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Benefits of mechanical weeding for weed control, rice growth characteristics and yield in paddy fields

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A R T I C L E I N F O

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A B S T R A C T

Context: Mechanical weed control method with autonomous weeding machine provides an alternative way for farmers to reduce the use of herbicides. This method can not only reduce the chemical load in the environment, but also have many other benefits, such as loosening soil and promoting plant growth. However, little is known in this regard. Therefore, field experiments were conducted to determine the benefits of mechanical weeding on rice growth.

Objective: The main objective of this study was to investigate the effects of mechanical weeding on weed control, rice growth characteristics and yield. The ultimate goal was to provide an efficient, non-chemical weed control method for rice production.

Methods: Three field experiments were conducted in 2020 and 2021 using an autonomous weeding machine that combined inter-row and intra-row weeding technologies. Three different rice cultivars (Qingyang, Yuetaiyouzhan, and Huahang 57) were grown in the three experimental sites in South China. At each site, the experimental treatments were mechanical weed control and chemical weed control. Plants with no weed control were taken as the control of the experiment. Weed control efficacy and crop performance were measured.

Results: The results showed that mechanical weeding using the autonomous weeding machine was able to achieve a high level of weed control efficacy (on average 80 %) for three weeks after weeding, and also reduced farmers' time and labor for weed management. Mechanical weeding significantly increased the tiller numbers by 7–23 %, SPAD values by 3–7 %, as well as the total biomass by 45 % after the jointing growth stage, compared with the chemical weed control method. Furthermore, the mechanical weeding obviously increased the activities of superoxide dismutase and peroxidase in the uppermost leaves of rice plants and grain yield by 2–11 % at the harvest maturity stage.

Conclusion: Mechanical weeding using the collectively inter-row and intra-row weeding technology was capable of avoiding using herbicides with no losses in weed control efficacy and grain yield. Due to the mechanical stimulation and inter-tillage effect of the autonomous driving weeding machine, the mechanical weed control method promoted rice growth, which provided an efficient and non-chemical weeding method for rice production.

Significance: The continuing advancement of this emerging technology is of great significance to the development of weed control in field crops. The results could be used to enhance rice production using mechanical weed control methods and develop smart-agriculture practices in China and similar agroecological regions around the globe.

1. Introduction

The weed problem in paddy fields is one of the main factors reducing the crop yield in rice production because they use part of the resources that are essential for rice growth. Weed management in paddy fields has significant seasonality, short weeding period, and large amount of labor,

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which brings more challenges (Zhu et al., 2020). Consequently, weed control is perceived to be an important aspect of research in paddy field management. Weed control methods include chemical, mechanical, biological, thermal, electric, and cultural approaches (Zeng et al., 2021). Due to the advantages of economy and labor savings, chemical weed control is a frequently used and efficient method, but it has high risk of herbicides contamination. The evolution of herbicide-resistance weeds will decrease the efficacy of chemical weed control, and it may cause adverse effects on crop growth and yield as well. With the accumulation of layers in the food chain, there could be herbicide residues in human bodies. Therefore, many countries require to reduce their dependence on herbicides, especially the European Union, which promotes the adoption of mechanical weed control strategies (Melander et al., 2015).

Mechanical weeding has always been an environment-friendly, sustainable weeding substitute in agricultural history, and it is also the most important alternative to chemical weed control (Van Der Weide et al., 2008; Kunz et al., 2015). As a rapid weed control technology to replace herbicides, mechanical weeding has reduced production costs and labor force, and enhanced weeding efficiency in recent years. With the rapid development of organic agriculture, this weeding method is progressively more favored by organic rice producers. Research and development of mechanical weed control methods for rice has been the focus of many studies in the past two decades (Van Der Weide et al., 2008; Melander et al., 2015), mainly driven by regional policies and the transition to organic production. The primary emphasis has been on the management of inter-row weeds which grow between crop rows and can be easily managed by most inter-row cultivators (Melander et al., 2015). However, the challenge for mechanical weeding is to control the weeds in the intra-row area of crops. Current intra-row mechanical weeding practices such as weed harrowing, torsion weeding (Melander et al., 2015), and finger weeding have been studied for weed control (Ascard et al., 2008). These methods are not guided by any intelligent system and are non-selective, relying on weed-crop root differences when passing through intra-row areas. Since intra-row weeding machines tend to injure seedlings when operating near seedlings, farmers need precise alignment operations to minimize the damage to seedlings.

Using ride-on weeders is currently the most efficient weeding method among the mechanical weeding methods applied in rice cultivation in China (Qi et al., 2017). However, this method has limitations. Some weeds usually survive the treatment, especially in curved seedling beltlines. It is difficult for the weeders to accurately match the seedling belt line, and multiple weeding operations are required to cleanse the field, which also increases the rate of seedling injury. The rapid development of autonomous driving technology has prompted the emergence of new high-efficiency intelligent paddy weeding machines, which integrate satellite navigation and positioning, automatic control, and inter-row and intra-row weeding. Autonomous driving weeding machines would not only replace the manual driving of weeding machinery but also improve the alignment accuracy with the use of autonomous driving rice transplanters. This transplanting-weeding technology effectively reduces the seedling injury rate and increases the crop yield.

Most existing studies on intelligent weeding machines focused on image processing analysis, control systems and mechanical structure optimization (Mink et al., 2018; Gerhards et al., 2022). Only a few scientifically-based evaluations were available on the effects of weeding machines on crop growth and yield. One study by R. Li et al. (2019) on rice yields showed that there were ecological dependencies between agronomic components and yield, such as filled grain number per panicle, 1000-grain-weight, plant height, panicle height, grains per panicle, seed setting rate, long growth period, which were the main reasons for high grain yield. Awan et al. (2015) compared agronomic indices, growth, yield-contributing components, and yield of dry-seeded rice under varying herbicides. The study found that all herbicide treatments and manual weeding significantly affected tiller number, biomass, crop growth rate, agronomic indices, yield-contributing parameters (panicle density and filled grains), and yield (biomass and grain) of rice. However, neither of the two studies dealt with intelligent weeders capable of controlling inter-row and intra-row weeds.

In this study, three field experiments were conducted using an autonomous driving weeding machine that could perform inter-row and intra-row weeding operations. The objectives were: (1) to compare the mechanical weed control with chemical weed control method in the field experiments; (2) to examine the effects of mechanical weeding on physiological and biochemical characteristics of rice (e.g. tiller numbers, SPAD values, biomasses and enzyme activities); (3) to investigate the effects of mechanical weeding on the grain yield and yield components of three rice cultivars.

2. Materials and methods

2.1. Autonomous weeding machine

An autonomous weeding machine (Fig. 1) was used for mechanical weeding. It was developed by College of Engineering, South China Agricultural University, Guangzhou, China. The machine had a GNSS-based autonomous driving system, a power system, a profiling mechanism, and synchronous inter-row and intra-row weeding devices (2 m wide). The intra-row weeding unit consisted of a pair of umbrella-like rollers where each roller was equipped with 8 tines designed mainly to cut the weeds at a soil depth range from 10 to 50 mm. The inter-row weeding was achieved by spiral scraper-like rollers that cultivate the inter-row area and kill weeds on either side of the crop row. When the autonomous weeding machine worked, its driving system automatically controlled the movement and weeding action of the machine according to the route of transplanted rice seedlings, while the computer set exactly when to adjust the direction to avoid injuring the rice seedlings. The operating efficiency of this weeding machine was 0.57 ha h^{-1}, with a timely weeding rate of 82.4 % and the seedling injury rate of 2.1 %.

2.2. Description of the experimental sites

In southern China, rice is planted twice a year, which are named as early-season rice and late-season rice. The first experiment was performed in the late growing season of 2020. The experimental site was located at Yayao Experimental Farm, Heshan Agriculture Technology Extension Center, in Jiangmen City, China (22°77′N, 112°97′E with 19 m of elevation). The soil texture was clay loam. The second experiment was conducted during the early growing season in 2021 at the same farm. During the same season in 2021, the third experiment was conducted at Shapu Experimental Farm of Zhaoqing Agricultural Research Institute in Zhaoqing City, China (23°15′N, 112°65′E with 17 m of elevation). The soil texture was sandy loam. The two farms were located in the same region. Generally, this region has a sub-tropical and monsoon type of climate (Li

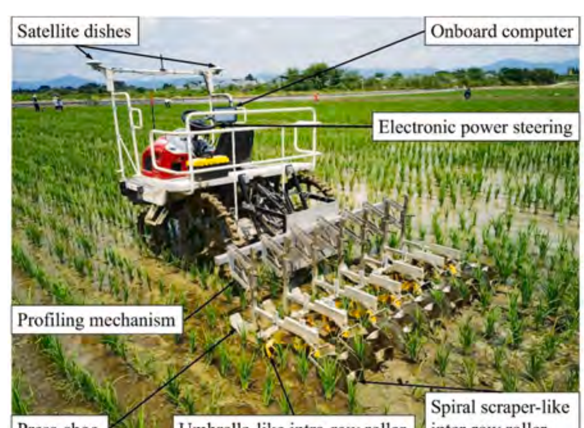

Fig. 1. Autonomous weeding machine used in the experiments.

et al., 2016). The mean annual average temperature, sunshine duration, precipitation, and humidity throughout the rice growing seasons are presented in Table 1.

2.3. Experimental design and treatments

Three rice cultivars: Qingyang, Yuetaiyouzhan, and Huahang 57 were used at three experimental sites: Yayao (late season), Yayao (early season), and Shapu (early season), respectively. At each site, the experimental treatments were two different weed control methods: mechanical weed control (MW) and chemical weed control (CW), and no weed control (NW) was used as the control of the experiment. The experimental treatments are summarized in Table 2. Except for different weeding methods, all other conditions such as fertilization and pest control were the same for all treatments. The rice husbandry practices are shown in Table 3. Fields were fertilized using urea and two types of nitrogen, phosphorus, and potassium (15: 15: 15 and 20: 9: 11 of N: P_2O_5: K_2O, respectively) compound fertilizer throughout the fertility period. Two application methods: 50-mm depth side banding and manual surface broadcast, were adopted. In 2020 and 2021, at Yayao Farm, a slow-release compound fertilizer with a N: P_2O_5: K_2O ratio of 20: 9: 11 was applied at a rate of 600 kg ha^{-1} at transplanting as the base fertilizer. The top-dressing was performed at a rate of 75 kg ha^{-1} on the 7th day. At Shapu farm in 2021, the compound fertilizer with a N: P_2O_5: K_2O ratio of 15: 15: 15 was applied three times for a total of 525 kg ha^{-1}: side banding fertilization at a rate of 225 kg ha^{-1} when transplanting and manual spreading at a rate of 150 kg ha^{-1} 15 and 27 days after rice transplanting. Additional urea (46 % N) was top-dressed at a rate of 75 kg ha^{-1} 7 days after rice transplanting. According to the growth situation of rice, local farmers used unmanned aerial vehicles to spray pesticides to control pests and diseases. Because there was only one experimental factor, the field experiments were set up as randomized block designs in triplicate, giving a total of 9 plots (3 treatments × 3 replicates) at each of the three sites. Each plot had a net plot size of 120 m^2 (4 m × 30 m), which was suitable for the autonomous weeding machine to turn around and continue its operation. Rice seedlings were transplanted in the plots on August 7, 2020 in the first experiment, and on March 19 and 30, 2021 in the second and third experiments. At those times, the seedlings developed 2–4 leaves (seedling age: 14–20 days) and reached a height of 100–150 mm. Each plot had twelve crop rows with an inter-row spacing of 0.3 m. Within the crop row, the intra-row spacing was 0.18 m between rice plants.

2.4. Experimental procedure

The autonomous driving rice transplanter was used to transplant the rice seedlings in the fields, and also to collect the navigation information of the transplanting paths that was later used for the weed control. Rice seedlings were transplanted in flood conditions with water depths ranging from 10-30 mm. After the transplanter completed all transplanting operations in the field, the navigation information of the path the transplanter had traveled was uploaded to the base station. The fields were irrigated with a water layer of about 30–50 mm on the fifth day. Next, weed control took place at 4–5 leaves stage of rice, or two weeks after rice transplanting, when all the weeds have grown out and were small. For the mechanical weed control plots, the autonomous weeding machine that had stored the travelling path of the transplanter moved along the wheel ruts created previously during the transplanting. Thus, the traveling paths of transplanting and weeding operations were completely overlapped, which improved alignment accuracy and reduced seedling injury rates.

For the chemical weed control plots, a mixture of 60 % Butachlor emulsion (a selective pre-bud herbicide; rate: 1.95 L ha^{-1}) and 10 % Benzosulfuron methyl wettable powder (a selective systemic-conducting herbicide; rate: 75 g ha^{-1}) was applied on the 7th day after transplanting. This mixed herbicide is mainly used for the control annual gramineous weeds and some broad-leaved weeds in paddy fields after plugging soil treatment. A stem and leaf herbicide, pentafluoride compound with a total active ingredient content of 60 g L^{-1} (10 g L^{-1} of Penoxsulam, 50 g L^{-1} of Cyhalothrin), applied with a backpack sprayer at a rate of 1.8 L ha^{-1} mixed with water according to the occurrence of weeds during the plant growth.

Table 1
Mean annual average temperature, sunshine duration, precipitation, and humidity of the experimental sites.

Year	Site	Temperature (°C)	Sunshine duration (h)	Precipitation (mm)	Humidity (%)
2020	Yayao	23.5	1714.8	1631.7	79.4
2021	Yayao	23.7	1933.1	1529.3	76.3
2021	Shapu	22.6	1194.2	1853.1	76.8

Table 2
Summary of experimental treatments.

Experiment	Growth season	Rice cultivar	Treatment*		
			MW	CW	NW
2020Yayao	Late	Qingyang	✓	✓	✓
2021Yayao	Early	Yuetaiyouzhan	✓	✓	✓
2021Shapu	Early	Huahang 57	✓	✓	✓

* MW, CW, and NW stand for mechanical weed control, chemical weed control, and no weed control respectively.

Table 3
The rice husbandry practices of experiments.

Experiment	Fertilizer*	Date		
		Sowing	Transplanting	Harvesting
2020Yayao	20:9:11 compound fertilizer	Jul. 20	Aug. 7	Nov. 3
2021Yayao	20:9:11 compound fertilizer	Feb. 28	Mar. 19	Jun. 25
2021Shapu	15:15:15 compound fertilizer + urea	Mar. 10	Mar. 30	Jul. 13

* The values of fertilizers represent the ratio of nitrogen, phosphorus and potassium respectively.

2.5. Measurements

2.5.1. Weed control efficacy

The number of weeds in each plot was counted three weeks after mechanical weeding. Five-point sampling method was adopted for each plot. First, the midpoint of the diagonal line was determined as the central sampling point, and four points on the diagonal at equal distances from the central sample point were selected as sample points. An area of 1 m^2 was taken for each point to determine the weed density. Weed control efficacy was calculated using the following equation:

$$E = \frac{n_N - n_W}{n_N} * 100$$

where E is the weed control efficacy (%); n_W is the number of weeds in the mechanical weed control (MW) or chemical weed control (CW) plot; n_N is the number of weeds in the no-weeding (NW) plot.

2.5.2. Physiological characteristics of rice plants

The physiological characteristics of rice plants were measured at several rice growth stages: the midterm tillering stage (MI), maximum tillering stage (MA), jointing stage (JS), and booting stage (BS). Ten rice plant samples were taken from each field plot. Tiller number, plant height, and chlorophyll SPAD value of the plants were measured in the field at each growth stage. The tiller number of each plant was calculated manually, and the plant height was measured by a ruler. The chlorophyll SPAD value was measured by using a portable chlorophyll SPAD meter (SPAD-502 Plus, Konica Minolta, Japan). In the measurements, three areas (30 mm from the leaf tip, middle of the leaf, and 30 mm from the leaf base) were selected from the uppermost leaf of the plant and the average value was taken.

2.5.3. Determination of enzyme activities

Antioxidant enzyme activities were measured at each of the aforementioned growth stages. Superoxide dismutase (SOD) and peroxidase (POD) were determined by following the methods of Pan et al., (2013, 2017) respectively. Leaf tissues were frozen in liquid nitrogen and ground with an ice-cold pestle and mortar, and then extracted in 50 mM sodium phosphate buffer (pH 7.0) containing 0.1 mM EDTA-Na_2, 1 mM L-isoascorbic acid, 1.0 % (w/v) insoluble PVP, and 0.05 % (w/v) Triton X-100.

2.5.4. Total biomass, grain yield components and grain yield

Rice plant samples were collected at each growth stage. Plants were washed thoroughly with sterile, distilled water to remove adhered soil, while the above-ground plants parts and roots were separated. The dry weight was measured after drying at 80 ℃ for 48 h. A root scanner (ScanMaker-i800 plus, MICROTEK, China) and LA-S root analysis system were used to measure and analyze the diameter, surface area, and height of roots before drying. To detect accurately and prevent the overlapping of roots, half of the roots of each sample were scanned. Grain yield components, including productive panicles, spikelet per panicle, percentage of grain filling, and 1000 grain weight, were measured according to Peng et al. (2004). At maturity, plants of each plot were sampled from three locations of 1.0 m^2 to determine the harvest yield. The theoretical yield was estimated by the following formula:

$$G_T = n_P * n_S * g_F * g_w * 10^{-6}$$

where G_T is the theoretical grain yield (t/ha); n_P is the number of productive panicles (10^4/ha); n_S is the number of spikelets per panicle; g_F is the grain filling (%); g_W is the 1000-grain-weight (g).

2.6. Statistical analysis

Data were analyzed using the Data Processing System (DPS), 9.01 version statistical software (Tang and Zhang, 2013). The analysis was done within each experiment, due to the different conditions in site, season, and rice cultivar. ANOVA was performed to examine the effects of the experimental factor (weed control method) within the dataset of each experiment. Duncan's multiple ranges tests were used for comparisons between treatments (MW, CW, and NW). Significant differences were determined at a probability of $p < 0.05$. Results were expressed as means ± standard error.

3. Results

3.1. Weed control efficacy

The most frequent weed species found in the fields were *Echinochloa crusgalli* (L.), Beauv, *LeMAochloa chinensis* (L) Nees, *Alternanthera philoxeroides* (Mart.) Griseb, *Cyperus difformis* L. and *Ludwigia prostrata* Roxb. Those weed species were typical local species. There were some variations in the weed density between the sites (Table 4). For the late season rice in the 2020Yayao site, weed densities in the NW plots had an average of 12 weeds m^{-2}. Whereas for the early season rice in the other two sites, much higher weed densities were observed. This meant that early rice practices may need to deal with more weeds. In all three experiments, there were no significant differences between the two weed control methods. The MW and CW gave similar efficacy in general. On average over three experimental sites, the efficacy of the CW was 79 %, and that of the MW was 80 %. The results indicated that mechanical weeding was as effective as using herbicides.

Table 4
Weed control efficacy as affected by the weeding method in three experiments.

Experiment	Weed density in NW (weeds m^{-2})	Weed species	Weed control efficacy, E (%)*	
			(MW)	(CW)
2020Yayao	11.7 ± 2.4	①②③⑤	76.5a	76.4a
2021Yayao	31.4 ± 2.9	①②③⑤	81.1a	76.0a
2021Shapu	24.2 ± 2.5	①②③④⑤	81.5a	83.5a

* Values labeled with the same letter in the same row were not statistically different at probability of $P < 0.05$. Weed species: ① *Echinochloa crusgalli* (L.) Beauv, ② *LeMAochloa chinensis* (L) Nees, ③ *Alternanthera philoxeroides* (Mart.) Griseb, ④ *Cyperus difformis* L., ⑤ *Ludwigia prostrata* Roxb.

3.2. Physiological characteristics of rice plants

The effect of weed control method on the tiller number, plant height, and SPAD value of rice at different growth stages are presented within each of the three rice cultivars: Qingyang and Yuetaiyouzhan at the 2020Yayao and 2021Yayao sites respectively, and Huahang 57 at the 2021Shapu site. The number of tillers varied slightly in response to the weeding treatments for the late-season rice of 2020 and early-season rice of 2021 (Fig. 2). In general, the number of tillers increased significantly during the MI stage and peaked at the MA stage. From the MA stage onward, the effective spikes were continuously declining and the ineffective tillers gradually withered. The trends of rice tiller numbers were similar among different cultivars and generally showed that MW > CW > NW. However, MW did not significantly increase the number of rice tillers at the MI, MA and JS stages, but significantly reduced ($P < 0.05$) the ineffective tillers of rice plants at the BS stage, compared to the CW treatment.

Before the jointing stage, the number of tillers for NW showed an obvious downward trend, while the change was not significant for MW and CW. At this growth stage, the number of tillers in the MW plots increased by 0.18 at the 2020Yayao site, 3.60 at the 2021Yayao site, and 2.86 at the 2021Shapu site, compared with the CW plots.

In the early stage of rice growth, there were no obvious differences in plant height among NW, MW, and CW (Fig. 3). However, with the development of rice over the growth period, the height of rice in the NW plots increased. In contrast, the heights of rice plants in the MW and CW plots were lower than that of NW, but there were no significant differences. Also, there were no significant differences in plant height between MW and CW.

Chlorophyll is the main pigment for rice to absorb solar energy during photosynthesis, and its SPAD value represents the changing trend of chlorophyll content and the utilization efficiency of nitrogen fertilizer. SPAD value at the MI, MA, JS and BS growth stages were shown in Fig. 4, where all trends were to increase first and then decrease over the growing stages. The differences amongst all the treatments were smaller at the early stage than at the later stage. During the BS stage, significant differences ($P < 0.05$) in SPAD values were observed among all treatments with the lowest and highest SPAD values being recorded in NW and MW for Qingyang and Yuetaiyouzhan cultivars respectively. For Huahang 57 cultivar, CW was found to be higher than NW but lower than MW, in terms of SPAD values.

3.3. Rice biomass and root morphology

The aboveground and underground biomass at the MI, MA and JS stages were shown in Fig. 5. The differences among all the treatments were small at the MI stage. At the later growth stages (MA and JS), significant differences ($P < 0.01$) in biomass were observed. The

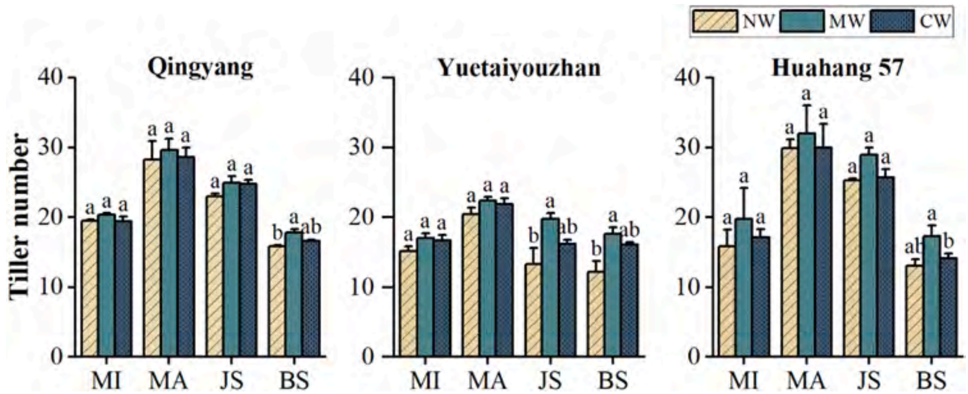

Fig. 2. The number of tillers in rice plants of different cultivars as affected by different weed control methods. NW: no weed control; MW: mechanical weed control; CW: chemical weed control; MI: mid-tillering growth stage; MA: maximum tillering stage; JS: jointing stage; BS: booting stage. Means labeled with the same letter in the same row were not statistically different at probability of P < 0.05; error bars stand for standard errors.

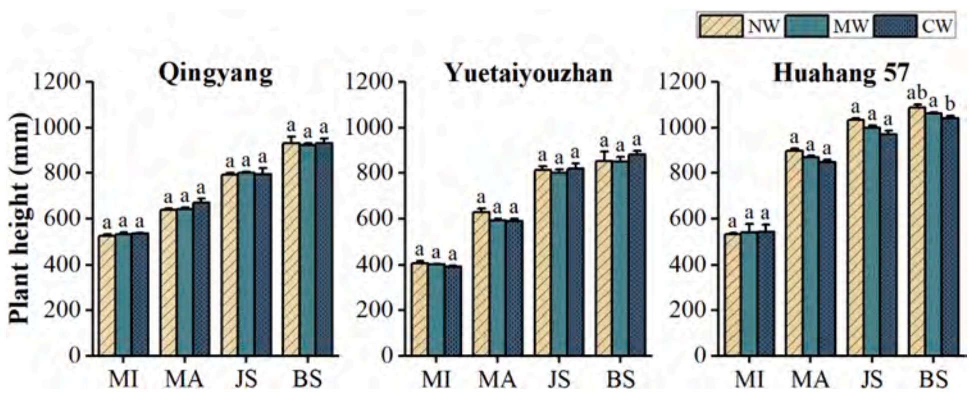

Fig. 3. Heights of rice plants of different cultivars as affected by different weed control methods. NW: no weed control; MW: mechanical weed control; CW: chemical weed control; MI: mid-tillering growth stage; MA: maximum tillering stage; JS: jointing stage; BS: booting stage. Means labeled with the same letter in the same row were not statistically different at probability of P < 0.05; error bars stand for standard error.

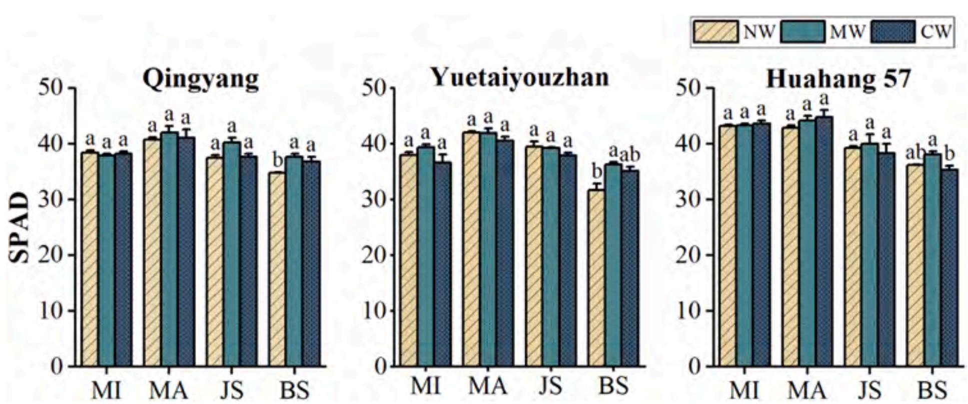

Fig. 4. SPAD values of rice plant of different cultivars as affected by different weed control methods. NW: no weed control; MW: mechanical weed control; CW: chemical weed control; MI: mid-tillering growth stage; MA: maximum tillering stage; JS: jointing stage; BS: booting stage. Means labeled with the same letter in the same row were not statistically different at probability of P < 0.05; error bars stand for standard error.

aboveground biomass of rice associated with the MW treatment were 584.9 and 1085.6 g m^{-2} in MA and JS respectively (Fig. 5a). The much lower amount of aboveground biomass was obtained in the other two treatments at these later growth stages. There were the same trends in underground biomass among all the treatments and growth stages. Again, the MW produced the highest underground biomass among all the treatments, which was 32 % higher than CW and 171 % higher than NW at the JS stage (Fig. 5b).

Underground root morphology of the MA stage in response to the weeding treatments in Huahang 57 for the late season of 2021 is shown in Fig. 6. The CW resulted in similar heights and surface areas of roots with the NW (Fig. 6a). However, when compared to the NW and CW treatments, the MW treatment increased the height and surface area of roots. The MW also favored root development in terms of volume and mean diameter of roots (Fig. 6b). The root volume of CW was quite low relative to the other two treatments.

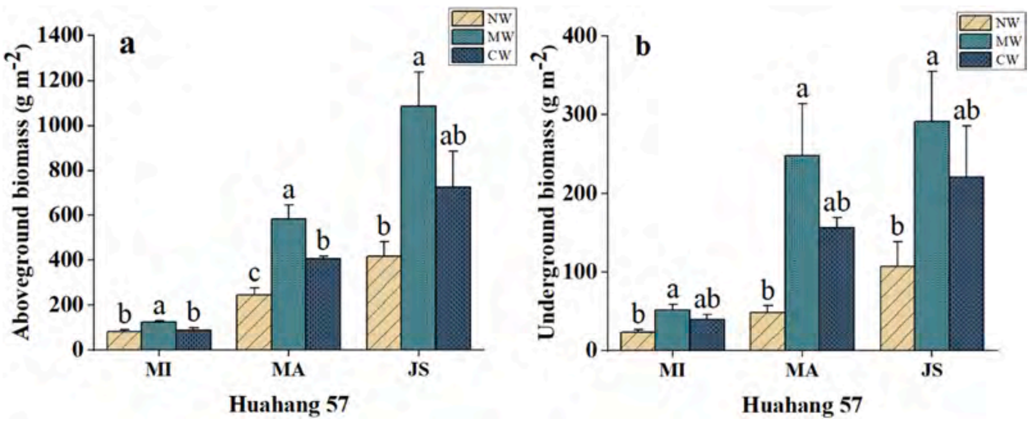

Fig. 5. Aboveground (a) and underground (b) dry biomass of rice plant as affected by different weed control methods in the late season of the 2021Shapu site. NW: no weed control; MW: mechanical weed control; CW: chemical weed control; MI: mid-tillering growth stage; MA: maximum tillering stage; JS: jointing stage. Means labeled with the same letter in the same row were not statistically different at probability of $P < 0.05$; error bars stand for standard error.

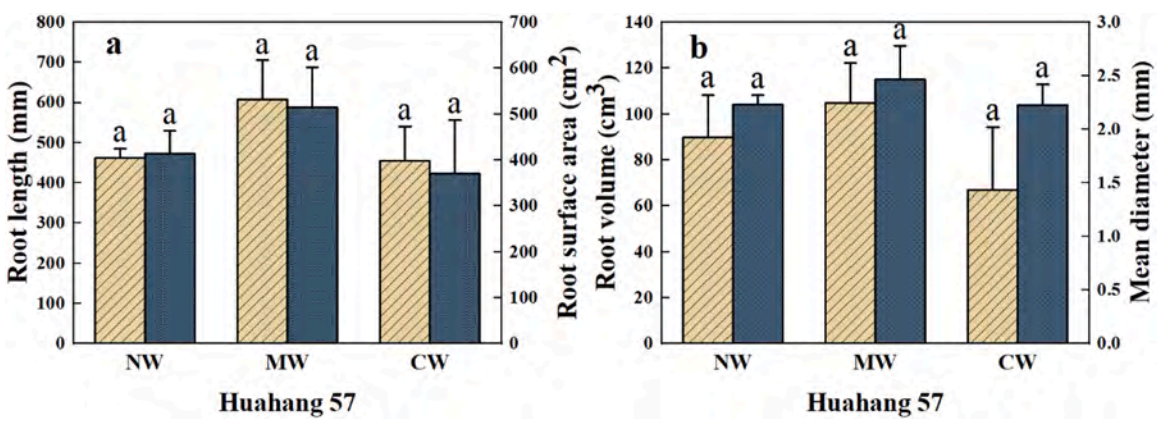

Fig. 6. Effect of different weed control methods on the length and surface area of roots (a) and the volume and mean diameter of roots (b) at the MA growth stage. NW: no weed control; MW: mechanical weed control; CW: chemical weed control. Means labeled with the same letter in the same row were not statistically different at probability of $P < 0.05$; error bars stand for standard error.

3.4. SOD and POD activities in the uppermost leave

Superoxide Dismutase (SOD) and Peroxidase (POD) activities at the BS growth stage of Qingyang rice in 2020 at Shapu Farm are shown in Fig. 7. The MW treatment significantly increased ($P < 0.05$) the SOD activity in the uppermost leaves, compared to the NW and CW treatments. The lowest activity of SOD was observed in the NW treatment. POD activity in the uppermost leave at the BS stage responded to the different treatments with the same trend as SOD activity, whilst the POD activity of rice in the CW treatment was lower than that in the NW treatment. However, the enzyme activities of each treatment tended to be at the same level in the later stage (not shown in the figure).

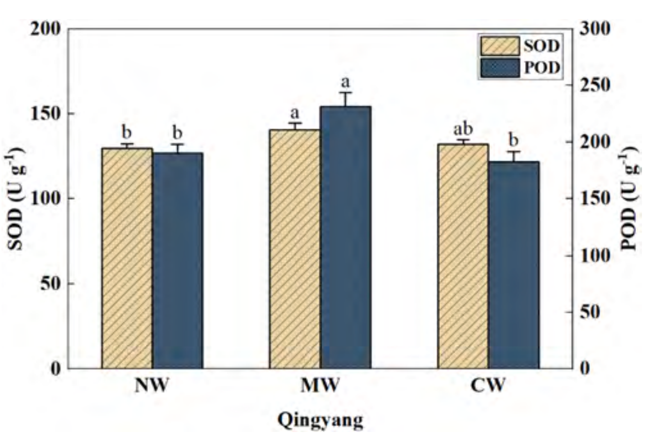

Fig. 7. Superoxide Dismutase (SOD) and Peroxidase (POD) activities in the uppermost leave at the BS growth stage as affected by different weed control methods. NW: no weed control; MW: mechanical weed control; CW: chemical weed control. Means labeled with the same letter in the same row were not statistically different at probability of $P < 0.05$; error bars stand for standard error.

3.5. Grain yield and yield components

Grain yield and yield components varied with different weeding treatments for all rice cultivars (Table 5). The moisture content of the grain at harvest was 19.6–24.8 %. The NW plots had the lowest harvest yield in all the three experiments, and the harvest yields at Yayao Farm were 4.33 t ha^{-1} in 2020 and 5.78 t ha^{-1} in 2021, and the harvest yields at Shapu Farm was 5.80 t ha^{-1} in 2021. The MW plots provided the higher harvest yields. As compared with the MW, the CW had slightly lower yields. When compared to the other treatments, the MW treatment had the highest theoretical yield, which was, on average, 15 % higher than NW and 6 % higher than CW treatment. However, the MW and CW treatments did not have significant differences in theoretical yield for all three cultivars.

As for the yield components, there were significant differences ($P < 0.05$) in the number of productive panicles among the treatments.

Table 5
Effect of different weed control methods on yield and its components in rice.

Rice cultivar	Treatment *	Productive panicle (10^4 ha^{-1})	Spikelet per panicle	Grain filling (%)	1000- grain- weight (g)	Theoretical yield (t ha^{-1})	Harvest yield (t ha^{-1})
Qingyang	NW	328.36b	108.09a	80.82ab	24.28a	6.82b	4.33b
	MW	379.10a	111.54a	81.98a	24.81a	8.36a	5.16a
	CW	356.88ab	113.82a	78.30b	24.26a	7.52ab	4.66ab
Yuetaiyouzhan	NW	181.50b	127.32b	68.78b	21.20a	4.36b	5.78b
	MW	259.28a	140.77a	71.65a	21.35a	7.23a	8.70a
	CW	230.94ab	139.35a	71.54a	21.30a	6.22a	8.11a
Huahang 57	NW	242.06b	111.30a	75.58b	16.93a	4.52b	5.80b
	MW	319.84a	116.17a	84.71a	16.99a	6.98a	7.51a
	CW	261.69b	112.00a	83.07a	17.08a	5.39ab	7.40a

* NW: no weed control; MW: mechanical weed control; CW: chemical weed control. Within a column, means followed by the same letter are not significantly different at the 0.05 probability level according to the least significant difference test.

The number of productive panicles in the MW plots was significantly higher than those in the CW and NW plots, with an average increase of 36.24 (10^4 ha^{-1}) panicles and 68.77 (10^4 ha^{-1}) panicles respectively. Also, the MW had the maximum spikelet per panicle and grain-filling percentage, but there were no significant differences between the MW and CW treatments. The 1000-grain-weight had no significant differences among all the treatments, regardless of rice cultivars.

4. Discussion

The role of mechanical weeding in weed control, rice growth and improving crop yield was studied in three experiments at two farms in Guangdong province, China, over two growing seasons. Results showed that in all cases, either mechanical or chemical weed control was able to significantly reduce the weed density as compared to the no weed control treatment (Table 4). The weed control efficacy of both mechanical and chemical methods reached over 80 %. There were no significant differences in the efficacy between the two weed control methods. However, this highlighted that the autonomous weeding machine was comparable to the herbicides, in terms of weed control efficacy. This showed the potential of mechanical weeding to be a valuable alternative to the common chemical weed control.

Rice typically blocks the photosynthesis of weeds 5–6 weeks after transplanting due to canopy closure, and then weeds would die slowly in the absence of sunlight (Uno et al., 2021). Thus, weed control during the early rice growing stage is more critical. The results demonstrated that mechanical weeding could effectively control various weeds five weeks after rice was transplanted, which was considered to be one of the key factors for the subsequent yield increase. In terms of efficiency, the use of automatic weeding machine was more timesaving than chemical weeding. This result is contrary to the advantage reported by Rodenburg et al. (2015) in Bagamoyo, Tanzania that the use of herbicides requires less time and energy than rotary weeders. In these experiments, the efficiency was about 3.3 times higher than manual herbicide application (about 0.17 ha h^{-1}, data not shown) due to the employment of more advanced autonomous driving technology and a ride-on weeder. An autonomous weeding machine can serve farmers in multiple seasons and on multiple farms. As farms expand in size, this new mechanical weed control method could further reduce the amount of time farmers spend managing weeds compared to conventional chemical weed control methods.

We found variable positive effects of mechanical weeding practices on rice plant growth and yield (Figs. 2–4). Mechanical weeding reduced the height of rice plants to a certain extent compared with the no weed control. Because of more weeds, the more competition would be for the light, which caused the increase in height of rice plants to get the appropriate condition. This explains the greater height of rice plants in the no weed control plots. This observation is consistent with the results indicated by Chauhan (2012). With the decrease of plant height in the mechanical weed control plots, the stem resistance to bending would increase, which would be beneficial to improve the lodging resistance of rice. The number of tillers for MW was 7–22 % and 13–45 % higher than CW and NW, respectively, in the middle and late stages of rice growth, indicating that mechanical weeding could promote the effective tillering of rice but also inhibit the formation of some ineffective tillers. Mechanical weeding also promoted increased the SPAD value of rice plants by 2–8 % compared to chemical weeding. It could improve the photosynthetic efficiency of rice, eventually delay the yellowing and withering of rice leaves, increase the accumulation of dry matter and improve the yield components of rice. These benefits were not only directly related to the effective weed control of mechanical weeding but also to the mechanical stimulation and stirring of weeding machine on rice plants. Previous research had reported significant effects of rice-duck co-culture system on the morphology and grain yield of rice. Rice-duck co-culture system decreased rice stem height but increased root biomass and chlorophyll contents, and improved rice plant lodging resistance and photosynthesis capacity, leading to increased rice production (M. Li et al., 2019). Rice-duck co-culture depends on ducks to eat and trample weeds, which can stir and rub the rice roots, and the mechanical weeding used in this study had similar functions resulting from the interaction between weeding rollers and plants. In contrast, Butachlor has negative effects on physiology and biochemistry of rice plants. According to the research of Wu et al. (2004), the number of rice tillers and plant heights declined on some rice with the butachlor treatment. Hence, these findings also supported the view that mechanical weed control could promote the growth of rice compared with chemical weed control in the present study.

In the present study, the weed control treatments significantly affected the aboveground and underground biomass of rice plants (Fig. 5). The results revealed that the mechanical weeding plots had the highest total biomass of rice, which was 45 % higher than the chemical weeding plots, and the no weeding plots had the lowest total biomass. The reason is that weedy plots may have had weeds competing with rice plants for nutrients and other resources, which reduced the amount of space and nutrients available to the rice plants, resulting in a decrease in biomass per unit area. This is in line with the work of Maimunah et al. (2021), who suggested that weed removal positively affected the tiller number and biomass of rice. Another benefit of mechanical weeding compared to chemical weeding is that the muddy water stirred by weeding rollers increased the dissolved oxygen in paddy water and soil, and thus, the growth environment of rice roots was improved (Kato and Okami, 2010). The function of inter-tillage of mechanical weeder can also reduce soil compaction. All these would favor the growth of rice roots, reflected by the increased height, surface area, volume, and mean diameter of the roots (Fig. 6), which is conducive to the full absorption and utilization of soil nutrients by rice. This is consistent with the research by Telewski (2006) who suggested that mechanical stimulation of weeding machine, such as touching, bending, and shaking plants, were identified as an environmental stress element that influenced the growth and development of plants. Yang et al. (2018) found that the improvement of soil oxygen conditions served to increase root activity, adsorptive area, root volume, root biomass, and root/shoot ratio, which is consistent with our findings. Mechanical stimulation had also been suggested as a method to control plant growth in agricultural and horticultural settings (Garner et al., 1996), and some farmers routinely use stress treading, trampling, or stamping of wheat and barley seedlings as a way to prevent spindly growth, strengthen the roots, shorten plant height, and ultimately to improve yield (Iida, 2014).

Furthermore, the mechanical stimulation on rice plants by weeding machine in paddy fields could also positively affect the rice plant physiology, including the leaf chlorophyll content, and SOD and POD activities improved in the uppermost leave (Fig. 7). Compared to chemical weed management, mechanical weed treatment increased SOD and POD activities by 6 % and 27 %, respectively. The minimal seedlings damage and mild mechanical stimulation increased the activity of SOD in rice leaves after weeding operations, which accelerated the scavenging of superoxide radicals produced by the organism. This facilitated the inhibition of membrane lipid peroxidation and maintained cytoplasmic membrane stability. Since POD is involved in a variety of metabolisms in cells, it breaks down H_2O_2 as well as harmful intermediates in plants. The moderate mechanical stimulation was beneficial to improve the ability of leaves to scavenge intracellular reactive oxygen species and synergistically defend the cell membrane system from reactive oxygen species as well as other peroxide radicals, which enhanced the stress resistance of rice plants. However, they could be negatively affected by chemical treatment. The reason for the increase of enzyme activity in rice treated by chemical weeding was that rice plants were capable of activating a series of enzymatic antioxidants through both molecular and physiological mechanisms to alleviate herbicide-induced stress. These findings agreed with those reported by Islam et al. (2017) and were considered the main cause of rice growth retardation.

Both mechanical and chemical weeding methods could improve harvest yield (Table 5). Although mechanical weeding could potentially cause some seedling injury, rice yield was not adversely affected. Compared with the chemical weed control, the mechanical weeding increased the yield by 2–11 %. In addition, the response of rice yield to weeding methods is influenced by numerous other factors including temperature, precipitation, fertilization, soil characteristics, and management practices in farmland. In the experiment of Yayao Farm in 2020, although the harvest yield was lower than the theoretical yield due to the influence of sheath blight and rice plant hopper (low rice resistance), the yield variation trend was consistent with the other two experiments. The increased yield of mechanical weeding could be due to higher productive panicles and grain-filling percentage, which was in agreement with the results of Akbar et al. (2011).

Overall, mechanical weeding showed great potential not only to improve the enzyme activities and biomass of rice, but also to promote chlorophyll accumulation and thereby increase rice grain yield. This can be explained by the following facts. First, the stirring effect of the weeding roller might have increased the supply of nutrients for plant growth by promoting the full integration of fertilizer-soil and increasing the oxygen content of the soil. This also enhanced rice plant photosynthesis and promoted total aboveground biomass accumulation and improved microclimate conditions. Second, mechanical weeding increased the grain-filling percentage, which may be due to the reduction in the loss of nitrogen and phosphorus. Sun et al. (2019) explained that rice required less N during the grain-filling stages than weeds. Weed leaves also require a high amount of nitrogen and absorb more nitrogen in highly enriched soil than rice leaves. The nitrogen content in the weeds was higher than in rice, and, as such, controlling the weed density was necessary to supply the rice with more N. Third, as the weeding machine moved around the field, it mechanically interacted with the plant roots, which would also improve the microclimate for rice plant growing (Zhang et al., 2013), as well as stimulate plant physiological mechanisms. Then those changes would occur in SOD and POD activities.

5. Conclusions

Collectively inter-row and intra-row weeding technology was able to achieve a high level of weed control efficacy (on average 80 %) for three weeks after weeding, and also reduced farmers' time and labor for weed management. Compared with chemical weed control method, although mechanical weed control method reduced the plant height but increased the number of tillers by 7–22 %, SPAD values by 2–8 %, and total biomass by 45 % after the jointing growth stage, which promoted the rice growth. The superoxide dismutase and peroxidase activities of the leaves were significantly higher under the mechanical weeding due to the mechanical stimulation and inter-tillage effect of the weeding machine. Based on these benefits, the mechanically weeded rice had the highest theoretical and harvest yields, with yield increases of 2–11 % compared to chemical weed control, because of its higher number of productive panicles and percentage of grain filling. Our study showed that the inter-row and intra-row mechanical weeding method using the autonomous driving machine could increase rice yields while reducing labor use and chemical loads. Continuing advancement in this emerging technology will have a great potential for environment-friendly agriculture in the development of weed control in field crops. For future research, experiments should investigate the effect of autonomous weeding machine on soil physicochemical properties and microorganisms in paddy fields, so as to further understand the additional benefits of adopting mechanical weed control on the field crop growing environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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