Optimizing Manual and Chemical Weeding Combinations and Herbicide Dosage for Strategic Upland Rice Weed Management

Zainah Kampi (Corresponding author)
Promotion of Rice Development Project, Phase Two (PRiDe II),
P.O. Box 12162, Kampala, Uganda.
Tel: +256-783-621-337 Email: kampi.zainah@gmail.com

Yoshino Minoru
Promotion of Rice Development Project, Phase Two (PRiDe II),
P.O. Box 12162, Kampala, Uganda.
Email: minoru.yoshino@nifty.com

Simon Alibu
National Crops Resources Research Institute (NaCRRI)
P.O. Box 7084, Kampala, Uganda
Tel: +256-772-397-674 Email: simoalibu@gmail.com

Arthur Wasukira
National Crops Resources Research Institute (NaCRRI)
P.O. Box 7084, Kampala, Uganda
Tel: +256-782-427-527 Email: awasukira@gmail.com

Solome Nakiyaga
Promotion of Rice Development Project, Phase Two (PRiDe II),
P.O. Box 12162, Kampala, Uganda.
Tel: +256-758-052-804 Email: solomenakiyaga@gmail.com

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Abstract

Weeds pose a significant threat to upland rice production, causing yield losses of up to 45% and threatening food security. Two field experiments were conducted over three cropping seasons to develop sustainable, adapted weed management strategies. Study 1 compared various combinations of mechanical and chemical weed control methods in three weeding frequencies at a three-week time interval. The highest paddy yield of 3.5t/ha was achieved in treatments where the first and second weeding were done mechanically, and the third weeding was performed using herbicide. This yield was significantly higher than that obtained with chemical weeding alone, underscoring the importance of integrated weed management. Chemical weed control at first weeding significantly affected rice tillering. Study 2 investigated quantity reduction, but with the same quality of herbicide application. The treatments were: recommended, half, and quarter herbicide dosages. For half and quarter dosages, herbicide quantity, application speed, and time were halved and quartered, respectively, but herbicide concentration and plot areas remained constant. Reducing the herbicide quantity reduced the yield by 17.6% and 25% for half and quarter, respectively. These yields were not significantly different from the recommended application rate. From this result, if rightful precautions such as sprayer calibration and application speed are taken depending on size and nature of the weeds, smaller quantities of herbicide can be used to effectively control weeds in upland rice. This approach is more economical, time-saving, and minimizes the negative environmental impacts associated with excessive herbicide usage.

Keywords: integrated weed management, sprayer calibration, herbicide dosage, upland rice, application speed

1. Introduction

1.1 Background

Rice is one of the most important food crops worldwide (Mishra et al., 2022; Mohidem et al., 2022; Kampi et al., 2025). It serves as a staple in more than half of the global population (Mishra et al., 2022; Mohamed et al., 2022). In Uganda, it is ranked fourth after maize, coffee, and cotton, and has significant potential to tackle food insecurity and poverty (Hypha et al., 2007; Hong et al., 2021). Rice is the second most produced cereal after maize, and its production is projected to increase from the current annual production of 350 000–700 000MT by 2030 (Hong et al., 2021).

In Uganda, Rice production is classified into rain-fed upland, rain-fed lowland, and irrigated lowland production ecologies, covering 50 000 ha, 60 000 ha, and 6 000 ha, respectively (Kankwatsa et al., 2019). Upland rice has the most significant potential for expansion; 70% of the arable land in Uganda (6.9 million hectares) is suitable for upland rice production (Kankwatsa et al., 2019).

It is mainly cultivated in the northern and Midwestern regions of the country, which receive between 1,300 and 1,800 mm of rainfall annually (Kankwatsa et al., 2019).

However, one limitation of growing upland rice in Uganda is its lower yield (1.3 t/ha) compared to irrigated (3.1 t/ha) and rain-fed lowland rice (2.7 t/ha) (Kilimo Trust, 2012; Kankwatsa et al., 2019). The lower average yield of uplands can be attributed to the lack of suitable varieties, unpredictable water supply, low soil fertility, and inadequate weed control (Kankwatsa et al., 2019; Kampi et al., 2025).

Weeds pose a significant constraint on upland rice production, often leading to significant yield losses and sometimes even total crop failure (Ogwuike et al., 2014; Kaiira et al., 2023). Improved weed control practices in rice result in a relative yield gain of 91.6% (equivalent to 1.2 t/ha of paddy) as compared to farmers' practices (Nhamo et al., 2014). Therefore, protecting the rice crop from weed infestation is one of the most important and influential factors for increasing yield (Nhamo et al., 2014; Ogwuike et al., 2014; Kaiira et al., 2023). Upland rice is particularly susceptible to weeds because upland conditions, such as moist but well-drained soils, high light availability, and warm temperatures, favor weed growth and proliferation, in contrast to the submerged conditions of irrigated and rain-fed lowlands, which suppress weeds (Ogwuike et al., 2014; Kaiira et al., 2023).

1.2 Problem Statement

Farmers in Uganda mostly use labor-intensive, costly, and time-consuming manual methods to control weeds in upland rice, such as hand-pulling or hand-hoe weeding. The average number of hours spent by one person using a hand hoe to weed one hectare of upland rice once is 173 (Ogwuike et al., 2014), costing $100 and $150, depending on labor availability (Kaiira et al., 2023). For these reasons, many Ugandan farmers are resorting to chemical weed control, which is less laborious, cheaper, and time-saving (Ogwuike et al., 2014; Kaiira et al., 2023). Chemical weeding is cheaper than mechanical weeding, but the cost is prohibitive for poor Ugandan farmers, as most of them live on less than $1.9 per day (Guloba et al., 2019; Kampi et al., 2025). Additionally, in an attempt to save on costs, farmers apply herbicide dosages below the recommended dosage, which reduces their effectiveness and may, over time, contribute to herbicide-resistant weed strains, leading to great negative environmental impacts (Otieno et al., 2023). Hence, the need to develop a cheaper, adoptable, and sustainable strategy to control weeds in upland rice in Uganda (Rodenburg et al., 2009; Ogwuike et al., 2014; Rodenburg et al., 2019; Kaiira et al., 2023).

1.3 Objectives of the Study

The study aims to develop an optimized weed management strategy for improved upland rice productivity. Specifically, (i)To identify sustainable cost-effective weed management practices for improved upland rice production. (ii) To determine the optimal herbicide dosage that provides effective weed control. (iii) To evaluate the effectiveness of different combinations of mechanical and chemical weeding methods on weed density.

1.4 Justification and Significance of the Study

Study one evaluated the efficiency of different combinations of manual weed control (using a hand hoe) and selective herbicides on the performance of upland rice and weeds at three weeding frequencies. Study two evaluated the effect of varying the application rate of a selective herbicide for weed control on the growth of upland rice and weeds and quantified the level of yield losses associated with reducing herbicide dosages. The results of these two studies will serve as a guide for developing effective and efficient weed control strategies for upland rice in Uganda and elsewhere.

2. Materials and Methods

2.1 Description of the Experimental Site

The study was conducted in an experimental field at the National Crops Resources Research Institute (NaCRRI). NaCRRI is located in Wakiso district, central Uganda (0°30'40.4"N, 32°37'53.1"E). It has a long-term mean annual precipitation of 1 280 mm with a bimodal rainfall pattern, having two distinct wet and dry seasons. The climatic conditions of the NaCCRI are tropical, humid, and dry, with average minimum and maximum temperatures of 25°C and 31°C, respectively (Alibu et al., 2022). The soils are predominantly silty loam, consisting of umbric gleysols, gleyian fluvisols, and histosols, showcasing a diverse range of soil types (Alibu et al., 2019). A summary of the weather at the three sites within the institute was compiled from March 2020 to February 2023, as shown in Figure 1. From Figure 1, the site has a bimodal rainfall pattern, which provides two distinct periods of favorable moisture, favoring weed germination and growth, greater weed diversity, and increasing the risk of perennial weeds. This increases weed pressure, and if the weeds are not well managed, there is high weed competition, hence affecting rice yield.

2.2 Experimental Design

Two studies were established in a randomized complete block design (RCBD) with three replications. Study 1 had nine treatments (Table 1) and study 2 had five treatments (Table 2). The rice variety used was NERICA4 which is an interspecific hybrid rice which is known for its high yield, medium maturity time (118 d after sowing), and tolerance to drought. It is widely known, especially in Africa, and is one of the most cultivated upland rice varieties in Uganda (Kaiira et al., 2023; Mumeen et al., 2024; Kampi et al., 2025).

Ploughing was performed twice, and the plots were well-leveled. Dry seeds were directly sown by dibbling seven seeds per hill at a depth of 3 cm, which were later thinned to five seedlings per hill 7 days after emergence. A 30 cm × 12.5 cm spacing was adopted, and each plot measured 4 m× 1.5 m, resulting in 6 m^2 for Study 1 and 5m × 1.5 m, corresponding to an area of 7.5 m^2 for Study 2. The plots were separated by a 0.5 m buffer space. Fertilizer was applied to all the study plots at a ratio of 60:30:30 kg NPK/ha. NPK fertilizer (17:17:17) was used in the basal post-emergence application three weeks after sowing at a rate of 30:30:30 kg NPK/ha. Urea fertilizer was used 70 days after sowing to provide the nitrogen balance at a rate of 30:0:0 kg NPK/ha. The fertilizer was evenly broadcasted in each experimental treatment area. The experiments were conducted for three seasons: the second half of 2020 (2020 B), the first half of 2021 (2021A), and then the first half of 2022 (2022A). The average of the data obtained in these three seasons was used in the data analysis.

Table 1. Weeding method combinations treatments

Treatments	3 WAS	6 WAS	9 WAS
Control	No weeding	No weeding	No weeding
CCC	Butachlor+Propanil	Butachlor+Propanil	2,4-Dichlorophenoyacetic acid
CCH	Butachlor+Propanil	Butachlor+Propanil	Hand
CHC	Butachlor+Propanil	Hand	2,4-Dichlorophenoyacetic acid
HCC	Hand	Butachlor+Propanil	2,4-Dichlorophenoyacetic acid
CHH	Butachlor+Propanil	Hand	Hand
HCH	Hand	Butachlor+Propanil	Hand
HHC	Hand	Hand	2,4-Dichlorophenoyacetic acid
HHH	Hand	Hand	Hand

Study 1 had three weeding frequencies with various combinations of hand hoe and chemical weeding at the various intervals, making a total of nine weeding combinations. H- manual (hand hoe weeding) and C- chemical (herbicide) weed control combinations, and the order of implementation at different weeks after sowing (WAS).

Table 2. Herbicide dosage treatments

Treatments	First weeding	Second weeding		Third weeding		Fourth weeding
	Butachlor (g/ha)	Butachlor (g/ha)	Propanil (g/ha)	Butachlor (g/ha)	Propanil (g/ha)	(2,4-Dichloro phenol acetic acid) (g/ha)
Control	No weeding	No weeding		No weeding		No weeding
25% of the Recommended Herbicide rate	750	438	438	438	438	540
50% of the recommended herbicide rate	1 500	875	875	875	875	1 080
Recommended herbicide rate	3 000	1 750	1 750	1 750	1 750	2 160
Weed free	3 000	Hand weeding		Hand weeding		Hand weeding

Study 2 had four weeding frequencies: a weed-free treatment where pre-emergence herbicide was applied one day after sowing at the recommended rate, with continuous weeding with a hand hoe, an un-weeded treatment, the control, and the other treatments included the recommended herbicide application rate 50% and 25% of the recommended rate. The first weed control, pre-emergence herbicide application using butachlor, was carried out one day after sowing, followed by the second, third, and fourth weed control at 3, 6, and 9 weeks after sowing, respectively, by either chemical or hand. Recommended rates were 3 000 g/ha of butachlor for pre-emergence, 1 750 g/ha of butachlor +1 750 g/ha of propanil for 2nd and 3rd weed control, and 2 160 g/ha of dichlorophenol acetic acid for 4th weed control (Berhan et al., 2021; Kaiira et al., 2023; Otieno et al., 2023).

2.3 Weed Control

Weed control was performed either by spraying with a rice-selective herbicide or manually using a hand hoe. The chemical active ingredients that were used in chemical weed control were butachlor, propanil, and 2,4-dichlorophenoxyacetic acid (Berhan et al., 2021; Kaiira et al., 2023; Otieno et al., 2023). Butachlor is a pre-emergent herbicide used to control grasses and broadleaf weeds. Propanil, on the other hand, is a post-emergence herbicide with no residual effect and is used against numerous grasses and broadleaf weeds in rice and wheat (Bergmann et al., 2024). Therefore, the combination of butachlor and propanil allows both pre-emergence and post-emergence control of broadleaf and grass weeds in rice. The third chemical, 2,4-dichlorophenoxyacetic acid, is a post-emergence herbicide used to control broad-leaved weeds in several cereal crops and non-crop situations (Berhan et al., 2021). The sources of the active ingredients were Butanil S, containing butachlor at 600g/l, Butanil 70, containing butachlor at 350g/l + propanil at 350g/l, and 2,4-D Amine, containing 720g/l of 2,4-dichlorophenoxyacetic acid (Kaiira et al., 2023; Otieno et al., 2023).

To minimize errors due to different weeding times, all treatments and replicates were weeded on the same day. Spraying was performed by the same person on a wind-free day. The chemically weeded plots were always surrounded by a tarpaulin fence during spraying to prevent the chemical from being blown by wind, preventing it from reaching non-target plots, and ensuring the safety of the environment. Spraying was always done on clear days when there were no signs of rain and after the rice plants dried, not very early in the morning when the dew was still on the plants. Spraying was always performed between 10:00 am and 3:00pm East Africa.

In study 1, 1st weeding was done at 3 weeks after sowing, 2nd weeding at 6 weeks after sowing, and 3rd weeding at 9 weeks after sowing, either by hand hoe or by chemical depending on the treatment. For the first and second herbicide applications, a solution of butachlor and propanil at a rate of 1 750 g/ha for each active ingredient was used (Berhan et al., 2021). 3 mls of Butanil 70 containing 1.05 g of butachlor +1.05 g of propanil were dissolved in 0.3 liters of water and in a 16 liter knap sack sprayer with one nozzle of capacity 50 liters per hour, and the solution was sprayed evenly in one plot of 6 m^2. For the third chemical weed control, 2,4-dichlorophenoxyacetic acid was used at a rate of 2 160 g/ha (Kaiira et al., 2023; Otieno, 2023). 1.8 mls of 2,4-D amine containing 1.3 g of dichlorophenoxyacetic acid was dissolved in 0.72 liters of water in the same knapsack sprayer as in 1st and 2nd weeding and the solution was uniformly sprayed in each chemical weeding plot of $6m^2$.

In study 2, 1st weed control was performed one day after sowing using a pre-emergence herbicide before the germination of the rice and weeds to ensure that the herbicide does not affect the rice (Rodenburg et al., 2009; Berhan et al.,2021), and it is still active when early emerging weed species start to sprout to provide an extended window of residual control during the growing season. A pre-emergency herbicide butachlor at a rate of 3 000 g/ha which was considered the recommended rate (Rodenburg et al., 2009; Berhan et al., 2021) was used for the weed free and the full herbicide dosage application treatment, 3.6 mls Butanil S containing 2.2 g of butachlor were mixed in 0.4 liters of water and evenly sprayed to each plot of 7.2 m^2 in 29 seconds at a speed of $4sm^{-2}$. Half and quarter rates of butachlor, water, time, and application speed were used for half and quarter application treatments, respectively. 2nd and 3rd weed control were performed at 3 and 6 weeks after sowing, respectively, using a hand-hoe for weed-free and butachlor + propanil solution for the herbicide weeding plots at rates of 1 750g/ha for each chemical for full herbicide application treatment, 875g/ha for half, and 438g/ha for quarter. 3.6 mL of Butanil 70 containing 1.3 g of each chemical was dissolved in 0.36 liters of water evenly onto each 7.2 m^2 plot in 26 seconds at a speed of 4 sm^{-2} for full herbicide dosage treatments. Half and quarter rates of butachlor, propanil, water, time, and application speed were used for half and quarter application treatments, respectively. 4th weed control was performed nine weeks after sowing using 2,4-dichlorophenoxyacetic acid at rates of 2 160, 1 080, and 540 g/ha for full, half, and quarter herbicide dosage applications, respectively. 2.2mls of 2,4-D Amine containing 1.6g of 2,4-dichlorophenoxyacetic acid were dissolved in 1 liter of water and sprayed evenly onto each plot in 72 seconds at a speed of 10 sm^{-2} for full herbicide application. Half and quarter rates of 2,4-dichlorophenoxyacetic acid, water, time, and application speed were used for half and quarter treatments, respectively.

2.4 Data Collection

For study 1, weed samples were collected three times at 3-week intervals at 6, 9, and 12 WAS. Each plot was partitioned into four micro plots (1m × 1.5m), for the 1st, 2nd, and 3rd sampling and the fourth plot for yield components and yield analysis, as shown in Figure 2.

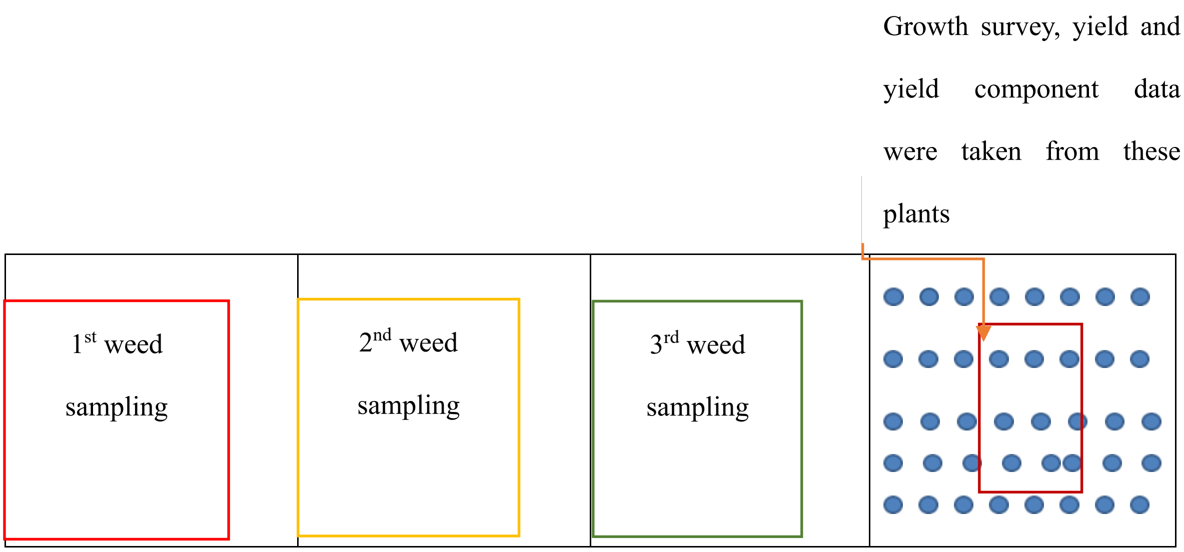


Figure 2. How the data was collected

Each experimental plot in study 2 was divided into five micro plots of 1m × 1.5m each, similar to Study 1, but for it had five micro plots, four plots for the 1st, 2nd, 3rd and 4th weed sampling, and the fifth plot was used for the growth survey, yield components, and yield survey.

Weeds were uprooted from 1 square meter (Figure 3), air-dried in the screen house for 1 week, and later dried in an electric oven at 105°C for 48 h. Plant height and tiller number data were taken from the 10 central plants in the 4 micro plots for study 1 and the 5 micro plots for study 2 (Figure 3). These ten hills were harvested, panicles were counted, threshed, and grains were separated into filled and unfilled spikelets by floatation using ordinary water (specific gravity 1.0). After drying, the 1 000-grain weight and the total number of filled and unfilled spikelets were determined, and the latter two parameters were used to compute the grain-filling ratio. The moisture content of the grains was measured using a Riceter Grain Moisture Meter (Kett Electric Laboratory, Tokyo, Japan), and the yield (kg/ha at 14% moisture content) was calculated from the weight of the filled grains.

2.5 Cost-Benefit Analysis

In this study, chemical weed control was done using 2,4-Dichlorophenoyacetic acid, propanil, and butachlor because they are the most commonly used herbicides in Uganda (Kaiira et al., 2023). The cost benefit analysis was performed using a commonly used solution called Butanil 70, which is mainly in one liter bottle containing 350 g of butachlor plus 350 g of propanil; the recommended application rate is 1 750 g of butachlor plus 1 750g of propanil; 5 liters per hectare, one liter costs between $8-$12, the total cost of the herbicide will be $40-$60, the labor cost ranges between $15-$25, and hence the total cost of weeding once with herbicide will be $55-$85 per hectare (Rodenburg et al., 2009). This cost is $45-$75, which is less than the cost of a hand hoe. The cost-benefit analysis was performed based on the cost at which the chemicals used in the study were purchased, average costs of the herbicides and labor on the open market in the country, and reviewing the latest relevant literature (Rodenburg et al., 2009; Ogwuike et al., 2014; Kaiira et al., 2023). For 1st and 2nd weeding, Butanil 70 was used and, on average, one liter costs $10 and one hectare requires 5 liters so the total cost of the herbicide is $50, the labor cost is $20 and hence the total cost of weeding one hectare once with herbicide is $70, with hand hoe is $100 and the average cost of paddy rice is $0.5 (Rodenburg et al., 2009; Ogwuike et al., 2014, Kaiira et al., 2023).

2.6 Data Analyses

Statistical analysis was performed using the Statistical Tool for Agricultural Research (IRRI; Los Banos, Philippines) (IRRI et al., 2014). Data were subjected to a combined analysis of variance (ANOVA) in a randomized complete block design (RCBD). Means were separated using Fisher's protected least significant difference (LSD).

3. Results

3.1 Weeding Method Combinations

3.1.1 Yield and Yield Components

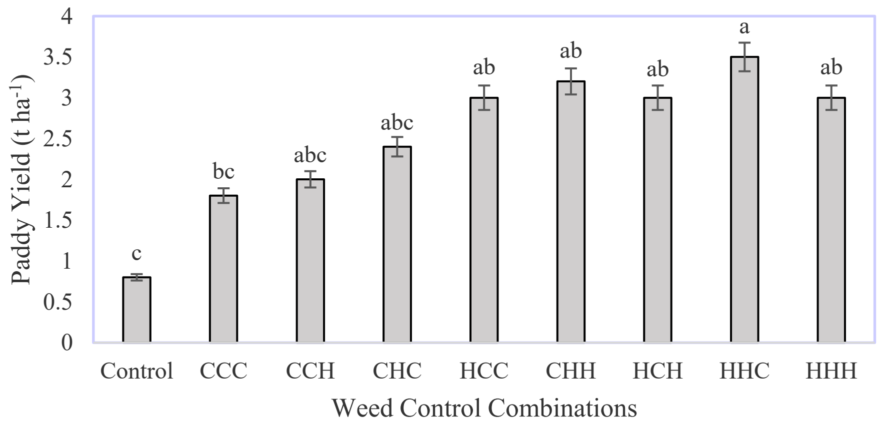


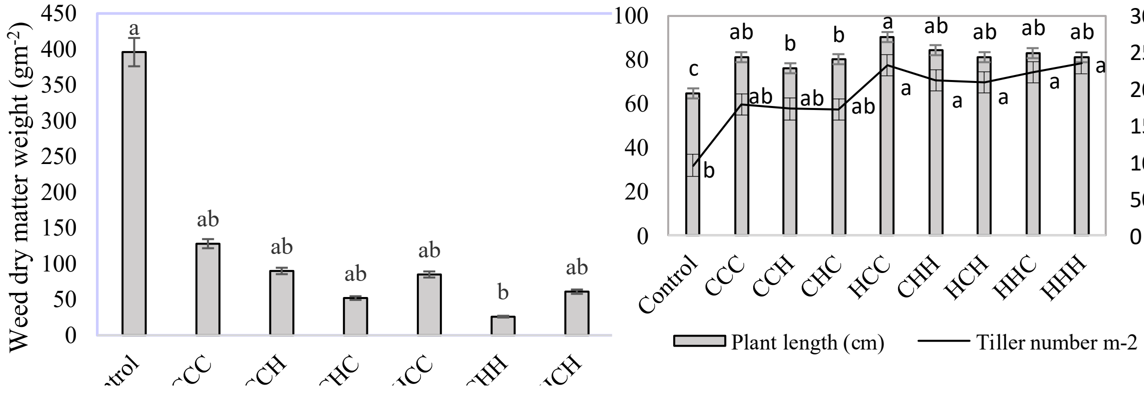
Figure 3. Effect of weed control combinations of hand weeding and selective herbicides on upland rice yield (Mean = 2.5 t ha-1, LSD (5%) = 1.7t ha-1, CV (%) = 22.

Table 3. Rice yield components as affected by different weed control method combinations

Weed Control Combination	Panicles m^{-2}	Grains per Panicle	Grains m^{-2}	Grain Filling (%)	1000 grain weight (g)
Control	152 a	26.3 b	152.0 a	85.4 a	25.8 a
CCC	162 a	51.4 ab	162.0 a	81.8 a	26.6 a
CCH	181 a	50.4 ab	181.3 a	81.8 a	26.4 a
CHC	199 a	53.6 ab	198.7 a	86.5 a	26.5 a
HCC	236 a	62.2 ab	235.7 a	83.0 a	23.9 a
CHH	227 a	64.9 a	226.3 a	80.7 a	26.8 a
HCH	195 a	65.4 a	194.7 a	89.0 a	26.8 a
HHC	241 a	63.0 a	241.3 a	88.2 a	26.2 a
HHH	225 a	58.4 a	225.0 a	85.4 a	26.8 a

Rice yields from all treatments, which had two or more chemical weeding, were not significantly different from that of the control, apart from the one which had hand weeding for 1st weeding (Figure 3). All treatments where 1st weeding was done mechanically or weeded at least twice had significantly higher yields than the control (Figure 3). Likewise, the grain number per panicle for all the treatments that had at least two mechanical weeding was significantly higher than the control, and there were no significant differences in the grain number per panicle between the treatments with at least two chemical weeding and the control. There were no significant differences in the number of panicles m^{-2}, 1 000 grain weight and grain filling % among all treatments (Table 3).

3.1.2 Plant Length, Tiller Number m^{-2} and Weed dry Matter Weight

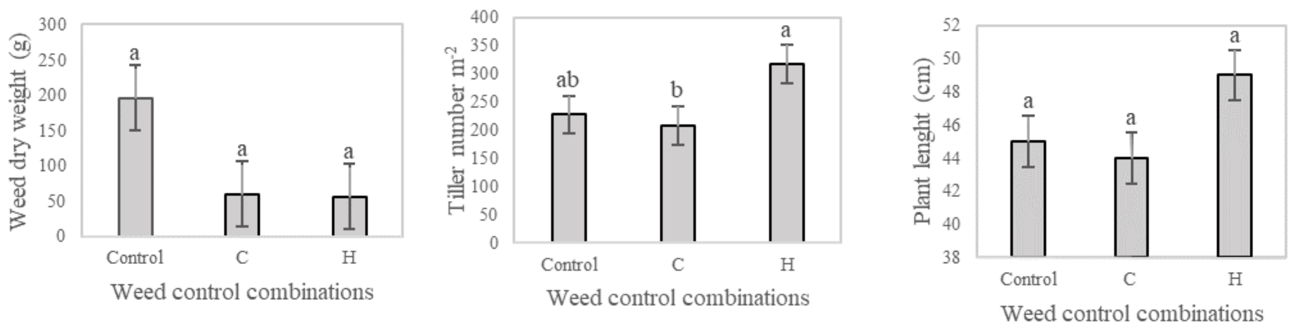


(a) (b)

Figure 4. Comparison of weed dry matter, plant length, and tiller number in the study plots under different weed control combinations at maturity.

The tiller number m^{-2} at maturity followed the same trend as the yield and hence it was the determinant for the yield in this study (Figure 4b). The use of herbicides in early weed control significantly affected the tillering of rice. Among the treatments which had two chemical weed control, HCC had a significantly higher plant length than CCH and CHC (Figure 4b). The treatments which had at least two mechanical weeding gave significantly lower weed dry weight than those which had at least two chemical weeding and the control at maturity apart from HCH (Figure 4a).

While there were no significant differences in weed dry matter and plant length among the treatments at three weeks after 1st weed control (Figure 5a) and (Figure 5c), chemical weed control significantly suppressed the tillering of rice (Figure 5b).



(a) (b) (c)

Figure 5. Comparison of weed dry matter accumulation (a), tillering (b), and growth (c) of upland rice under different weed control combinations three weeks after the first weed control

Weed control in upland rice by hand weeding at the onset significantly increased tillering and was therefore more effective than chemical control. A similar observation was made when weed dry matter accumulation, tillering, and growth of upland rice were compared under different weed control combinations three weeks after the second weed control (Figure 6). Upland rice that was hand-weeded twice had significantly higher tillering performance than rice that was subjected to chemical weed control twice (Figure 6b). The tillering and growth performance of upland rice also appeared to depend on the order in which chemical or manual weed control was applied. Although weed dry matter was similar in the CH and HC treatments (Figure 6a), HC produced significantly higher tillering and growth performance (plant height) than CH (Figures 6a and 6b). In the first three rounds of weed control, chemical weed control appeared to significantly suppress the tillering of upland rice compared to the hand-weeded treatments and the control. The findings revealed that hand weeding is more effective than chemical weed control in managing weeds and suppressing weed growth for up to 3 weeks after implementation.

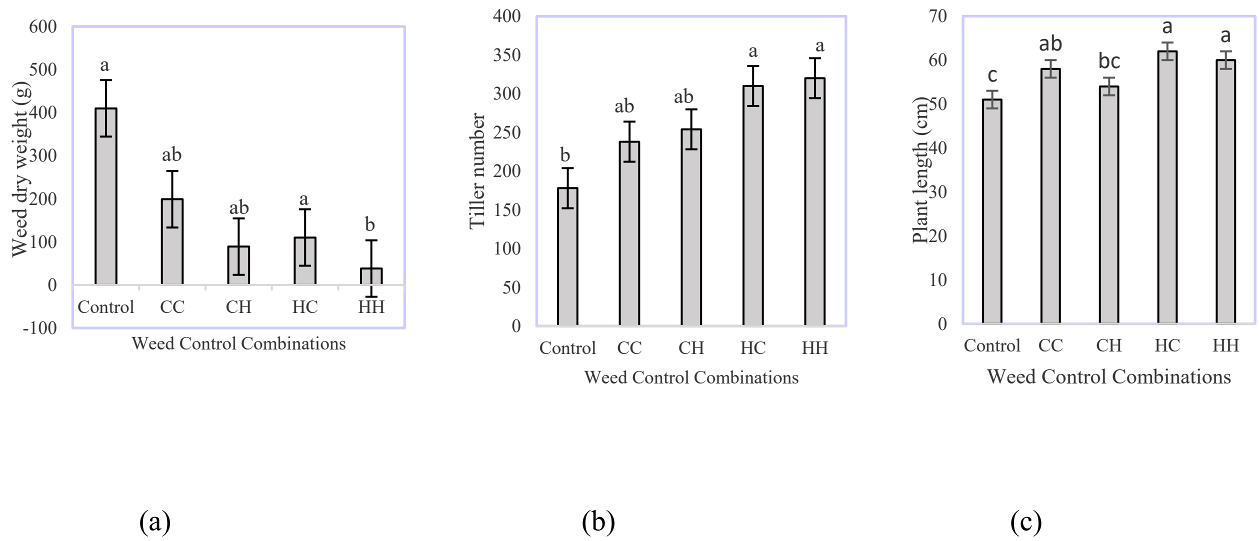


Figure 6. Comparison of weed dry matter accumulation (a), tillering (b), and growth (c) of upland rice under different weed control combinations three weeks after the second weed control

The most common weeds were mostly broad-leaved weeds: *Commelina benghalensis*, *Ageratum conyzoides*, *Enchinochloa colona*, *Portalaca cheracea*, *Bidens pilosa*, very few grasses, and other weeds, as shown in Figure 7 below.

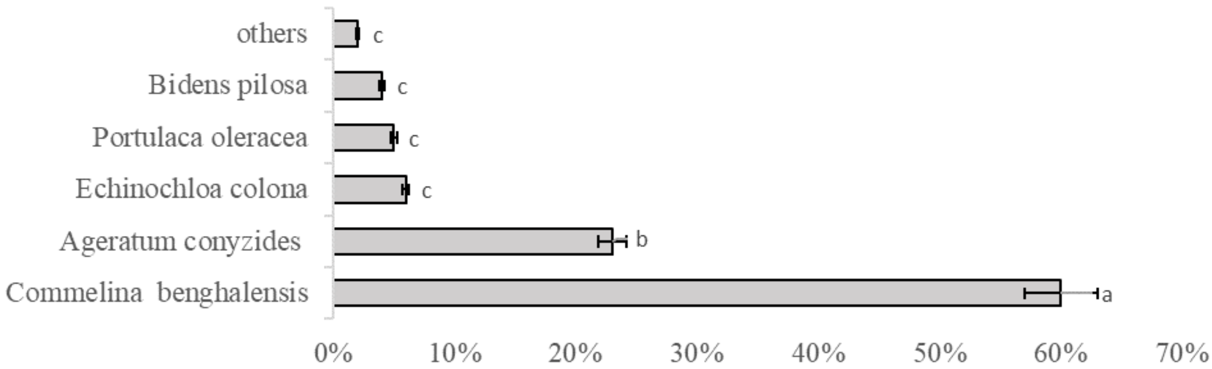


Figure 7. The percentages of the different weed species in the weedy check at 45 days after sowing

3.1.3 Cost Benefit Analysis for the Various Weeding Method Combinations

Table 4: Cost-benefit analysis for the different weeding combinations.

Weeding combination	Weeding cost $	Yield t/ha	Benefit $	Net benefit $
Control	0	0.9 c	450	450
CCC	210	1.8 bc	900	690
CCH	240	2.0 abc	1 000	760
CHC	240	2.4 abc	1 200	960
HCC	240	3.1 ab	1 550	1 310
CHH	270	3.3 ab	1 650	1 380
HCH	270	3.0 ab	1 500	1 230
HHC	270	3.5 a	1 750	1 480
HHH	300	3.0 ab	1 500	1 200

Note: The average cost of one kilogram of paddy rice in Uganda is $0.5, the average cost of hand weeding for one hectare is $100, and the average cost of herbicide weeding is $70

3.2 Herbicide Dosage

3.2.1 The Effect of Herbicide Dosage Reduction on the Rice Yield

This study showed that reducing herbicide dosage to 50% had no significant negative impact on the yield and weed dry matter, but further reduction of herbicide dosage to 25% significantly increased weed dry matter, resulting in significantly lower rice yields (Figure 8). Based on this result, half the herbicide rates can be used to effectively control weeds in upland rice, but further reduction in the herbicide rates reduces the effectiveness of the herbicides. This study has highlighted that weeds can potentially reduce upland rice yields by up to 95%, from a potential 4.1t/ha with weed-free treatment to a mere 0.2t/ha if weed control is avoided altogether. Additionally, using a quarter of the recommended herbicide rate significantly reduced upland rice yield by 25%.

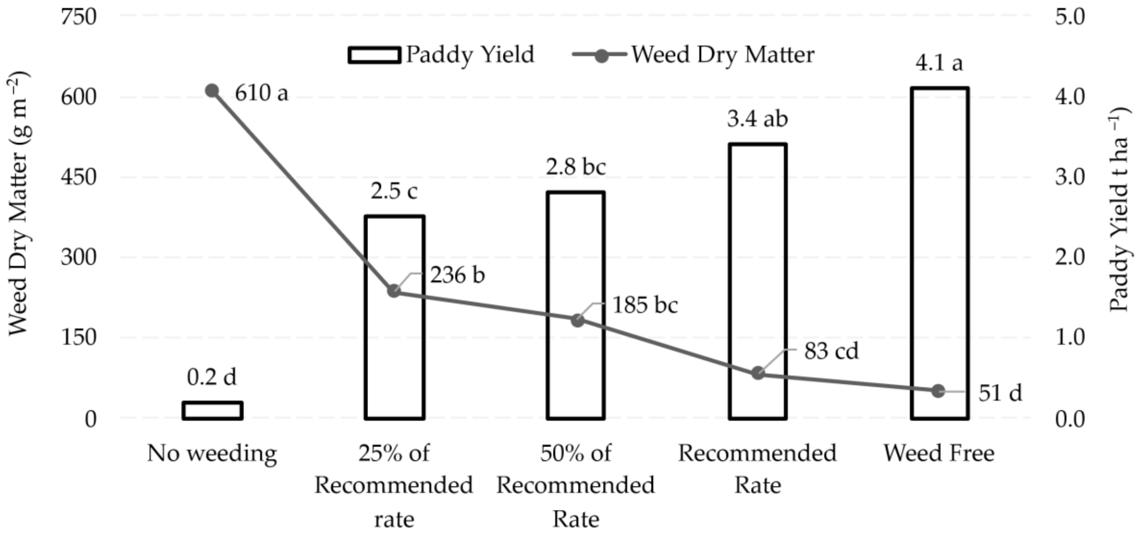


Figure 8. Effect of variable rate application of selective herbicides on weed dry matter at harvesting and paddy yield of Upland rice.

3.2.2 Yield Components as Affected by Reducing Herbicide Dosage

Reducing the herbicide application rate by either half or three-quarters did not have a significant effect on the number of panicles per square meter or the grain filling ratio, except for the un-weeded treatments, which showed significantly lower values for these parameters (Table 5). However, herbicide application significantly reduced the number of grains per panicle by 10% when the recommended rate was used, and by 12% when half of the recommended rates were used. A further reduction in the herbicide application rate to 75% resulted in even fewer grains per panicle, with a significant reduction of up to 21%.

Table 5. Yield components of upland rice as affected by variable rate application of a selective herbicide.

Weed Management	Panicles per m^2	Grains per Panicle	Grains m^{-2}	Grain Filling (%)	1 000 grain weight (g)
Control	45 b	29 d	44.7 b	36.5 b	25.8 a
25% of Recommended rate	248 a	54 c	248.3 a	71.9 a	25.6 a
50% of Recommended rate	286 a	60 bc	286.0 a	66.7 a	25.8 a
Recommended rate	300 a	61 b	300 a	74.3 a	25.5 a
Weed Free	294 a	68 a	294.3 a	78.2 a	26.0 a
Mean	235	54.5	293.3	65.5	25.7
P-Value	<0.05	<0.05	<0.05	<0.05	<0.05
LSD (5%)	80	6.15	99.8	17.7	8.7
CV (%)	18.2	6.0	32.3	14.3	2.8

3.2.4 Effect of Herbicide Dosage Reduction on Weed Dry Matter Weight

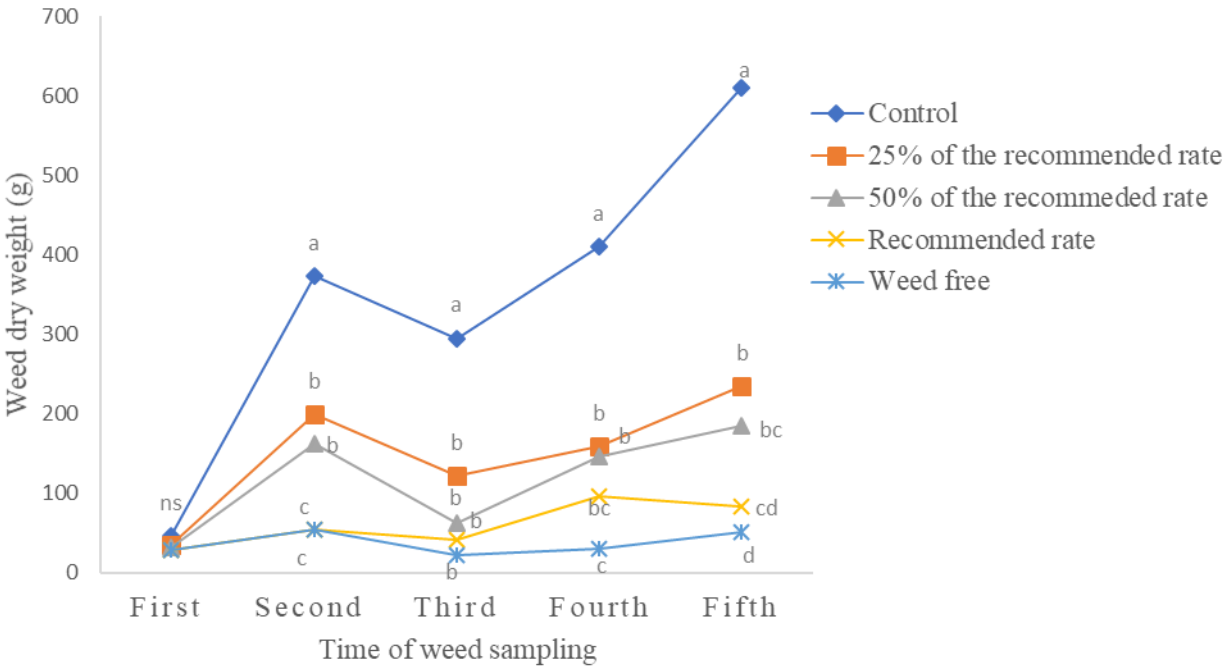


Figure 9. Effect of variable rate application of selective herbicides on weed dry matter accumulation

From Figure 9, at the first weed sampling, there was no significant difference in weed dry matter weight among all treatments. at this stage, the weed intensity and diversity were still low, and even smaller dosages would effectively control the weeds. At the second weed sampling, the weed dry matter weight for half and quarter herbicide dosages was significantly higher than that of the full herbicide dosage. This was because of the increase in weed diversity and intensity, requiring higher dosages for effective control. At the third and fourth weed sampling, there was no significant difference in weed dry matter weight among the different herbicide dosages, this was because of canopy suppression and at the fifth weed sampling, the weed dry matter weight for the quarter herbicide dosage was significantly higher than those of the half and full herbicide dosage treatments. This was because of senescence, which caused a reduction of the canopy, creating favorable conditions for weed growth.

3.2.5 Plant Length and Tiller Number as Affected by Reduction in Herbicide Dosage

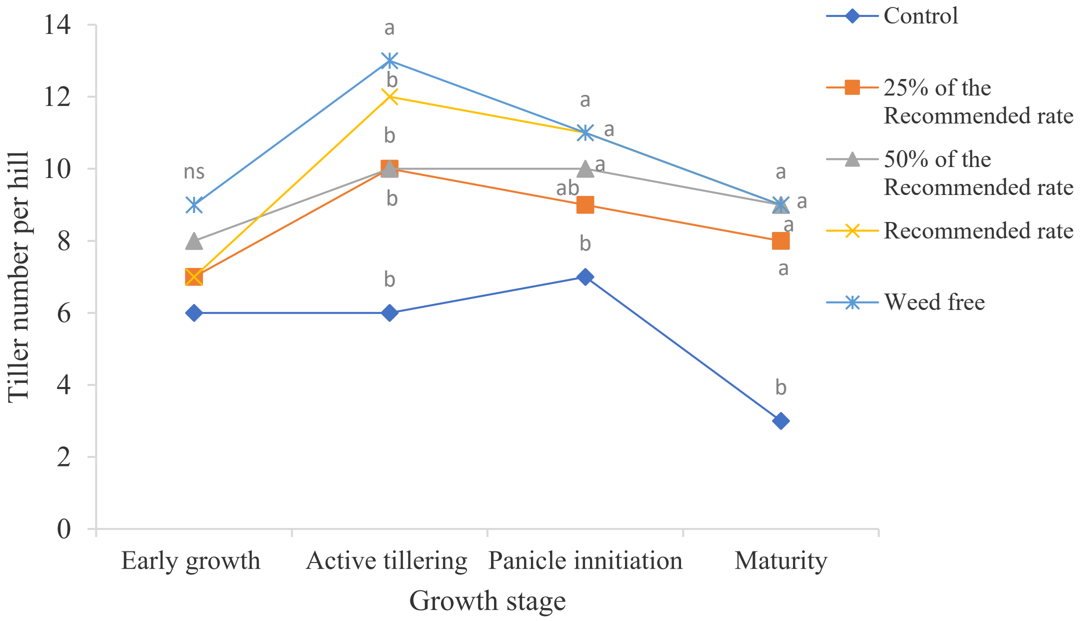


Figure 10. Tillering of upland rice as affected by varying the application rate of selective herbicides

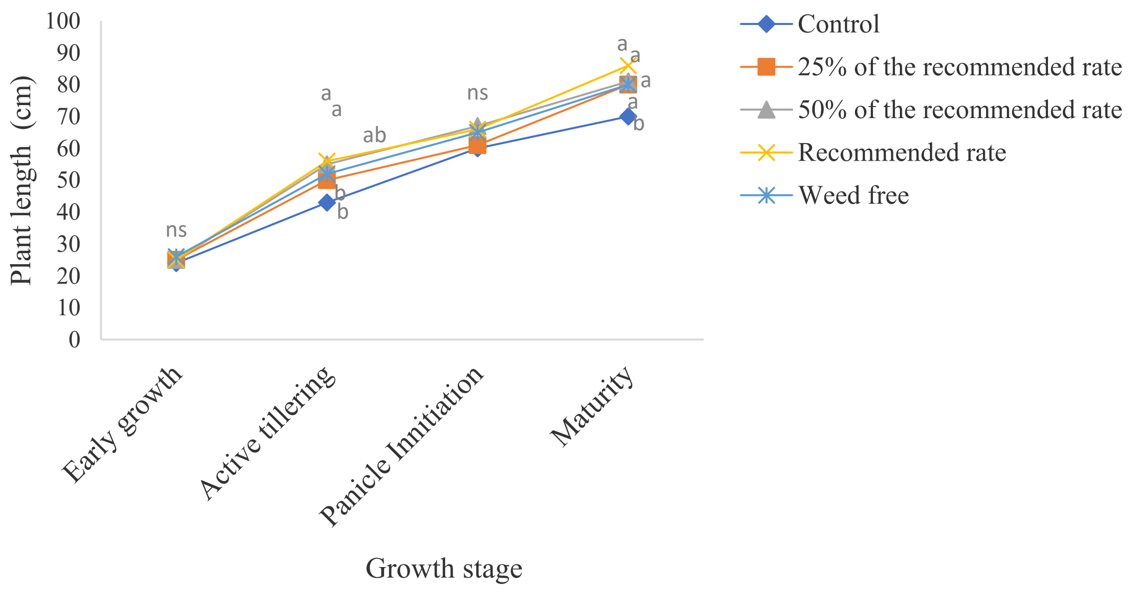


Figure 11. Plant height of upland rice as affected by varying the application rate of selective herbicides

There was no significant difference in plant length and tiller number per m^2 among the different herbicide dosage treatments at all stages. This result supports that even lower herbicide dosages controlled weeds without negatively affecting crop growth (Figures 10 and 11).

4. Discussions

4.1 Weeding Method Combinations

This study compared different combinations of mechanical and chemical weed control confirmed the importance of integrated weed control; in three times weeding, CCC was the cheapest, but least in terms of yield and weed control; HHC, CHH and HHC were the most effective in weed control and among these HHH had the highest cost of weed management; CHH and HHC had the same cost of weed management which was lower than HHH; HHC had the highest net benefit with lower cost of weed control and hence the recommended combination from this study. When herbicides are to be incorporated into weed management in upland rice, it is recommended to integrate them with mechanical weeding. Integrating chemical and mechanical weeding enhances weed control efficacy as herbicide-tolerant weeds are removed by mechanical weeding (Alagbo et al., 2022), reducing herbicide resistance (Bergmann et al., 2024), lowering environmental impacts by reducing chemical reliance (Parven et al., 2024), improving crop yields, and optimizing economic returns (Liu et al., 2023). Early weed control is essential, and based on this study, it is better to do 1st weeding mechanically. Some herbicides disrupt hormonal balances critical for tillering, particularly auxin and gibberellins, which play a key role in tiller outgrowth. They impact auxin pathways in rice, potentially suppressing or altering tiller formation, (Liu et al., 2024 and Takai, 2024). Which was evident from the results of this study that the tiller number at three weeks after 1st weeding for all the treatments that received herbicide for 1st weeding was significantly lower than that of those that received hand weeding. From this study, if chemical weed control is to be used once, HHC is recommended, and if chemical weed control is to be done twice, HCC is recommended, and the use of an integrated approach in weed control is highly recommended (Khaliq et al., 2013).

Another study focusing on the impact of mechanical weeding on weed control, rice growth, and yield indicated that mechanical weeding, akin to hand weeding with a hand hoe, achieved a high level of weed control effectiveness, averaging 80% for three weeks post-weeding (Liu et al., 2023). Additionally, it improved tiller numbers by 7-23% compared with chemical weed control (Liu et al., 2023). Similar field trials on upland rice in Nigeria concluded that hand weeding provides better weed control, crop vigor, and grain yield than herbicide application (Alagbo et al., 2022). Hand-weeding removes all weeds, whereas selective herbicides may only kill some weeds because of their limited target range or mode of action (Khaliq et al., 2013). Incorrect herbicide application can further reduce the effectiveness of herbicides in upland rice (UC IPM, 2023). However, combining hand weeding with herbicides can effectively control weeds in upland rice, and based on this study, it is recommended to begin with hand weeding and alternate between chemical and hand weeding (Khaliq et al., 2013).

4.2 Herbicide Dosage Reduction

This study studied the effect of varying herbicide dosages on weeds and upland rice. There was no significant difference in the grains per panicle and the yield for 50% herbicide reduction compared to those of the recommended rate, showing that the herbicidal effect was complete and effective at the 50% application rate, similar to the full application rate. This is a very important finding that shows that half of the herbicide rate can be used in weed control if appropriate precautions are taken. This makes weeding less costly and reduces the environmental risks of herbicides (Parven et al., 2024). The significantly lower grains per panicle and yield of the 75% herbicide rate reduction were due to the incomplete herbicide effect, which led to ineffective weed control (Liu et al., 2024; Takai, 2024). The significant decrease in the number of grains per panicle in the herbicide treatments compared with the weed-free treatment could have been due to poor tiller development (Kaiira et al., 2023). This result is similar to the findings of study one, where tiller numbers were significantly lower in the treatments that received chemical weeding for 1st weeding. A significant reduction in upland rice yields by up to 95%, from a potential 4.1 t/ha in the weed-free treatment to only 0.2 t/ha in the weedy control was due to the weeds outcompeting the rice crop for water, space and nutrients and hence the low yields in the weedy check (Ogwuike et al., 2014; Kaiira et al., 2023).

4.3 Limitations of the Study and Suggestions for Further Research

The major limitations of this study were: (i)The study was conducted in one location and yet the results are to be adopted in a wide range of environments. (ii) The plot sizes were quite small, so these results have to be tested on a larger scale to test the practicality of the findings. (iii) The results of the herbicide dosage study are greatly affected by the application speed, which has many influencing factors such as the type and growth stage of the weeds, the health and status of the person applying the herbicide, and weather conditions, making it difficult to implement, especially for quarter applications. These limitations might influence the generalizability of the findings.

Further research should focus on the long-term effects of these weed management strategies on soil health and the potential for herbicide resistance. Further research could explore the impact of combining mechanical weeding with reduced herbicide dosages on upland rice and weeds.

5. Conclusions

The mechanical and chemical weed control combinations study highlighted the critical role of the integrated approaches in optimizing weed management in upland rice. From the findings of this study, combining mechanical weeding with judicious herbicide application significantly enhances weed suppression while minimizing the negative environmental impacts associated with excessive herbicide use. Additionally, it is better to perform the first weeding mechanically; herbicides significantly affected rice tillering. The herbicide dosage study showed that adjusting herbicide dosages based on the type of weed species and their growth stages proved to be an effective strategy for maximizing weed control efficiency without compromising crop yields. The study showed that half the herbicide dosages can be used to effectively control weeds while minimizing the negative impacts of herbicides on rice plants. Lower herbicide dosages were economical and environmentally beneficial, with reduced herbicide residues in the soil. These findings not only offer a more practical and sustainable weed management approach for smaller holder upland rice farmers but also contribute new evidence on optimal herbicide dosage and timing of integrating chemical and mechanical weeding methods.

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Authors contributions

Z.K., Conceptualization, visualization, methodology, investigation, data curation, writing—original draft preparation, writing—review and editing, S.A.; conceptualization, investigation, data curation, writing—original draft preparation, writing—review, and editing, M.Y.; visualization. Conceptualization, methodology, investigation, data curation, writing—review and editing, supervision S.N.; writing—original draft preparation, writing—review and editing, A.W.; writing—original draft preparation, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Competing interests

The authors declare no conflicts of interest.

Informed consent

Obtained.

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Data sharing statement

No additional data are available.

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