ammannia auriculata* (eared redstem) [10], *Sagittaria trifolia* L. (three-leaf arrowhead) [11], *Cyperus difformis* (variable flatsedge) [12], and *Potamogeton distinctus* A. Benn. (roundleaf pondweed) [13] have developed resistant populations to commonly used ALS-inhibitor herbicides. Therefore, there is an urgent need to develop effective, environmentally safe, and sustainable non-chemical weed control strategies in paddy rice cropping systems.

Oilseed rape (*Brassica napus* L.) is one of the main oil crops grown in the world. Globally, 34.7 million hectares (Mha) of oilseed rape were planted in 2017, with Canada (8.4 Mha), China (6.7 Mha), and India (6.0 Mha) leading the land area planted to this crop. In 2017, oilseed rape production totaled 13.3 million tons in China [14]. In southern China, farmers commonly plant oilseed rape in rotation with rice. Given the shoot-to-seed biomass ratio in oilseed rape of 2.9:1 [15], the amount of oilseed rape straw produced across the country totals nearly 36 million tons. Dried oilseed rape straw is comprised of 0.82% N, 0.32% P_2O_5, and 2.24% K_2O [16] and can thus be used as an organic fertilizer source to increase soil fertility and improve soil structure [17].

Straw from crops such as oilseed rape, maize, and soybeans is traditionally burned in China [18]. However, increasing awareness of the negative environmental impacts of burning crop residues has increased interest by farmers to maintain crop straw in their fields [19]. Prior to the 1990s, straw mulching was used mainly as a method to increase water availability, preserve heat, and increase organic matter content in soil [20,21]. Mendoza and Samson [22] however, proposed a new strategy of using straw in cropping systems, namely to control weeds. Guo et al. [23] reported that mulching with wheat straw reduced weed densities by 25.5% compared with non-weeded control plots without wheat residue. Khaliq et al. [24] reported that mulching a maize crop with straw from sunflower, sorghum, and brassica residues reduced the densities and dry weights of *Portulaca oleracea* L. (common purslane) and *Cyperus rotundus* L. (purple nutsedge) by more than 90% compared with control plots not receiving straw mulch. Yang et al. [25] reported that the fresh weight of monocot weeds, sedges, and dicot weeds was reduced by 99%, 100%, and 85%, respectively when a 20-cm deep mulch comprised of maize stalks and rice straw was used in maize fields.

Research on the use of straw mulch to control weeds has received increasing attention in recent years. To our knowledge, no studies have reported on the efficacy of controlling weeds using oilseed rape straw mulch in rice cropping systems. In this paper, we used oilseed rape straw to control paddy weeds in direct-seeded and transplanted rice crops under greenhouse and field conditions. The objective of this research was to evaluate the effects of oilseed rape straw of different lengths on the emergence and growth of rice and its potential to reduce the emergence and growth of common weeds in paddy rice cropping systems.

2. Materials and Methods

2.1. Impact of Different Lengths of Oilseed Rape Straw Mulch to Simulated Direct-Seeded Rice and Its Effect on Major Paddy Weeds

Test plants used in this study included five major paddy weeds and rice (cultivar Zhefujing 83). The oilseed rape straw was derived from cultivar Zheda 619. The straw material was pulverized into powder (0.2 mm) or 1 cm length with a mower (Zhejiang Jinghua Shengshi Hardware Machinery Co., Ltd., Zhejiang, China), or cut with a hand hay-cutter to lengths of 3, 5, 7, and 9 cm.

Studies were conducted in a greenhouse on the Experimental Farm at Huajiachi campus, Zhejiang University (30°16′ N, 120°12′ E) in Hangzhou, China. The temperature range in the greenhouse was 20

°C to 30 °C, humidity ranged from 50% to 90%, and 14 h of natural light was provided. The soil used was a silty loam, with a pH of 6.6, 1.43% organic matter content, and a total nitrogen of 0.14 %. The soil was oven-dried at 110 °C for 3 h to kill any resident weed seeds, and then a 3-cm thick layer of soil was placed in a 42-cm-diameter plastic pot. Each pot received 2.5 g (180 kg ha^{-1}) compound fertilizer (N + P_2O_5 + K_2O ≥ 45% (15-15-15), Jiangsu Zhongdong fertilizer Co., Ltd., Jiangsu, China) and mixed with water. Rice seeds were germinated in an incubator (28 °C), and 40 seeds with a visible hypocotyl (~ 0.5 cm long) were sown on the soil surface of each pot. At the same time, seeds of *Echinochloa crus-galli* (L.) P. Beauv., *Leptochloa chinensis* (L.) Nees., *Ammannia auriculata* Willd., *Ludwigia prostrata* Roxb. and *Cyperus difformis* L. which were collected from Jiaxing, Zhejiang Province in 2017 and stored in a refrigerator (4 °C) until needed, were sown at a density of 70, 130, 110, 100, and 120 seeds per pot, respectively. The germination levels of these weeds were approximately 90%, 50%, 90%, 75%, and 50%, respectively, and the densities were based on these for each of the species to provide typical field densities found in paddy fields in Zhejiang province. Water was added to keep the soil moist. At 4 days after sowing (DAS), pots were subjected to various mulch treatments: pots were mulched with oilseed rape straw (900 g m^{-2}) of 1 cm (T1), 3 cm (T3), 5 cm (T5), 7 cm (T7), and 9 cm (T9) length. A rice-only control without mulch treatment (CK) and a rice + the five-weed species control without straw mulch treatment (WCK) were also included. Treatments were set up in a completely randomized design (CRD) with four replicates. After mulching, 500 ml of water was evenly applied to each pot to maintain the straw moisture. The soil was kept moist until 6 DAS and then kept flooded to a depth of 2 cm. Urea (N≥46.4%) (Shandong Hualu-hengsheng Chemical Co., Ltd., Shandong, China) was applied at 108 kg ha^{-1} after 20 days of straw mulching (DAM) and re-applied (144 kg ha^{-1}) at 30 DAM. The number of weeds was recorded at 10, 20, 30, and 40 DAM. At 40 DAM, aboveground weed tissues were harvested in each pot, dried at 110 °C for 1 h, followed by drying at 80 °C to constant weight before weighing. The number of rice plants and the height of 10 randomly selected plants per pot was also recorded at 10 DAM. At 20, 30, and 40 DAM, ten rice plants were randomly selected to determine plant height and tiller number. Aboveground tissues of 20 rice plants per pot were harvested, dried, and weighed at 40 DAM, as described above for weeds.

2.2. Impact of Oilseed Rape Straw Mulch of Different Lengths on Simulated Transplanted Rice and its Effect on Major Paddy Weeds

Twelve tufts (3 plants/tuft) of rice seedlings were transplanted into 42-cm-diameter plastic pots when rice was at the four-leaf stage. At the same time, the seeds of *E. crus-galli*, *L. chinensis*, *A. auriculata*, *L. prostrata*, and *C. difformis* were sown at densities of 70, 130, 110, 100, and 120 seeds per pot, respectively. Water was added to keep the soil moist. At 4 days after rice transplanting (DAT), pots were subjected to various mulch treatments: pots were mulched with oilseed rape straw (900 g m^{-2}) of powder (T0), 1 cm (T1), 3 cm (T3), 5 cm (T5), 7 cm (T7), and 9 cm (T9) length. A rice-only control (CK) and rice + five-weed species control (WCK) treatment not receiving the straw mulch were also included. Treatments were set up in a completely randomized design (CRD) with four replicates. After mulching, 500 ml of water was evenly applied in each pot to maintain the straw moisture. The water level was adjusted to a 2 cm depth at 6 DAT. The experimental conditions, procedures, and data collection were similar to those described above for the direct-seeded trial.

2.3. Field Study on Impact of Oilseed Rape Straw Mulch on Rice and Its Effect on Paddy Weeds

Experiments were conducted in direct-seeded and transplanted rice fields in 2017 in Linhai City, Zhejiang Province (28.76° N, 121.13° E). The rice cultivar used was Yeyou 12. The oilseed rape straw was derived from cultivar Zheda 619. The straw material was pulverized into a powder of 1-cm length with a mower. The field soil was comprised of 3.3% organic matter content, 2.1 g kg^{-1} total nitrogen, 231.8 mg kg^{-1} alkali-hydrolyzable nitrogen, 44.0 mg kg^{-1} available phosphorus, and 171.0 mg kg^{-1} available potassium. The main weeds in the field were *E. crus-galli*, *L. chinensis*, *A. auriculata*, *L. prostrata*, *C. difformis*, *Monochoria vaginalis* (Burm. f.) C. Presl ex Kunth (heart shape false pickerelweed), and *Rotala indica* (Willd.) Koehne (Indian toothcup).

At 4 days after sowing (DAS), direct-seeded rice fields were subjected to three treatments: 700 g m^{-2} oilseed straw mulch (A), 900 g m^{-2} oilseed straw mulch (B), and a no-straw mulch control (CK). At 7 days after transplanting (DAT), transplanted rice fields were subjected to five treatments: 700 g m^{-2} oilseed straw mulch (A), 900 g m^{-2} oilseed straw mulch (B), 35% oxadiargyl + butachlor EW 1.5 L ha^{-1} (Bayer) (C), hand weeding (D) which was carried out at 10 and 30 DAT, and a no-straw mulch and non-herbicide control (CK). Compound fertilizer ($N + P_2O_5 + K_2O \geq 45$ % (15-15-15) was applied at 525 kg ha^{-1} before rice sowing or transplanting, urea (N > 46.4%) was applied at 75 kg ha^{-1} after 15 and 30 DAS in direct-seeded rice. Urea was applied at 75 kg ha^{-1} 7 DAT and re-applied at 150 kg ha^{-1} 17 DAT. All other agricultural operations, such as water and pest control followed local management protocols. The temperature range during the experiment was 20~32 °C. There were two rainfall events within 15 days after treatment, one of 1.0 mm 3 DAM and one of 2.6 mm 7 DAM.

The field studies were performed as a randomized complete block design with three replicates. Measurements were taken within a 20-m^2 area in each plot. Seven days after mulch was added (DAM), the number of rice seedlings in the direct-seeded rice trial was recorded from three (50 by 50 cm) subplots that were located randomly along a diagonal line of the plot. At 35 DAM, the number of rice tillers in the transplanted rice trial was recorded by randomly selecting 10 plants in each plot. The rice yield was measured at 136 DAS and 125 DAT, respectively. In both the direct-seeded and transplanting trials, the density of weeds was assessed at 20 and 35 DAM from three (50 by 50 cm) subplots that were located randomly along a diagonal line of the plot, and the aboveground fresh weight of weeds determined at 35 DAM.

2.4. Statistical Analysis

Data were analyzed using Fisher's Analysis of Variance (ANOVA) technique. Straw length and days after mulching (DAM) were considered fixed factors in the greenhouse study, and treatments were considered fixed factors in the field study. Treatment means were compared using the least significant difference (LSD) test at $p \leq 0.05$. Statistical analyses were carried out using the SPSS statistical analytical package (version 21). Rice seedling numbers, plant height, tiller numbers, and dry weight data were analyzed by comparing them with data from the control treatments (CK and WCK). Weed number and dry weight data were calculated as a percentage by comparing the data with control treatments (WCK or CK) before analysis.

3. Results

3.1. Impact of Different Lengths of Oilseed Rape Straw Mulch to Simulated Direct-Seeded Rice and Its Effect on Major Paddy Weeds

3.1.1. Impact of Oilseed Rape Straw Mulching in Simulated Direct-Seeded Rice

After 10 days of oilseed rape straw mulching (DAM), the 1~7 cm straw length treatments had no effect on rice emergence. However, the number of rice seedlings in the 9-cm length straw mulch treatment decreased by 8.8% compared with the control (CK) treatment (Table 1). The height, tiller number, and dry weight of rice plants at 40 DAM for the 1~9 cm straw length mulch treatments did not differ from the rice control (CK) treatment. In contrast, the height and tiller number of rice plants in pots without straw mulching (WCK) decreased significantly.

Table 1. Effects of oilseed rape straw mulch in simulated direct-seeded rice.

Treatments	Number of Rice Plants Per Pot	Plant Height (cm)				Tillers Per Plant			Dry Weight (g/20 Plants)
	10 DAM	10 DAM	20 DAM	30 DAM	40 DAM	20 DAM	30 DAM	40 DAM	40 DAM
CK	40 aA	17.70 aA	24.74 aA	27.49 aA	43.46 aAB	2.13 abA	3.2 abA	3.73 abcAB	13.48 abAB
WCK	40 aA	17.81 aA	21.92 bB	25.84 bB	41.79 bB	1.48 cB	2.43 cB	2.83 dC	10.67 cB
T1	40 aA	18.53 aA	25.13 aA	27.32 aAB	44.12 aA	2.28 aA	3.23 aA	4.13 aA	15.55 aA
T3	39.5 aA	17.90 aA	25.21 aA	27.8 aB	43.53 aAB	2.27 aA	3.21 abA	4.05 abA	15.2 abA
T5	38 abAB	18.05 aA	25.27 aA	28.47 aB	44.21 aA	2.28 aA	3.2 abA	3.88 abAB	15.50 abA
T7	39 aAB	17.84 aA	25.18 aA	27.81 aB	43.97 aA	2.1 abA	3.04 abA	3.63 bcBC	14.72 abA
T9	36.5 bB	17.92 aA	25.03 aA	28.22 aB	44.04 aA	1.97 bA	2.98 bA	3.23 cdBC	12.93 bAB

CK, rice control; WCK, rice and weed control; T refers to oilseed straw mulch treatment (900 g m^{-2}) applied 4 days after sowing; T1, straw length = 1 cm; T3, straw length = 3 cm; T5, straw length = 5 cm; T7, straw length = 7 cm; T9, straw length = 9 cm; DAM, days after mulch application; In each column, different lowercase letters indicate significant differences at $p \leq 0.05$ while different capital letters indicate highly significant differences at $p \leq 0.01$.

3.1.2. Inhibition of Oilseed Rape Straw Mulching on Major Weeds in Simulated Direct-Seeded Rice

Oilseed rape straw mulch was generally effective at suppressing the emergence and growth of the weed species tested, although effects varied by species. Suppression of *E. crus-galli* was best achieved with the straw mulch of 1–3 cm length, which resulted in at least a 64.6% decrease in dry weight at 40 DAM (Table 2). The inhibitory effect of the mulch was reduced when the straw mulch of 5~9 cm length was used. For example, the 9-cm straw mulch only reduced *E. crus-galli* aboveground dry weight by 22.9% (Table 2). The 1–3 cm length mulch treatment was most effective at suppressing *L. chinensis* and *L. prostrata*. Applying 1-cm long straw mulch decreased dry weight of these two troublesome weeds by as much as 99.7% and 97.4%, respectively. In contrast, the suppressive effects of the mulch on weed dry weight decreased when straw mulch greater than 3 cm in length was used (Table 2). However, straw mulch lengths of 1~5 cm were most effective for suppressing *A. auriculata* and *C. difformis* dry weight, with reductions above 98.7% and 99.1%, respectively. Substantial reductions in dry weight of these two weed species were also achieved using the other straw mulch lengths (Table 2). For all five weed species combined, oilseed rape straw mulch lengths of 1~3 cm were most effective in reducing both density and aboveground dry biomass of weeds. For instance, these straw mulch length treatments reduced overall weed densities and aboveground dry biomass by more than 83.5% and 68.3%, respectively (Table 2). The efficacy of the straw mulch to suppress the growth of the five weed species decreased with sampling time, especially for the longer length straw mulch treatments.

Table 2. Inhibitory effects of oilseed rape straw mulch on five major weeds in simulated direct-seeded rice.

Treatments	Inhibition of Weed Number (%)				Inhibition of Weed Dry Weight (%)
	10 DAM	20 DAM	30 DAM	40 DAM	40 DAM
			Echinochloa crus-galli		
T1	65.36 aA	63.88 aA	63.56 aA	62.14 aA	65.57 aA
T3	63.58 aA	61.67 aA	59.32 aA	55.97 aA	64.63 aA
T5	46.71 bB	43.03 bB	42.37 bB	41.56 bB	50.28 bA
T7	36.94 cC	31.28 cB	29.24 cC	29.22 cC	27.59 cB
T9	34.28 cC	30.69 cB	29.94 cC	28.81 cC	22.89 cB
			Leptochloa chinensis		
T1	100 aA	97.39 aA	95.42 aA	94.53 aA	99.67 aA
T3	99.13 aA	96.09 abA	91.67 bAB	89.06 bB	98.67 abA
T5	99.56 aA	93.04 bcAB	90.00 bB	88.02 bB	98.27 bA
T7	99.13 aA	89.13 cB	83.89 cC	81.77 cC	95.60 cB
T9	98.69 aA	89.13 cB	83.33 cC	81.25 cC	89.87 dC
			Ludwigia prostrata		
T1	99.00 aA	94.35 aA	93.62 aA	92.95 aA	97.39 aA
T3	96.00 abA	91.30 abAB	88.17 bAB	87.97 bA	96.93 aA
T5	94.50 abA	83.91 bcBC	81.28 cBC	79.67 cB	92.50 bB
T7	87.5 abA	82.61 cBC	80.43 cC	78.42 cBC	87.95 cC
T9	85 bA	77.39 cC	75.74 dC	73.86 dC	85.68 dC
			Ammannia auriculata		
T1	100 aA	100 aA	97.33 aA	96.76 aA	99.40 aA
T3	100 aA	99.46 aA	96.95 aA	96.22 aAB	98.71 aAB
T5	100 aA	100 aA	97.12 aA	95.68 aAB	98.97 aA
T7	100 aA	97.17 bA	93.52 bA	92.44 bBC	96.98 bBC
T9	100 aA	96.36 bA	93.52 bA	91.36 bC	95.52 cC
			Cyperus difformis		
T1	97.70 aA	97.73 aA	97.76 aA	97.01 aA	99.26 aA
T3	100 aA	100 aA	94.39 aA	94.50 aA	99.22 aA
T5	100 aA	98.64 aA	91.03 abA	91.03 abA	99.12 aAB
T7	97.70 aA	97.73 aA	83.56 bA	83.56 bA	98.73 bBC
T9	100 aA	100 aA	83.18 bA	83.18 bA	98.53 bC
			Total weeds		
T1	92.72 aA	89.92 aA	89.08 aA	88.51 aA	68.50 aA
T3	91.60 aA	88.45 aA	84.46 bAB	83.50 bAB	68.34 aA
T5	86.90 bB	81.31 bB	79.38 cB	77.85 cBC	58.05 bA
T7	79.73 cC	77.40 cBC	73.26 dC	72.10 dCD	39.23 cB
T9	79.73 cC	76.13 cC	72.32 dC	71.27 dD	37.66 cB

CK, rice control; WCK, rice and weed control; T refers to oilseed rape straw mulch treatment (900 g m^{-2}) initiated 4 days after sowing; T1, straw length = 1 cm; T3, straw length = 3 cm; T5, straw length = 5 cm; T7, straw length = 7 cm; and T9, straw length = 9 cm; DAM, days after mulch application; In each column, different lowercase letters indicate significant differences at $p \leq 0.05$ while different capital letters indicate highly significant differences at $p \leq 0.01$.

3.2. Impact of Oilseed Rape Straw Mulch of Different Lengths on Simulated Transplanted Rice and Its Effect on Major Paddy Weeds

3.2.1. Impact of Oilseed Rape Straw Mulching in Simulated Transplanted Rice

There was no difference in the number of rice plants, height, tiller number, and dry weight between the rice-only control (CK) treatment and the straw mulching treatments of 7-cm length or shorter at 10 DAM (Table 3). However, the height of rice plants subjected to the 9-cm straw mulch treatment was lower than for rice plants in the control treatment (CK) at 10~30 DAM. No differences in rice height were observed at 40 DAM (Table 3).

3.2.2. Suppression by Oilseed Rape Straw Mulch of Major Weeds in Simulated Transplanted Rice

Oilseed rape straw mulch length had a significant impact on weed suppression when applied 4 DAT. When subjected to the 1–5 cm straw mulch treatments, *E. crus-galli* aboveground dry biomass decreased more than 71% at 40 DAM (Table 4). In contrast, aboveground dry biomass decreased by only 27.2 % when subjected to the 9-cm long straw mulch treatment (Table 4). Reductions in aboveground dry biomass for *L. chinensis* and *C. difformis* were above 96.5% when subjected to the 1~5 cm straw treatments. The suppressive ability of straw mulch for the 7 cm and 9 cm treatments was also acceptable even if lower than the 1-5 cm straw treatments. Aboveground dry biomass reductions for *L. prostrata* and *A. auriculata* were above 97.9% in the 1~3 cm straw mulch treatments. Although decreases in the biomass of these two weeds were lower for the other straw mulch lengths, reductions were still above 91.4% (Table 4). Overall, mulch treatments of 1~3 cm straw length were most effective in reducing weed densities (77.9%) and aboveground dry biomass (86.7%). The optimal suppressive ability of the straw mulch appeared to occur for intermediate (1~5 cm) oilseed rape straw mulch lengths (Table 4).

The suppressive ability of straw mulch decreased slightly with sampling time, especially for *L. chinensis*, *A. auriculata*, *L. prostrata*, and *C. difformis*. These differences in the suppressive ability of the straw mulch over time were not very pronounced.

3.3. Impact of Oilseed Rape Straw Mulch on Rice and Its Effect on Paddy Weeds in the Field

There was no difference in the emergence of rice plants between the rape straw mulch treatments and control (CK) treatment in direct-seeded rice. However, rice yield was significantly higher than for the control (CK) treatment. In the transplanted-rice field trial, the number of tillers and yield of rice for the 900 g m^{-2}mulch treatment were significantly higher than for the oxadiargyl + butachlor herbicide treatment and the hand-weeded control treatment (Table 5).

Table 3. Effect of oilseed rape straw mulch in simulated transplanted rice.

Treatments	Number of Rice Plants Per Pot	Plant Height (cm)				Tillers Per Tuft			Dry Weight (g/6 Tufts)
	10 DAM	10 DAM	20 DAM	30 DAM	40 DAM	20 DAM	30 DAM	40 DAM	40 DAM
CK	36 aA	29.88 aA	34.35 aA	46.32 aA	58.60 aA	7.06 aA	9.38 abA	11.42 abA	35.33 aA
WCK	36 aA	29.77 aA	34.03 abA	44.14 bA	56.56 bA	6.94 aA	7.56 cA	7.92 cB	28.31 bA
T0	36 aA	29.61 aAB	34.74 aA	46.09 aA	58.78 aA	6.94 aA	9.72 abA	12.17 aA	35.98 aA
T1	36 aA	29.75 aA	34.25 aA	45.52 abA	58.08 abA	7.19 aA	9.90 aA	12.58 aA	35.50 aA
T3	36 aA	29.60 aAB	34.90 aA	45.65 abA	57.59 abA	7.31 aA	8.92 abcA	11.81 abA	35.34 aA
T5	36 aA	29.14 abAB	34.58 aA	45.25 abA	57.82 abA	7.17 aA	9.30 abcA	11.52 abA	34.19 aA
T7	36 aA	28.55 abAB	33.61 abA	44.72 abA	57.35 abA	6.50 aA	8.40 abcA	10.69 abAB	31.42 abA
T9	36 aA	27.83 bB	32.44 bA	44.07 bA	57.23 abA	6.42 aA	7.86 bcA	9.83 bcAB	31.01 abA

Rice was transplanted at the four-leaf stage; CK, rice control; WCK, rice and weed control; T refers to the oilseed rape straw mulch treatment (900 g m^{-2}) applied 4 days after transplanting; T0, straw powder; T1, straw length = 1 cm; T3, straw length = 3 cm; T5, straw length = 5 cm; T7, straw length = 7 cm; T9, straw length = 9 cm; DAM, days after mulch application; In each column, different lowercase letters indicate significant differences at $p \leq 0.05$ while different capital letters indicate highly significant differences at $p \leq 0.01$.

Table 4. Inhibitory effects of oilseed rape straw mulch on five major weeds in simulated transplanted rice.

Treatments	Inhibition of Weed Number (%)				Inhibition of Weed Dry Weight (%)
	10 DAM	20 DAM	30 DAM	40 DAM	40 DAM
			Echinochloa crus-galli		
T0	35.12 cC	33.33 dC	32.30 dD	32.33 dD	65.74 bcAB
T1	55.83 aA	53.33 aA	52.21 aA	51.72 aA	80.18 aA
T3	56.75 aA	50.81 abA	48.23 abAB	47.13 abAB	81.15 aA
T5	48.46 bAB	44.44 bcAB	42.48 bcBC	41.95 bcBC	70.99 abAB
T7	40.18 cBC	38.37 cdBC	38.05 cdCD	35.78 cdCD	55.65 cB
T9	35.58 cC	33.04 dC	31.86 dD	31.47 dD	27.22 dC
			Leptochloa chinensis		
T0	95.28 bB	92.09 bA	86.25 bB	84.72 cB	94.54 bB
T1	97.48 abAB	97.32 aA	95.81 aA	95.20 aA	98.85 aA
T3	100 aA	96.74 aA	95.22 aA	94.32 aA	97.99 aA
T5	99.53 aA	97.21 aA	94.62 aA	94.18 abA	97.61 aA
T7	97.48 abAB	94.88 abA	90.43 bAB	88.94 bcAB	94.64 bB
T9	98.74 aAB	94.42 abA	90.58 bAB	88.94 bcAB	94.35 bB
			Ludwigia prostrata		
T0	98.99 aA	80.78 bAB	77.73 bcB	74.90 cB	91.41 cC
T1	94.97 aA	91.89 aA	89.96 aA	88.70 aA	97.56 aA
T3	96.48 aA	86.19 abAB	83.84 abAB	82.71 abAB	97.90 aA
T5	95.97 aA	79.58 bAB	77.87 bcB	77.68 bcAB	94.02 bB
T7	95.47 aA	80.18 bAB	77.29 bcB	76.01 bcB	92.26 cBC
T9	96.64 aA	78.83 bB	76.86 cB	72.66 cB	91.75 cC
			Ammannia auriculata		
T0	100 aA	96.60 aA	86.39 cBC	83.52 cC	96.55 cB
T1	100 aA	97.41 aA	95.10 aA	94.89 aA	99.12 aA
T3	100 aA	93.53 aA	92.93 aAB	91.83 abAB	98.08 abAB
T5	100 aA	92.88 aA	91.84 abABC	90.42 abABC	98.00 bAB
T7	97.05 aA	93.69 aA	87.35 bcBC	86.97 bcBC	97.28 bcB
T9	100 aA	95.15 aA	86.12 cC	84.29 cBC	96.71 cB
			Cyperus difformis		
T0	100 aA	83.59 bB	74.81 cC	64.43 cB	79.13 cD
T1	100 aA	96.88 aA	94.07 aA	93.96 aA	97.34 aA
T3	100 aA	98.44 aA	97.78 aA	93.96 aA	97.34 aA
T5	100 aA	97.66 aA	95.56 aAB	93.96 aA	96.46 aAB
T7	100 aA	96.09 aA	88.89 bB	86.58 bA	88.19 bC
T9	100 aA	96.09 aA	88.89 bB	85.23 bA	90.55 bBC
			Total weeds		
T0	83.10 cB	75.10 dE	73.03 dC	69.49 eE	80.33 abA
T1	87.74 abA	86.55 aA	84.69 aA	83.90 aA	88.17 aA
T3	88.84 aA	84.47 abAB	82.23 abAB	80.78 abAB	88.62 aA
T5	86.63 bA	82.53 bBC	78.92 bcB	77.93 bcBC	86.72 abA
T7	83.32 cB	79.52 cCD	77.50 cBC	75.14 cdCD	78.91 bA
T9	82.88 cB	78.98 cD	77.79 cBC	73.51 dDE	54.30 cB

Rice was transplanted at the four-leaf stage; CK, rice control; WCK, rice and weed control; T refers to oilseed straw mulch treatment (900 g m^{-2}) applied 4 days after transplanting; T0, straw powder; T1, straw length =1 cm; T3, straw length = 3 cm; T5, straw length = 5 cm; T7, straw length = 7 cm; T9, straw length = 9 cm; DAM, days after mulch application; In each column, different lowercase letters indicate significant differences at $p \leq 0.05$ while different capital letters indicate highly significant differences at $p \leq 0.01$.

Table 5. Effects of various oilseed rape straw mulch treatments and herbicide application on direct-seeded and transplanted rice in field trials.

Treatments [1]	Number of Rice Seedlings (0.75 m^2)	Rice Tiller Number (10 Clusters)	Percentage of CK (%)	Yield (kg ha^{-1})	Yield Increase Rate (%)
		Direct-seeded rice			
A	76.3 aA	—	101.3	10020.5aA	163.0
B	75.0 aA	—	99.2	10188.8 aA	165.7
C	—	—	—	—	—
D	—	—	—	—	—
CK	75.7 aA	—	100	3985.2 bB	—
		Transplanted rice			
A	—	269.4	105.6 abA	10823.1	138.3 abAB
B	—	275.9	108.2 aA	11029.5	142.8 aA
C	—	255.8	100.2 bA	10367.7	128.4 bcA
D	—	258.2	101.3 bA	10221.6	124.7 cA
CK	—	255.1	100 bA	4552.4	—

[1] A, 700 g m^{-2} oilseed rape straw mulch treatment; B, 900 g m^{-2} oilseed rape straw mulch treatment; C, 35% oxadiargyl + butachlor EW 1.5L ha^{-1}; D, hand weeding; CK, no straw mulch and no herbicide control treatment. In each column, different lowercase letters indicate significant differences at $p \leq 0.05$ while different capital letters indicate highly significant differences at $p \leq 0.01$.

Oilseed rape straw mulch length had a significant impact on weed suppression in the field trials. In direct-seeded rice, the 700 g m^{-2} and 900 g m^{-2} straw mulch treatments reduced weed density by more than 98.0% at 20 DAM, and weed fresh weight by more than 96.9% at 35 DAM. For transplanted rice, there was no difference in weed suppression between the 900 g m^{-2} straw mulch treatment and the oxadiargyl + butachlor herbicide treatment, but both treatments were more effective than the hand-weeded treatment. The 700 g m^{-2} straw mulch treatment suppressed weeds as effectively as the hand-weeded treatment (Table 6).

Table 6. Effects of various oilseed rape straw mulch treatments and herbicide application on the density and fresh biomass of weeds in direct-seeded and transplanted rice field trials.

Treatments [1]	20DAM		35DAM			
	Total Number of Weeds (0.75 m^2)	Inhibition Rate (%)	Total Number of Weeds (0.75 m^2)	Inhibition Rate (%)	Weed Fresh Weight (g/0.75 m^2)	Inhibition Rate (%)
			Direct-seeded rice			
A	4.3	98.4 aA	10.7	96.6 aA	24.0	96.9 aA
B	1.3	99.5 aA	6.3	98.1 aA	14.4	98.3 aA
C	—	—	—	—	—	—
D	—	—	—	—	—	—
CK	279.0	—	316.7	—	802.9	—
			Transplanted rice			
A	3.7	92.0 bBC	13.3	90.9 bBC	52.0	91.1 bcB
B	2.0	95.7 aAB	10.0	93.2 abAB	37.1	93.6 abAB
C	1.3	97.2 aA	6.3	95.8 aA	21.9	96.3 aA
D	4.3	90.6 bC	18.7	87.4 cC	59.5	89.9 cB
CK	46.7	—	149.3	—	587.4	—

[1] A, 700 g m^{-2} oilseed rape straw mulch treatment; B, 900 g m^{-2} oilseed rape straw mulch treatment; C, 35% oxadiargyl + butachlor EW 1.5L ha^{-1}; D, hand-weeding; CK, no straw mulch and herbicide control treatment. In each column, different lowercase letters indicate significant differences at $p \leq 0.05$ while different capital letters indicate highly significant differences at $p \leq 0.01$.

4. Discussion

Crop residues including straw are an important resource in modern agriculture. The use of crop residues plays a critical role in stabilizing agricultural systems by providing ecosystem services, increasing farmer income, and alleviating energy and environmental pressures. Our findings demonstrate that oilseed rape straw (900 g m^{-2}) may be safe to use in direct-seeded rice cropping systems when mulching with 1~7 cm length straw at four DAS. A possible reason for this finding is that rice seedlings were largely at the two-leaf growth stage and the leaf incline angle was relatively small when mulch was applied. Rice stems are typically thick and at the seedling stage still protected by the coleoptile [26,27], such that rice seedlings at four DAS are strong enough to overcome the downward pressure caused by the straw mulch. In contrast, the use of straw mulch of 9-cm length decreased the number of rice seedlings emerging from the mulch. It is possible that the longer straw mulch (i.e., 9 cm), may simply be too heavy to allow rice seedlings to push through it and emerge. Similarly, in transplanted rice, the straw powder and 1~7-cm straw length treatments had no significant effect on any of the rice parameters measured. However, when 9-cm long mulch straw was applied, the height of rice plants was significantly reduced. This negative effect of the mulch on rice plant height may be due to leaf damage caused by the longer straw mulch, the effect of which gradually declines with the emergence of new leaves over time. Importantly, our field trial results confirmed that oilseed rape straw mulch (700 or 900 g m^{-2}) of 1-cm length was safe to use in direct-seeded and transplanted rice.

The effect of straw length on weed suppression showed that 1~3 cm straw is suitable for the management of *E. crus-galli* and *L. prostrata*, while 1~5 cm straw is suitable for the management of *L. chinensis*, *A. auriculata*, and *C. difformis*. Interestingly, weed suppression was reduced when the straw mulch length is too short (i.e., powder) or too long (e.g., 9 cm). This suggests that a straw layer of intermediate length probably allows greater straw overlap and coverage of the soil surface, thus more effectively shading weeds from sunlight and also physically suppressing their emergence. Weed seedlings need to overcome greater mulch resistance under such conditions, which may also be the reason why the weed suppressive ability of straw powder was relatively lower than intermediate straw lengths. Application of mulch comprised of longer straw (e.g., 9 cm) may allow more soil gaps, which are suitable for weed growth.

The efficacy of the straw mulch to suppress the monocot, *E. crus-galli*, was not as good as for the other weeds tested in our trials. This finding may be due to the early growth characteristics of the different weeds used. We found that the germination of *E. crus-galli* was relatively fast, with germination beginning within two days of sowing. Moreover, the young seedlings have needle-like narrow leaves with a small incline angle [28]. Thus, seedlings of this grass weed can germinate and grow for a few days prior to the application of the mulch and, therefore, likely "escape" to some degree the straw mulch or are strong enough to overcome the suppressive effect of the straw layer. In contrast, seedlings of *L. chinensis* are very short and its first two leaves are relatively flat and held horizontally [29], thus making it difficult for seedlings of this weed to push through the straw mulch. Although seedlings of the sedge, *C. difformis*, are also needle-like, its stem is relatively thin. Hence, seedlings of this weed species would have more difficulty penetrating through a mulch layer than *E. crus-galli*. Our field trial results confirmed that oilseed rape straw mulch (700 or 900 g m^{-2}) of 1cm length can effectively suppress troublesome paddy weeds. Certainly, factors such as the precise timing of mulch application, the amount of straw applied, and water level, all affect rice growth, productivity, and weed suppression. Further research is needed to better understand how these factors alone and in combination affect crop growth and weed suppression. This additional research would aid in optimizing management strategies in this cropping system.

There are several possible mechanisms responsible for the strong weed suppression reported in our study. First, we observed that the amount of water absorbed by the oilseed rape 1-cm long dry straw might result in a weight several times that of its original weight, such that the heavy straw layer may form an effective physical barrier against the emergence of weed seedlings. Allelopathic substances released from crop straw may be another important mechanism by which straw mulching may effectively suppress weeds [30]. Numerous secondary metabolites have been reported in oilseed rape straw including isothiocyanate, glucosinolates [31,32], and erucic acid [33] that have allelopathic effects on germination and growth of various weed species [34,35]. Asaduzzaman et al. [36] found oilseed rape cultivars Pak85388-502, JC134, Roy47-99P1, and Av-opal to have strong allelopathic effects on *Lolium rigidum* Gaudin (rigid ryegrass). *Lolium rigidum* root biomass was reduced by up to 70% when grown with oilseed rape at a density of 30 plants pot^{-1}. Similarly, oilseed rape straw extract from cultivar Huiyou 50 (1 g straw/20 ml water) resulted in complete suppression of germination in *L. chinensis*. The straw of this cultivar includes primarily organic acids, phenols, alkaloids, and neutral substances with these compounds decreasing seed germination levels in *L. chinensis* by 100%, 10.5%, 5.6% and 12.9%, respectively [33]. Although not directly assessed in our study, differences in weed suppression of the oilseed rape straw mulch might have been due to differences in the type and concentration of allelochemicals present in the straw. Future research should focus on identifying the specific allelopathic compounds and their concentrations present in oilseed rape straw as well as their biological activity.

In a rapidly changing agricultural landscape where sustainable, economical, and environmentally acceptable management practices are sought, the increased use of oilseed rape straw in rice cropping systems provides significant benefits in all these areas. Currently, there is a large overlap in the area planted to oilseed rape and the area planted to rice in China, especially since the oilseed rape-rice rotation is a traditional cropping system in the country. To our knowledge, this is the first report on the use of oilseed rape straw from a previous crop to manage weeds in a subsequent paddy rice crop. The appropriate use of rape straw mulch in rice cropping systems is likely to have the added benefit of effectively controlling herbicide-resistant weeds and of markedly decreasing herbicide use. Moreover, decomposition of the straw in rice systems leads to several soil health benefits including reductions in soil bulk density, increases in soil organic matter content, and decreases in fertilizer use. The use of oilseed rape straw as a mulch holds great promise as both an effective weed management tactic and contributor to soil health, thus allowing more sustainable and profitable rice production.

5. Conclusions

Oilseed rape mulch (900 g m^{-2}) from straw 1-to-7 cm long was found to be safe for rice, when applied four days after sowing (DAS) in direct-seeded rice or four-to-seven days after transplanting (DAT). Straw of 1~3 cm length is suitable for the management of *Echinochloa crus-galli* and *Ludwigia prostrata*, while 1~5 cm long straw is suitable for the management of *Leptochloa chinensis*, *Ammannia auriculata*, and *Cyperus difformis*. Weed suppression was as effective as the standard herbicide (oxadiargyl + butachlor) treatment.

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