Critical period of weed management in direct-seeded rice (*Oryza sativa* L.) in Lorestan, Iran

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Abstract

The concept of the critical period for weed control is fundamental to integration of weed management and serves as an essential starting point for developing effective control strategies. To assess the critical period for weed control in aerobic rice lines (E-104, Helal, and Ali-Kazemi), field experiments were conducted in the experimental farm of the Agricultural Research Institute, Doroud, Lorestan Province, Iran over two consecutive growing seasons in 2022 and 2023. The experiment was a factorial design with three factors in a randomized complete block with three replicates. Treatments included five levels of varying durations of weed interference, five levels of differing lengths of weed-free periods, and three levels of rice varieties, resulting in a total of 75 treatment combinations. The findings indicated that the critical period occurred 42 days after seeding to achieve 77% of a weed-free yield. For a 90% weed-free yield, the critical period ranged from 7 to 14 days in the growing season. Considering that a 5% yield loss is economically impractical, a threshold of 10% yield loss is deemed acceptable for economic viability. Consequently, it is advisable to maintain a weed-free condition for aerobic rice within the timeframe of 7 to 42 days to optimize yield and enhance economic returns. Results showed to archive the highest rice grain yield a more extended duration of weed-free in aerobic rice is necessary.

Keywords: aerobic rice, weed competitiveness, *Oryza sativa* L., CPWC, grain yield

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Introduction

Human culture and rice share a historically significant and intricate relationship (Horton, 2023). Throughout history, rice has played an essential role in food systems, economies, religious practices, and civilizations of numerous countries worldwide (Van Dijk et al., 2021). Various mythologies concerning the origins of rice can be found within the histories of Myanmar, China, and Japan. In Asia, rice accounts for over 60% of cereal production while contributing to approximately 25% global cereal output. It constitutes nearly 30% of the total food consumption in the region (Ashraf et al., 2024). For billions of people in Asia, rice is the primary food source and serves as a vital nutritional foundation in some of the world's most densely populated nations, including China and Bangladesh. Specifically, rice contributes to an estimated 30, 30, 50, 70, 60, 50, and 30% of the daily caloric intake in China, India, Indonesia, Bangladesh,

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Vietnam, the Philippines, and South Korea, respectively (Dorairaj and Govender., 2023). Estimates suggest that nearly half of the global population relies on rice as their main staple food. Moreover, the labor required for rice cultivation provides essential livelihoods for many, particularly those from economically disadvantaged backgrounds. The continuous rise in population further emphasizes the critical importance of rice as a food source. While global per capita rice consumption saw an upward trend until 2000, it has experienced a slight decline in the years following.

The traditional method of rice cultivation involves flooding paddy fields, where rice seedlings are either manually or mechanically transplanted in submerged conditions (Thirumurugan et al., 1998; Panda et al., 2021). However, this approach has significant drawbacks, including high labor and water requirements (Laskar et al., 2005). In contrast, cultivating rice under aerobic conditions can conserve 36-41% more water than conventional methods (Kathirsan and Manoharen, 2002; Singh et al., 2008b). To address the challenges associated with labor and water shortages, researchers have proposed several alternative rice production methods globally (Upasani et al., 2010). These include alternate wetting and drying, direct seeding, and aerobic rice production systems (Mahajan et al., 2006; Payman and Singh, 2008; Chauhan et al., 2010; Jabran et al., 2012). Aerobic rice cultivation has been found to be more cost-effective, more water-efficient, and yield comparable results to flooded rice systems (Zho et al., 2006; Amudha et al., 2009). Aerobic rice can be cultivated through various techniques, which depend on factors such as soil type, climate, available resources, and farmer preferences (Saini et al., 2025).

The most prevalent method involves direct drilling of rice seeds in a well-prepared seedbed using either manual or tractor-drawn drills. This technique is characterized by significant savings in time, labor, water, and energy (Rao et al., 2007; Mousa et al., 2024). Another effective method is wet seeding, which entails broadcasting pre-germinated rice seeds onto saturated soil, either following puddling or directly. Wet seeding after puddling is the predominant practice in this category. The crop is subsequently irrigated similarly to the dry direct-seeded aerobic rice systems (Thirumurugan et al., 1998; Bouman, 2001). While this method results in savings in time, labor, energy, and water compared to conventional transplanting, it does demand slightly more water than dry direct-seeding (Mousa et al., 2024). An alternative practice within the aerobic rice system involves transplanting rice seedlings onto a flat, saturated area, with irrigation applied as the soil dries, reminiscent of irrigation practices used for maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.). Nevertheless, this method necessitates greater labor, time, and energy than dry direct-seeding or wet direct-seeding methods due to the tasks involved in seedling production and transplantation (Anwar et al., 2013b). The furrow-bed system represents another innovative approach to aerobic rice cultivation. In this system, furrow beds are formed using a tractor-drawn bed shaper. Rice seedlings can be transplanted onto the raised surfaces, or seeds can be drilled into these beds. During irrigation, water is delivered to the furrows only, allowing it to seep towards the roots of the rice plants, thereby minimizing moist soil surface area and enhancing water conservation compared to aerobic rice grown on flat land. This method is occasionally referred to as the "furrow-irrigated raised-bed system." The furrow-ridge system is another technique suited for aerobic rice production (Gobrial, 1981).

Weed infestation remains a significant challenge for the effective implementation of aerobic rice systems (Sanjoy Saha et al., 2005; Walia et al., 2009), as weed proliferation is typically greater than in conventional flooded rice cultivation. In aerobic rice systems, it has been reported that weed-related yield losses can reach as high as 70-80% (Katiyar and Kolhe, 2006; Singh et al., 2006a). Conversely, employing appropriate weed control measures has been shown to enhance rice yields in aerobic conditions by 27-300% (Lasker et al., 2005; Hussain et al., 2008; Chakraborti et al., 2017). Although earlier research has recommended a multifaceted approach to weed management in aerobic rice systems, literature detailing the practical execution of such management strategies is limited (Mahanjan et al., 2009). Substantial yield losses are attributed to weeds, impeding the increase in rice yields under effective management in aerobic rice systems (Mahajan et al., 2009).

The Critical Period of Weed Control (CPWC) plays a vital role in Integrated Weed Management (IWM) and serves as a foundational element in the design of effective weed control strategies (Ramachandiran et al., 2012a). Defined as the timeframe in the crop life cycle during which weed management is essential to avert unacceptable economic yield losses, the CPWC is a crucial consideration (Moorthy and Saha, 2005). Theoretically, the presence of weeds outside this critical timeframe is not expected to significantly impact crop yields (Hussain et al., 2008). Consequently, yields achieved with weed management during the CPWC closely resemble those obtained in conditions where the crop is weed-free throughout the entire growing season (Rao et al., 2017b). Typically, approximately one-third of the crop life cycle is deemed critical for effective weed control. A prolonged CPWC suggests that the crop is less competitive relative to weeds, or that the weeds themselves are particularly competitive (Pendy et al., 2003). Analyzing the CPWC can aid in determining the necessary residual actions for preemergence of herbicides, enhance the timing of applications, and decrease reliance on postemergence herbicides (Dixit and Varshney, 2008), thereby potentially mitigating environmental and ecological harm (Azmi et al., 2007).

The Critical Period of Weed Control (CPWC) is expected to vary uniquely among different crop species due to their distinct morphophysiological characteristics (Azmi et al., 2007). Rather than being an intrinsic attribute of the crop itself, CPWC is more accurately understood as a function of the interactions between the crop, weeds, and their environment (Ramachandiran and Balasubramanian, 2012). For instance, in West Africa, Johnson et al. (1998) estimated the CPWC for lowland irrigated rice to range from 0 to 32 days after sowing (DAS) during the wet season and from 4 to 83 DAS in the dry season to achieve 95% yield. Similarly, research conducted in Malaysia highlighted that based on a threshold of 5% yield loss, flood-irrigated rice should remain weed-free between 14 and 28 DAS while direct-seeded rice should be maintained weed-free for periods ranging from 2 to 71 DAS under saturated conditions and from 15 to 73 DAS in flooded conditions (Rao et al., 2017; Dorairaj and Govender, 2023). In the Philippines the CPWC for rice was estimated between 18 and 52 DAS to secure 95% of the potential yield without weed interference (Chakraborti et al., 2017). The primary objective of this study was to define and estimate the critical period of weed control for direct-seeded aerobic rice, with the aim of developing a weed management strategy that relies less on herbicides. Another significant goal was to assess the impact of different weed interference durations on various agronomic and physiological traits of rice under aerobic soil conditions.

Materials and Methods

Experimental site and soil

The experiments were conducted at the Experimental Farm of the Agricultural Doroud Research Institute, located in Doroud city, Iran (33.29° N, 49. 40° E) over two growing seasons in 2023 and 2024. The climate of experimental site is temperate and relatively dry with an elevation of 1815 meters which usually receives the highest rainfall in Lorestan Province, Iran, with an annual average of rainfall and temperature 622 mm and 16.2°C respectively (Table 1). The average monthly maximum and minimum temperatures ranged from 22°C to 10.7°C, while relative humidity varied from 25.7% to 57.8%. The experimental soil was classified as sandy clay loam, composed of 57.07% sand, 22.32% silt, and 20.61% clay, with an acidic pH of 7.11. Additionally, it contained 2.73% organic carbon, a bulk density of 1.68 g/cc, and a cation exchange capacity (CEC) of 21.32 me/100 g soil. The nutrient profile of the soil indicated a total nitrogen content of 0.28%, 18.7 ppm of available phosphorus, 403 ppm of available potassium, 648 ppm of calcium, and 177 ppm of magnesium. At field capacity, the soil exhibited a water retention capacity of 24.73% on a wet basis and 31.25% on a dry basis.

Plant material

In this study, the aerobic rice lines E-104, Helal, and Ali-Kazemi, obtained from the Iranian Rice Research Institute, served as the plant material. This specific rice lines were chosen due to their demonstrated suitability for aerobic soil environments, as evidenced in prior research (Raiesi et al., 2017).

Experimental design and treatments

The experiment was a factorial design with three factors in a randomized complete block with three replications. To ascertain the critical period for weed control (CPWC), a quantitative series of treatments was implemented, consisting of two key components: (a) an escalating duration of weed interference and (b) an increasing length of the weed-free period. The timing for the removal of weeds was determined based on the number of weeks following rice seeding. To establish the onset of the CPWC, the first component - escalating duration of weed interference - was organized by permitting weeds to compete with the crops for 2, 4, 6, and 8-week intervals after seeding (WAS); these were designated as weedy plots. Following these intervals, the plots were maintained in a weed-free state until harvest. To assess the conclusion of the CPWC, the second component—increasing length of the weed-free period—was established by sustaining a weed-free condition for 2, 4, 6, and 8 WAS (designated as weed-free plots) before allowing newly emerging weeds to compete for the remainder of the growing season. Additionally, control treatments included a season-long weedy check and a weed-free check. It is noteworthy that no herbicides were utilized; instead, weed control was performed through manual weeding. The experiment was executed under conditions with a naturally occurring population of mixed weed species.

Crop husbandry

The experimental field underwent dry ploughing and harrowing but was not puddled during the land preparation phase. Each plot measured 5.0 meters in length and 3.0 meters in width, consisting of 12 rows with an interrow spacing of 25 centimeters. Rice seeds were directly sown in rows with an interrow spacing of 15 centimeters, utilizing a seeding rate of five seeds per hill. For fertilizer application, each plot received a basal dose of triple superphosphate (TSP) and potassium chloride (muriate of potash) at 120 kg and 100 kg per hectare, respectively. Additionally, urea was applied as a top dressing three times during the season, with each application providing 50 kg of nitrogen per hectare 2, 4, and 6 weeks after sowing (WAS). The field was maintained under non-saturated aerobic conditions throughout the growing season. While the trial was primarily rain-fed during both growing years, supplemental sprinkler irrigation was administered as necessary. Overflow canals were constructed to facilitate drainage in the event of heavy rainfall leading to ponding. Plant protection measures were implemented as required to mitigate any potential confounding effects arising from competition with pests and diseases. Various intercultural operations and plant protection strategies were carried out following established standard practices.

Data collection procedure

During each weed removal session, a 25 cm × 25 cm quadrate was systematically placed at four random locations within each plot for the purpose of documenting weed data. The weeds were trimmed to ground level, identified by species, and counted; subsequently, they were individually oven-dried at 70°C for a duration of 72 hours. Weed density (WD) and weed dry weight (WDW) were quantified and expressed in terms of number per square meter (no./m²) and grams per square meter (g/m²), respectively. The identification of dominant weed species was performed using the summed dominance ratio (SDR), calculated as outlined in reference ().

$$SDR\ of\ a\ weed\ species = \frac{Relative\ density\ (RD)\ +\ Relative\ dry\ weight\ (RDW)}{2}$$

where RD (%) = (Density of a given weed species/Total weed density) × 100, and

RDW (%) = (Dry weight of a given weed species/Total weed dry weight) × 100.

Table1
Weed composition in perennial weedy plots of aerobic rice during 2022 and 2023, expressed as Cumulative Dominance Ratio (SDR ± SE)

Scientific name	Family name	Weed type	Summed Dominance Ratio
Echinochloa crus-galli (L.) P.Beauv.	Poaceae	G	10.25 ± 049
Echinochloa colona (L.) Link	Poaceae	G	4.15 ± 0.35
Cyperus rotundus L.	Cyperaceae	S	8.23 ± 1.12
Paspalum distichum L.	Poaceae	G	3.51 ± 0.95
Chenopodium album L.	Amaranthaceae	B	9.78 ± *335*
Sorghum halepense (L.) Pers.	Poaceae	G	2.90 ± 0.68
Xanthium strumarium L.	Asteraceae	B	4.10 ± 1.20
Abutilon theophrasti Medic.	Malvaceae	B	1.98 ± 2.01
Digitaria ciliaris (Retz.) Koel.	Poaceae	G	1.68 ± 0.47
Amaranthus viridis L.	Amaranthaceae	B	1.07 ± 0.84

B: broadleaf; S: sedge; G: grass

Data collection was conducted using four central rows, omitting the harvesting area. Aboveground crop biomass was oven-dried at 70 °C for a duration of 72 hours and measured at three critical growth stages: panicle initiation, heading, and harvesting. Upon maturity, key yield components, including the number of panicles per square meter and the number of grains per panicle, were documented from ten randomly chosen hills. Additionally, the central 3 m² section of each plot was hand-harvested to determine the grain yield and thousand-seed weight. Both the grain yield and thousand-seed weight were adjusted to a moisture content of 14%.

Statistical Analysis

Data analysis was conducted using the Statistical Analysis System software, which facilitated the application of analysis of variance (ANOVA) and mean comparisons through a protected least significant difference (LSD) procedure at a 5% significance level (SAS 9.1, 2012).

Results

Weed composition

In the conducted experiment, the naturally occurring weed community exhibited a diverse spectrum of weed types, encompassing grasses, broadleaf plants and sedges. The weed population had a slight dominance of grasses, with broadleaf being second and sedges contributing to only a minor amount. During the first year of experiment, the weed community was identified as consisting of 10 species, while in the second year it comprised 11 species, representing a total of 5 distinct families (Table 1). The most prevalent species in both seasons included barnyard grass (*Echinochloa crus-galli* (L.) P. Beauv.), jungle rice (*Echinochloa colona* (L.) Link), purple nutsedge (*Cyperus rotundus* L.) knotgrass (*Paspalum distichum* L.), johnsongrass (*Sorghum halepense* (L.) Pers.), lambsquarters (*Chenopodium album* L.), common cocklebur (*Xanthium strumarium* L.), velvetleaf (*Abutilon theophrasti* Medic.), southern crabgrass (*Digitaria ciliaris* (Retz.) Koel.) all emerging as the most abundant species, with an average of approximately 54.36 plants m^{-2} recorded in the both experimental years.

Patterns of dominance among weed species

The dominance of weed species exhibited variability throughout the growing seasons (Table 2). In both agricultural seasons, barnyard grass, a representative of the grass group, was identified as the most prevalent species during the early growth phase of rice. However, as the season progressed, grasses were progressively overtaken by sedges and broadleaf weeds. Among the grasses, only barnyard grass was consistently recorded among the top dominant species at the early growth stages across both seasons, after which it was no longer observed. Conversely,

Table 2
The ten most common weed species identified at the end of multiple weedy intervals across are detailed, including their summed dominance ratios (SDRs) with their standard errors (SE).

Weed species	Weedy 2 weeks	Weedy 4 weeks	Weedy 6 weeks	Weedy 8 weeks	Weedy Season long
Echinochloa crus-galli (L.) P.Beauv.	9.85 ± 1.60	3.05 ± 0.47	-	-	
Echinochloa colona (L.) Link	2.85 ± 0.58	1.15 ± 0.73	-	-	-
Cyperus rotundus L.	2.73 ± 0.64	4.7 ± 6.30	7.82 ± 2.60	10.39 ± 1.67	6.92 ± 0.86
Paspalum distichum L.	5.73 ± 0.67	-	-	-	-
Chenopodium album L.	-	-	8.41 ± 2.28	6.54 ± 1.35	4.23 ± 0.42
Sorghum halepense (L.) Pers.	3.15 ± 0.60	1.95 ± 0.78	-	-	-
Xanthium strumarium L.	-	-	3.16 ± 0.46	2.21 ± 0.11	1.66 ± 0.08
Abutilon theophrasti Medic.	2.65 ± 0.34	-	-	-	-
Digitaria ciliaris (Retz.) Koel.	5.68 ± 1.08	-	-	-	-
Amaranthus viridis L.	-	-	4.83 ± 0.16	2.34 ± 0.09	1.53 ± 0.06

Table 3
Effect of duration of weed competition on density and dry weight of weeds in both seasons (2022-2023)

Duration of Weed Competition	2022 Weed Density (per/m²)	2022 Weed dry weight (g/m²)	2023 Weed Density (no./m²)	2023 Weed dry weight (g/m²)
Weedy until 2 WAS	38.81a	72.08a	33.42a	57.36a
Weedy until 4 WAS	53.07b	94.14b	47.37b	81.04b
Weedy until 6 WAS	67.13c	123.83a	61.09c	117.39c
Weedy until 8 WAS	87.92d	184.72c	78.14d	170.34d
Weedy check	77.41d	152.78a	69.63d	136.13d
Weed-free until 2 WAS	70.17c	133.83d	67.19c	123.59c
Weed-free until 4 WAS	62.25b	129.14b	58.46b	114.52b
Weed-free until 6 WAS	35.38a	68.54a	30.09a	54.88a
Weed-free until 8 WAS	23.73e	49.59e	17.29e	33.87e

Data for the weedy treatments were collected at the time of weed removal, while data for the weed-free treatments were recorded at the time of rice harvest. Means followed by the same letter in each column a.re not significantly different according to LSD test at 5%.

purple nutsedge, lambsquarters and common cocklebur emerged as the predominant species during the later growth stages of the main seasons. Additionally, broadleaf weed such as velvetleaf and knotgrass began to dominate the weed community from the mid-growth stage of rice until maturity in both seasons.

Weed population density and biomass assessment

Weed population density and dry weight were measured following various durations of weed competition. Under aerobic soil conditions, weed dry biomass were significantly elevated, with values ranging from 33.87 to 184.72 g/m², across both growing seasons, as illustrated in Table 3. Notably, the dry weight of weeds was greater during the first growing season (184.72 g m^{-2}) compared to the second season (170.34 g m^{-2}). In the weedy control treatment, at the first experiment season a weed density of 87.92 plants/m² was recorded. Furthermore, it was observed that weed density and dry weight peaked 8 weeks after sowing (WAS), after which both metrics declined in both seasons. Conversely, an increase in the duration of the weed-free period resulted in a decrease in both weed density and dry weight (Table 3).

Table 4
Effect of duration of weed competition on the yield and yield components of an aerobic rice variety across both growing seasons in both seasons (2022-2023)

Year	Rice lines	Duration of Weed Competition (weeks)	Tiller (per plant)	Panicle (per plants)	Grains (per panicle)	1000-seed weight (g)	Grain Yield (t ha^{-1})
		0	7.52a	4.22a	65.81a	25.67ad	1.97a
	E-104	2	6.54bi	3.78b	60.34b	24.39a	1.83b
		4	5.28c	3.19cg	58.17bh	23.51ab	1.69c
		6	4.21d	2.90d	51.29cd	21.47bc	1.51d
		8	3.25e	2.75d	47.14c	19.84c	1.24e
		0	7.14f	4.13a	67.30a	26.33ad	1.84b
2022	Helal	2	6.31b	3.67b	64.02a	25.11a	1.70c
		4	5.04c	3.15c	60.89b	23.06ab	1.5d
		6	3.89g	2.79dh	54.11d	21.58bc	1.37e
		8	2.66h	2.53e	49.30cd	20.45bc	1.16f
		0	7.76a	4.51f	72.94f	27.76d	2.25g
	Ali-Kazemi	2	6.73i	4.21a	67.11a	25.81ad	2.13a
		4	5.82ab	3.83b	62.89g	24.14a	1.84b
		6	4.33d	3.37g	58.86bh	22.47b	1.68c
		8	3.41e	3.17c	52.19cd	20.83c	1.31e
		0	7.70a	4.27a	66.79a	25.89a	2.04a
	E-104	2	6.61i	3.86b	62.48g	24.92a	1.85b
		4	5.33c	3.31g	59.17b	23.78ab	1.71c
		6	4.29d	3.10c	53.30d	21.97bc	1.54d
		8	3.37e	2.94d	49.16cd	20.14bc	1.06f
		0	7.21f	4.18a	68.35ai	26.93ad	1.89b
2023	Helal	2	6.39b	3.81b	65.13a	25.63ad	1.75c
		4	5.13c	3.29c	61.95b	23.88ab	1.58d
		6	4.06d	2.95h	56.08dh	22.08bc	1.43d
		8	2.73h	2.81dh	51.26cd	20.95c	1.29e
		0	7.81a	4.66i	73.94f	27.96d	2.31g
		2	7.02j	4.21a	69.12fi	26.11ad	2.23g
	Ali-Kazemi	4	6.11k	3.68b	63.89g	24.64a	1.85b
		6	4.87l	3.37g	59.98b	22.98b	1.71c
		8	3.46e	3.08d	53.20cd	21.16bc	1.42d

Means followed by the same letter in each column are not significantly different according to LSD test at 5%.

Yield components and overall yield

The yield components and overall grain yield of rice varieties were notably affected by the duration of weed competition during both experimental years (Table 4). Specifically, the metrics of panicle density (number of panicles per square meter), grain count per panicle, and thousand-seed weight demonstrated an increase with extended periods of weed-free conditions, while a corresponding decrease was observed with prolonged weed presence. Notably, maintaining a weed-free status beyond 8 weeks after sowing (WAS) did not yield further enhancements in key yield components, such as panicle density and thousand-seed weight. However, for the number of grains per panicle, weed interference occurring after 6 WAS did not produce detrimental effects. Prolonged weed competition led to reductions of 34.83, 38.74 and 29.71% in panicle per plants of E-104, Helal, and Ali-Kazemi rice lines, respectively (Table 4).

The results showed that the number of grains per panicle was significantly affected with the duration of weed presence. The presence of weed in experimental plots decreased the grains per panicle in E-104, Helal, and Ali-Kazemi rice lines by 28.36, 26.74, and 28.44%, respectively, after eight weeks. Also, a significant (P<0.001) decreases in thousand-seed weight of rice lines were observed with increases in weed competition duration.

Compared with the weed-free experimental plots, the thousand-seed weight of E-104, Helal, and Ali-Kazemi rice lines reduced by 22.71, 22.33 and 24.96% respectively at the present of weeds until 8 weeks after sowing.

The grain yield of rice varieties was significantly affected by the duration of weed interference in both growing seasons. Yield increased with longer periods of weed-free conditions up to 6 WAS, beyond which no substantial improvements were noted. Conversely, grain yield decreased significantly with extended periods of weed competition up to 8 WAS, after which it stabilized. It was also observed that grain yield was marginally higher in the second season compared to the first season. Maintaining weed-free conditions throughout the season resulted in yield advantages of 48.03, 31.74 and 38.52% of E-104, Helal, and Ali-Kazemi rice lines, respectively, compared with 8 WAS.

Discussion

Weed infestation represents a significant challenge to the efficacy of aerobic rice systems, as established by previous studies (Hussain et al., 2008). The prevalence of weeds in these systems exceeds that observed in traditional flooded rice cultivation (Choubey et al., 1999). Consequently, yield losses attributable to weeds in aerobic rice systems can reach as high as 70-80% (Azmi et al., 2007). Notably, the implementation of effective weed control strategies has been associated with an increase in rice yields ranging from 27% to 300% under aerobic conditions (Anwar et al., 2012a). While earlier research has emphasized the need for diverse weed management techniques in aerobic rice systems, there remains a paucity of literature on the practical application of these methods (Anwar et al., 2013b). The substantial yield losses due to weed competition on one hand, and the potential for enhanced rice production through effective weed management on the other, underscores the importance of addressing this issue (Bhowmick and Ghosh, 2002)

In recent decades, weed management strategies have predominantly relied on herbicides, raising public concerns regarding their residual toxicity (Choubey et al., 2001; Dixit and Varshney, 2008). This situation underscores the urgent need to establish a weed management system that is less dependent on herbicides (Chauhan et al., 2010). Understanding the critical period of weed competition (CPWC) is essential for ensuring sustainability, as it helps to optimize the timing for implementing and maintaining weed control measures such as scheduling herbicide applications, thereby mitigating ecological risks and enhancing the economic efficiency of herbicide use (Singh et al., 2006a; Singh and Singh, 2010). Consequently, the sustainable management of weeds in aerobic rice cultivation heavily depends on accurately identifying the CPWC (Azmi et al., 2007). The present experiment was conducted within a naturally occurring weed population, which consisted of average 11 species during the both experimental years.

Utilizing the summed dominance ratio (SDR) to assess weed prevalence across both years revealed that the most dominant species were identified in the following order: jungle rice, purple nutsedge, knotgrass, johnsongrass, lambsquarters, common cocklebur, velvetleaf, and southern crabgrass emerged as the most abundant species. The dominance of weed species exhibited variability throughout the growing seasons (Table 2). In both agricultural seasons, barnyard grass, a representative of the grass group, was identified as the most prevalent species during the early growth phase of rice. However, as the season progressed, grasses were progressively overtaken by sedges and broadleaf weeds. Among the grasses, only barnyard grass was consistently recorded among the top dominant species at the early growth stages across both seasons, after which it was no longer observed. Conversely, purple nutsedge, lambsquarters, and common cocklebur emerged as the predominant species during the later growth stages of the main seasons. Additionally, broadleaf weed such as velvetleaf and knotgrass began to dominate the weed community from the mid-growth stage of rice until maturity in both seasons.

The similarity in weed composition noted throughout different seasons can be attributed to the proximity of the experimental sites, as well as the similarities in the cropping systems and weed management strategies implemented. Notably, the weed community was largely dominated by grasses followed by sedges and broadleaf species, which deviates from typical findings in aerobic rice fields. For instance, Rao and Moody (1992) and Gowda et al., (2009) reported that grasses and sedges were the predominant weed groups in Karnataka, India, while Dorairaj and Govender (2023) noted that grassy weeds accounted for approximately 80% of the total weed community in their study of aerobic rice in Penang, Malaysia. It was found that broadleaf weeds exhibited lower aggressiveness with an SDR of 14%, compared to 30% in grasses followed by sedges, probably as a result of the less moisture conditions that favored grassy weeds over broadleaves. Mahajan et al., (2006) reported a similar abundance of grassy weeds under aerobic rice soil conditions.

In both growing seasons, the prevalence of weeds was significantly greater during the first season in comparison to the second season, which can be attributed to more favorable conditions marked by increased soil moisture levels. Habimana et al. (2019) have previously recorded fluctuations in weed dry matter across various rice seasons. The heightened weed pressure observed in this study aligns with findings from a number of other researchers who have indicated that weed pressure in aerobic rice systems is typically higher than in other rice cultivation ecosystems (Shyamsunder et al., 2024).

Long-term evaluations conducted in weedy control plots, e.g., a study by Shyamsunder et al. (2024) indicated that the dry matter of weeds in aerobic rice generally ranged from 458 to 692 g/m² across different seasons. In comparison, the current study recorded weed dry matter levels between 49.59 and 184.72 g/m², representing a reduction by 10-22%. This variation may be explained by factors such as differences in rice variety, composition of weed species, soil moisture conditions, and the particular agroclimatic environments of the experimental locations.

The yield and yield components of aerobic rice varieties across both growing seasons were negatively impacted by an extended duration of weed interference, while an increased length of the weed-free period positively affected biomass accumulation up to 8 weeks after sowing (WAS). However, maintaining weed-free conditions beyond this period did not lead to further improvements in rice biomass. In scenarios where rice has a competitive advantage over weeds, it tends to exhibit superior growth compared to when the two are in competition. During the early stages of crop development, weeds often compete more effectively than rice, probably due to their ability to preempt resources. As time progresses, the rice crop begins to outcompete the weeds, diminishing the latter's threat to crop growth. Beyond a certain growth stage, controlling weeds does not significantly enhance the growth of the crop. Similar observations have been made by numerous researchers, who noted that weed interference had a detrimental effect on rice growth up to a specific developmental stage (Saha, 2006b; Habimana et al., 2019).

The experimental rice varieties demonstrated a significant reduction in grain yield with prolonged delays in the removal of weeds; conversely, an enhancement in grain yield was noted with an extended duration of weed-free conditions throughout both growing seasons. Continuous weed competition throughout the growing period led to an approximate 73% reduction in crop yield compared to a season-long weed-free group. Such findings align closely with previous research indicating a yield reduction of about 50% due to persistent weed competition (Pendey et al., 2003; Ramachandiran et al., 2012a). Habimana et al. (2019) observed yield reductions of 79% and 66% in rice due to weed interference until harvest in flooded and saturated environments, respectively. Chauhan and Johnson (2010) documented yield reductions of up to 95% in aerobic rice attributed to persistent weed competition during the entire growing season. The discrepancies in findings may be ascribed to differences in rice varieties, agroclimatic conditions, soil moisture levels, and the specific weed flora present at the experimental sites. Prolonged competition from weeds has been shown to result in reduced biomass accumulation, fewer panicles per square meter, lower grains per panicle, and decreased thousand-seed weight, ultimately leading to a reduction in grain yield. Additionally, the increased biomass accumulation of weeds during extended periods of interference may significantly contribute to the observed decline in rice yield. Juraimi et al. (2010) have indicated a strong correlation between weed dry matter and the loss of crop yield.

Zimdahl (1988) argues that the critical period for weed control (CPWC) is not an intrinsic characteristic of the crop. Instead, it is influenced by specific weed species, environmental site conditions, and seasonal factors. Johnson et al. (1998) evaluated the CPWC for lowland irrigated rice, observing that it ranged from 0 to 32 days after sowing (DAS) in the wet season and from 4 to 83 DAS in the dry season, in order to attain a 95% yield in West Africa. Habimana et al. (2019) fond in Malaysia that to avoid a 5% yield loss in flood-irrigated rice, it is essential to eliminate weed competition between 14 and 28 days after seeding (DAS). In a similar vein, Anwar et al. (2012a) suggested that direct-seeded rice should remain weed-free for 2 to 71 DAS under saturated conditions and for 15 to 73 DAS under flooded conditions. In the Philippines, Mishara (2000) determined that the critical period for weed control (CPWC) for aerobic rice spans from 18 to 52 DAS to achieve 95% of the potential weed-free yield. These results underscore the significant variation in CPWC, which is influenced by the timing of crop seeding in relation to the emergence patterns of the local weed community at specific locations.

The initiation of the critical period for weed competition (CPWC) exhibited a consistent pattern across various seasons, whereas its conclusion displayed more variability. This observation has been supported by several researchers (Singh and Singh, 2010; Ramachandiran et al., 2012b) who indicated that the end of CPWC is influenced by factors including weed density, competitive interactions, and the timing of weed emergence. During the primary growing season, the Critical Period for Weed Control (CPWC) commenced earlier and extended for a longer duration compared to the second year. An extended critical period typically suggests either a diminished competitive advantage for the crop or an increased competitive ability of the weed population, with this relationship being reciprocal. One potential explanation for the earlier onset and extended duration of CPWC during the second season may be the environmental conditions that promote weed germination and growth. Specifically, the second growing year is characterized by higher rainfall levels than the first year, which may confer a competitive advantage to the weeds over the rice crop. Pendey et al. (2003) reported a longer CPWC for rice in the second year and a shorter duration in the first year, irrespective of flooding or saturation conditions. Conversely, Johnson et al. (1998) identified differences in CPWC between seasons, particularly in the context of irrigated lowland rice.

The research highlights the crucial necessity of determining the Critical Period for Weed Control (CPWC) to enhance sustainable weed management practices in aerobic rice cultivation. The results indicate that, under comparable experimental conditions, aerobic rice fields should remain weed-free from 7 to 49 days after seeding (DAS) during the off-season and from 7 to 53 DAS during the main season in order to achieve a 95% weed-free yield. To reach a 90% weed-free yield, it is essential for the fields to be devoid of weeds from 23 to 40 DAS in the off-season and from 21 to 43 DAS in the main season. Given that a 5% yield loss is economically unfeasible, a 10% yield loss is deemed acceptable with regard to economic returns. This extent of loss can be effectively managed through early post-emergence herbicide application or manual weeding conducted between 10 and 15 DAS, followed by an additional application between 30 and 35 DAS. Weeds that emerge after this critical timeframe are less likely to result in significant yield reductions; therefore, the necessity for further herbicide applications or multiple weeding practices often adopted by numerous farmers may be diminished, leading to substantial cost efficiencies. Nevertheless, the objective may extend beyond yield maximization to encompass the prevention of weed seed dispersal and the mitigation of the weed seed bank, which poses a significant challenge for the sustainability of long-term weed management practices.

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