Herbicide Strategies for Effective Weed Control in Drip-Irrigated Rice Fields in Türkiye

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ABSTRACT

Rice (*Oryza sativa* L.) remains a cornerstone of global food security, supplying a substantial share of daily caloric intake for billions of people. In Türkiye, rice cultivation is expanding steadily; however, rising challenges from climate change and water scarcity threaten its sustainability. Drip irrigation systems, offering improved water and energy efficiency, have emerged as a viable alternative to traditional methods.

This two-year field study evaluated the effectiveness of fourteen herbicide programs in managing weed populations in drip-irrigated rice fields planted with the 'Osmancık-97' rice variety. Key weed species included *Amaranthus retroflexus*, *Chenopodium album*, *Portulaca oleracea*, *Setaria viridis*, *Sorghum halepense*, *Cyperus rotundus*, *Xanthium strumarium*, and *Convolvulus arvensis*.

Initial findings revealed that combining pre-emergence herbicide applications with two sequential post-emergence treatments achieved more than 90% weed control, significantly enhancing yield outcomes. Among all tested programs, Programs 6 [500 g/L Pretilachlor (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT], 7 [300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)], and 10 [300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)] demonstrated superior performance, resulting in yields up to 6540 kg/ha. Conversely, untreated plots suffered from severe weed infestation, causing yields to drop to as low as 280 kg/ha.

These results underscore the critical role of integrated herbicide strategies tailored for drip-irrigated rice systems. Further investigations into long-term sustainability, including resistance management and integrated weed control approaches, are warranted.

Keywords: direct-seeded rice, herbigation, herbicide, integrated management, sustainable agriculture.

INTRODUCTION

Rice (*Oryza sativa* L.) is among the most vital staple crops worldwide, providing 35-60% of the daily caloric intake for approximately three billion people, particularly across Asia. In Türkiye, rice cultivation has expanded steadily over recent decades. By 2020, nearly 126,000 hectares of land were dedicated to rice production, yielding approximately 980,000 tons of grain (Anonymous, 2020; TUIK, 2023). Key rice-producing regions include Edirne, Samsun, Balıkesir, Çanakkale, Çorum, Sinop, Tekirdağ, Kırklareli, Bursa, and Çankırı, with the Meriç and Ergene rivers in Edirne serving as major irrigation sources (Figure 1).

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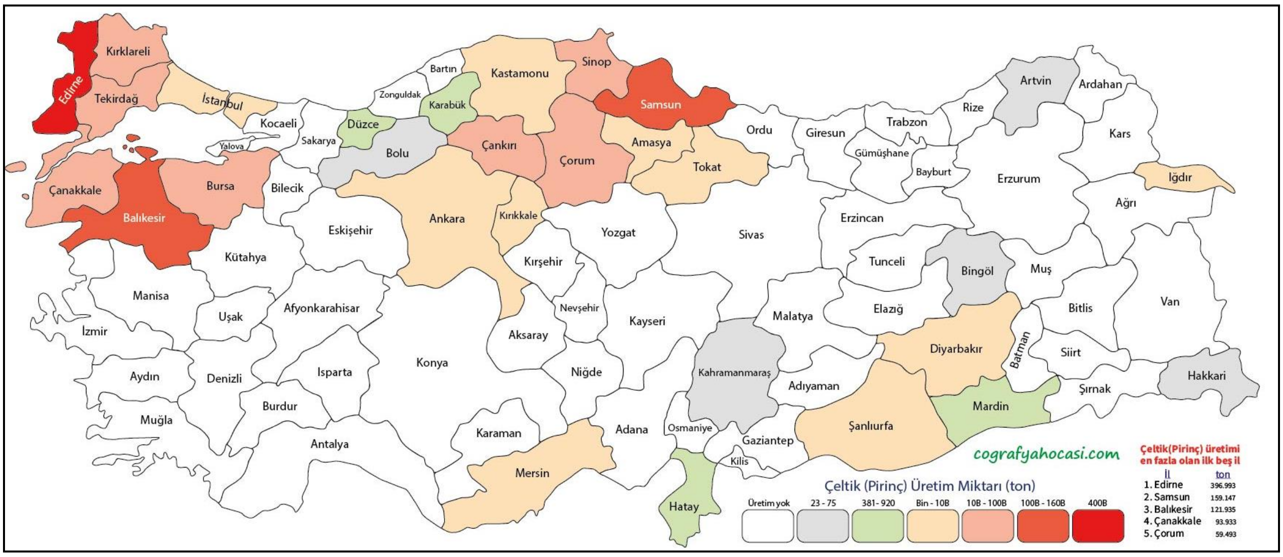

Figure 1. Rice cultivation areas in Turkey (Anonymous, 2020)

One of the most critical limitations in rice production is the availability and management of irrigation water. Traditional practices often result in excessive water consumption, with losses far exceeding estimated plant water needs. Although the crop's water requirement typically ranges between 810 and 1,625 mm depending on climatic conditions, practical use often exceeds 4,000-5,000 liters per kilogram of grain, despite recommendations suggesting only 1,000-1,200 liters (Anonymous, 2019). Rice production is highly sensitive to environmental and agronomic factors, particularly competition from weeds and irrigation management practices (Mukherjee, 2006). Weeds compete with rice for water, nutrients, light, and space, leading to significant yield reductions if unmanaged (Smith et al., 1977; Işık, 2000; Gibson et al, 2002; Busconi et al., 2012; Chauhan and Abugho, 2013). Dominant species such as *Echinochloa crus-galli* (L.) P. Beauv. and *Cyperus difformis* L. have been noted to cause major yield losses in rice cultivation, necessitating effective control measures (Damar, 2006; Uzun, 2009; Kaya Altop and Mennan, 2011, 2018). Although hand-weeding remains a traditional approach, it is often labor-intensive and economically unfeasible, prompting a shift toward chemical weed control strategies (Kıral et al., 1985). Several herbicides have demonstrated high efficacy against diverse weed populations; for instance, penoxsulam-based formulations have proven effective in managing complex weed assemblages (Yadav et al., 2008). Additionally, plastic mulching has been cited as a supplementary measure to enhance weed control (Ramesh and Rathika, 2020).

Water-saving irrigation methods have gained prominence in rice farming, with drip irrigation emerging as a particularly promising approach. Studies suggest that compared to conventional flooded systems, drip irrigation not only reduces water use by 30-35% but can also enhance yields by up to 19% (Bansal et al., 2018; Singh et al., 2018; Nar, 2019). Optimal ponding depths for maximizing rice yield, such as maintaining 9 cm of standing water, have been recommended (Gürel, 2010), while subsurface drip and intermittent irrigation techniques are increasingly evaluated for their potential contributions to sustainable rice production (Tuna, 2012; Sharda et al., 2017). However, experience from farmers adopting drip irrigation indicates that weed infestation is often more pronounced compared to conventional flooded systems, posing a significant barrier to the broader adoption of drip technology. Although limited studies have explored weed management under drip-irrigated conditions in Türkiye, comprehensive research remains lacking.

Therefore, this study aimed to assess the biological efficacy of pre- and post-emergence herbicide applications under drip irrigation conditions in rice. The ultimate goal was to propose an effective herbicide program tailored to local farming conditions, thereby facilitating the expansion of drip-irrigated rice cultivation while maintaining productivity and sustainability.

MATERIAL AND METHODS

Field experiments were conducted over two consecutive growing seasons (2021 and 2022) in the same drip-irrigated rice field to evaluate the biological efficacy of herbicide programs and their impact on weed control and grain yield.

Experimental Materials

The main material consisted of the conventional rice variety 'Osmancık-97' (*Oryza sativa* L.) and the naturally occurring weed flora. Additional materials included various herbicides (Table 1), a drip irrigation system, a knapsack sprayer, ¼ m² sampling frames, and standard field equipment required for field trials.

Table 1. Herbicide information used in the trial in 2021 and 2022

Active Ingredient	Application Rate	Application Time	Targeted Weeds
450 g/l Pendimethalin	300 ml/da	Pre Sowing	Monocots and Dicots
200 g/l Cyhalofop-butyl	150 ml/da	Post Emergence	Dicots
160 g/l Cyhalofop-butyl + 12 g/l Florpyrauxifen-benzyl	200 ml/da	Post Emergence	Monocots and Dicots
100 g/l Cyhalofop-butyl + 13,3 g/l Penoxsulam	250 ml/da	Post Emergence	Monocots and Dicots
500 g/l Pretilachlor	250 ml/da	Post Emergence	Monocots and Dicots
300 g/l Pretilachlor + 20 g/l Pyribenzoxim	150 ml/da	Post Emergence	Monocots and Dicots
250 g/l Quinclorac	150 ml/da	Post Emergence	Monocots and Dicots
20 g/l Penoxsulam + 12.5 g/l Florpyrauxifen-benzyl	200 ml/da	Post Emergence	Monocots and Dicots
300 g/l Pretilachlor + 10 g/l Florpyrauxifen-benzyl	200 ml/da	Post Emergence	Monocots and Dicots
250 g/l Bentazone + 125 g/l MCPA	200 ml/da	Post Emergence	Dicots

Weed Survey and Species Identification (2021)

Weed surveys were performed using the quadrat method, as described by Bora and Karaca (1970). Ten ¼ m² frames were randomly placed within a 3-decare field to assess weed species composition and density. Weed density was calculated on a per-square-meter basis. The relative frequency (RS) of each species was determined using the formula:

R.S = 100 x [Number of measurements where a species was found (n) / Total number of measurements made (m)]

where *n* represents the number of frames in which the species was observed and *m* indicates the total number of frames surveyed (Odum, 1971). Species identification followed the taxonomic references of Davis (1965-1985), Davis et al. (1988), and Güner et al. (2000), with nomenclature updates based on Uluğ et al. (1993).

Herbicide Applications and Efficacy Assessment

2021 Field Applications

Field trials (2021) were conducted over consecutive growing season to evaluate the biological efficacy of herbicide programs in drip-irrigated rice. A split-plot design was adopted to ensure systematic evaluation and statistical rigor.

The main plots were assigned three different pre-emergence herbicide treatments:

- A: 450 g/L Pendimethalin (pre-sowing application);
- B: 300 g/L Pentoxazone (pre-sowing application);
- C: 360 g/L Clomazone + 150 g/L Pentoxazone (pre-sowing application).

Each main plot was further subdivided into nine subplots to evaluate different post-emergence herbicide programs. These treatments were randomly assigned within each main plot. The subplot treatments included:

- 250 g/L Bentazone + 125 g/L MCPA;
- 250 g/L Quinclorac;
- 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl;
- 330 g/L Pendimethalin (herbigation);
- 500 g/L Pretilachlor (herbigation);
- 300 g/L Pretilachlor + 20 g/L Pyribenzoxim (herbigation);
- 480 g/L 2,4-D acid equivalent Isooctylester;
- Season-long weedy plot (no herbicide application);
- Season-long weed-free plot (manual weeding).

Each treatment combination was replicated four times to ensure the reliability of results. Buffer zones were maintained around and between plots to minimize edge effects and avoid treatment interference. Herbicide efficacy was evaluated at five intervals, as recommended by the Standard Herbicide Trial Method (SIDM, 2023):

- First evaluation: 3-5 days after application;
- Second evaluation: 10-20 days after application;
- Third evaluation: 30-50 days after application;
- Fourth evaluation: Spike (panicle) initiation stage;
- Fifth evaluation: Pre-harvest stage.

2022 Field Applications

Due to these unsatisfactory outcomes from first year, the study design was revised in the second year (2022), incorporating changes in herbicide combinations and application timings. The trial was structured according to a randomized complete block design (RCBD) comprising 15 different treatments (Table 2). Each plot measured 20 m² (2 × 10 m), with 1 m buffer zones between blocks and 0.5 m between plots.

Table 2. Different herbicide application programs addressed in the trial in 2022

Program Number	Active Ingredients Used (Application Times)
1	Untreated
2	250 g/L Quinclorac (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 250 g/L Bentazone + 125 g/L MCPA (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (35-40 DAT)
3	250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 250 g/L Bentazone + 125 g/L MCPA (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
4	300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 250 g/L Bentazone + 125 g/L MCPA (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
5	160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 500 g/L Pretilachlor (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
6	500 g/L Pretilachlor (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
7	300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)
8	250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
9	500 g/L Pretilachlor (16-20 DAT), 400 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
10	300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)
11	250 g/L Quinclorac (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (16-20 DAT), 250 g/L Bentazone + 125 g/L MCPA (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
12	250 g/L Quinclorac (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (35-40 DAT)
13	250 g/L Quinclorac (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (35-40 DAT)
14	100 g/L Cyhalofop-butyl + 13.3 g/L Penoxsulam (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)
15	300 g/L Pretilachlor + 10 g/L Florpyrauxifen-benzyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)

DAT: Day after treatment

Pre-emergence herbicide applications were conducted on May 16, 2022, using 450 g/L pendimethalin before sowing. Rice was seeded on May 18, 2022. Post-emergence applications were carried out on July 5 and July 18, 2022, using a spray volume of 300 L/ha at a pressure of 3 atm. The efficacy of herbicide treatments was assessed at the same intervals as in 2021:

- First evaluation: July 21, 2022 (3-5 days after the last spraying);
- Second evaluation: August 3, 2022 (10-20 days after);
- Third evaluation: August 17, 2022 (30-50 days after);
- Fourth evaluation: October 6, 2022 (spike initiation stage);
- Fifth evaluation: November 2, 2022 (pre-harvest).

Weed control efficacy was determined based on the percentage reduction in weed cover compared to the untreated control. Programs achieving ≥90% control were considered effective. The evaluation on August 3, 2022 - 16 days after the final post-emergence application - served as the primary basis for statistical analysis.

Grain Yield Determination

Prior to harvest, four random ¼ m² quadrats were placed within each plot. All rice panicles within the frames were collected, bagged separately for each treatment, and processed in the laboratory. After threshing, total grain weight was recorded, and yields were extrapolated to kilograms per hectare (kg/ha).

Statistical Analysis

Weed control percentage data were arcsine square-root transformed to normalize variance prior to statistical analysis. Analysis of variance (ANOVA) was conducted, and treatment means were separated using Fisher's Protected Least Significant Difference (LSD) test at a significance level of $P<0.05$. Subsequent mean comparisons were conducted with Duncan's Multiple Range Test using SPSS version 20.0.

RESULTS AND DISCUSSION

Weed Flora and Infestation Dynamics

In the first year of the study (2021), weed surveys conducted in the drip-irrigated rice fields revealed that *Amaranthus retroflexus* and *Chenopodium album* were the most frequently encountered species, each appearing in 90% of the surveyed frames. *Convolvulus arvensis* ranked third with an 80% occurrence frequency (Table 3).

Table 3. Density and frequency of weeds found in the trial area in 2021

Weeds	Density (Plants/m²)	Frequency (%)
Cyperus rotundus L. (Cyperaceae)	36	70
Amaranthus retroflexus L. (Amaranthaceae)	11.6	90
Chenopodium album L. (Chenopodiceae)	7.6	90
Convolvulus arvensis L. (Convolvuluceae)	3.6	80
Rumex crispus L. (Polygonaceae)	0.4	10
Amaranthus blitoides S.Watson (Amaranthaceae)	0.4	10
Fumaria officinalis L. (Papaveraceae)	0.4	10
Galium aparine L. (Rubiaceae)	0.4	10
Xanthium strumarium L. (Asteraceae)	0.4	10

These results align with previous findings indicating that *Amaranthus* and *Chenopodium* species are highly competitive and adaptive under varying soil moisture conditions (Chauhan and Abugho, 2013). Herbicide applications demonstrated high initial effectiveness during the first two evaluations (5 and 20 days after application), significantly reducing weed populations. However, a notable decline in herbicidal efficacy was observed in the third, fourth, and fifth evaluations, conducted later in the growing season. Approximately 30 days after the treatments, weed regrowth became prominent, leading to reduced plant height and grain yield in rice plots. Such loss of residual control under drip irrigation has been similarly reported by Yadav et al. (2008), highlighting the importance of maintaining herbicide coverage throughout the crop cycle.

The herbigation technique, wherein herbicides were delivered through the drip system, proved ineffective for weed management under the conditions of this study. This observation is consistent with the findings of Ramesh and Rathika (2020), who reported limited success of herbigation for controlling diverse weed species in paddy systems.

Due to these unsatisfactory outcomes, the study design was revised in the second year (2022), incorporating changes in herbicide combinations and application timings.

Weed Infestation and Control (2022)

During the second growing season, *Amaranthus retroflexus* (20% coverage) and *Cyperus rotundus* (15%) were identified as the dominant weed species in the experimental plots (Table 4).

Table 4. Weeds occured during herbicide application in the trial area in 2022 and their coverage rates

Weeds	Covarage Rate (%)
Amaranthus retroflexus	20
Chenopodium album	10
Portulaca oleracea	5
Setaria viridis	10
Sorghum halepense	5
Cyperus rotundus	15
Xanthium strumarium	5
Convolvulus arvensis	10

The persistence of *C. rotundus* under drip irrigation conditions is consistent with earlier reports by Singh et al. (2018), who highlighted its resilience to reduced soil moisture and its competitiveness in rice systems.

No phytotoxic effects on rice plants were observed across all herbicide treatments, suggesting a high degree of crop selectivity. Herbicide programs were evaluated based on weed control percentages at five different intervals (Table 5).

Table 5. Effects of herbicide application programs against weeds on the second evaluation time

Programs	Biological Efficacy Rates (%) at Second Evaluation (03.08.2022)							
	AMARE	CHEAL	POROL	SETVI	SORHA	CYPRO	XANTS	CONAR
1	0	0	0	0	0	0	0	0
2	95.25 ab	96.25 def	94.25 bcd	96.25 bcde	90.75 a	91.75 bc	93.25 a	97.75 bcd
3	95.50 ab	93.5 abc	91 a	92 a	92.5 abcd	85.5 a	95.5 abc	98.5 d
4	97.50 bc	95.5 bcde	97.5 e	94.5 abc	96.5 ef	94.5 cde	97.5 c	98.25 d
5	96.50 abc	96.5 def	97.5 e	98.25 e	97.5 f	91.5 b	97.5 c	94.5 a
6	97.75 bc	97 ef	96 bcde	97 cde	94 abcde	96.25 ef	96.5 bc	97.25 abcd
7	98.50 c	98 f	97 de	98 de	95 cde	97.25 f	97.5 c	98 cd
8	95.75 ab	94.75 abcde	96.5 cde	97.75 de	95.75 ef	96.5 ef	96.75 bc	96.5 abcd
9	96.50 abc	94.5 abcd	97.5 e	98.25 e	97.5 f	95.5 ef	97.5 c	94.5 a
10	96.75 abc	96 cde	95 bcd	96 bcde	93 abcd	95.5 ef	95.5 abc	96.25 abcd
11	95.75 ab	95 abcde	94 abc	95 abc	92 abc	94.25 bcde	94.5 ab	95.25 abc
12	94.00 a	92.5 a	92.75 ab	93.5 ab	91.75 ab	95 de	95 abc	97.25 abcd
13	95.25 ab	94 abcd	95.75 cde	95 abcd	95 de	94.25 cde	96.25 bc	96.5 abcd
14	95.75 ab	94.25 abcd	94.75 bcd	94.75 abc	94 bcde	92.5 bcd	94.25 ab	95 ab
15	97.00 bc	93 ab	97 de	95 abcd	92.25 abcd	94.25 bcde	93.25 a	96.5 abcd

AMARE: Amaranthus retroflexus; CHEAL: Chenopodium album; POROL: Portulaca oleracea; SETVI: Setaria viridis; SORHA: Sorghum halapense; CYPRO: Cyperus rotundus; XANTS: Xanthium stumarium; CONAR: Convolvulus arvensis.

The programs exhibiting the highest overall efficacy were Programs 6, 7, and 10, consistently achieving over 90% control across multiple evaluation stages (Table 6; Figures 2-4).

Table 6. Herbicide programs: mean weed control efficacy and grain yield

Program No.	Mean Weed Control (%)	Grain Yield (kg/ha)	Program No.	Mean Weed Control (%)	Grain Yield (kg/ha)
1	0.00	280	9	96.81	5880
2	94.94	620	10	95.44	6300
3	93.06	1840	11	94.19	5480
4	96.56	3690	12	93.28	5450
5	96.56	5090	13	95.16	5660
6	96.97	6540	14	94.31	5770
7	97.88	6330	15	94.31	5870
8	96.44	5940			

Figure 2. Number 6 of Programs Effect on Weeds compared to untreated plots [Number 6: 500 g/L Pretilachlor (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT)]

Figure 3. Number 7 of Programs Effect on Weeds compared to untreated plots [Number 7: 300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)]

Figure 4. Number 10 of Programs Effect on Weed [Number 10: 300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)]

These results support findings by Anusha and Nagaraju (2015), who emphasized the critical role of integrating pre- and post-emergence applications to achieve season-long weed suppression in rice fields. Furthermore, the decline in herbicidal efficacy beyond 30 days post-treatment underlines the importance of multiple sequential applications to prevent late-season weed resurgence (Mukherjee, 2006).

Grain Yield Responses

Grain yield analysis revealed that Programs 6 [500 g/L Pretilachlor (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT), 7 (300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT), and 10 (300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)] achieved the highest yields, reaching 6,540, 6,330, and 6,300 kg/ha, respectively (Figure 6). Conversely, Programs 2, 3, and 4 recorded the lowest yields (620, 1,840, and 3,690 kg/ha, respectively). Comparative studies conducted by Bansal et al. (2018) and Singh et al. (2018) also reported that drip irrigation, when combined with effective weed control measures, can enhance rice yields by up to 20-30% compared to conventional flood irrigation systems. However, it is important to note that in this study, yields remained approximately 20% lower than Türkiye's national rice average. This reduction was primarily attributed to weed competition during the first trial year, where insufficient weed management negatively impacted crop performance. These findings reaffirm the critical importance of efficient weed control strategies in ensuring the success of drip-irrigated rice cultivation systems.

Implications for Drip-Irrigated Rice Cultivation

The data presented in this study clearly demonstrate that effective weed management in drip-irrigated rice requires a structured herbicide program, consisting of:

- A pre-emergence application immediately after sowing,
- Followed by two sequential post-emergence treatments, the first at 20-25 days after emergence and the second 15-20 days after the first.

Without adequate weed control, yields dropped dramatically, as evidenced by the untreated control plots, which produced only 280 kg/ha. This significant yield loss highlights the critical role of integrated weed management strategies for sustaining productivity under drip irrigation conditions (Chauhan and Abugho, 2013). By tailoring herbicide programs to the unique challenges posed by drip irrigation systems, this study offers valuable insights into optimizing weed control and enhancing resource use efficiency in rice cultivation. The proposed management approach not only improves grain yields but also supports water conservation efforts, contributing to broader goals of sustainable agricultural development. Future research should focus on integrating chemical control with cultural and mechanical methods to strengthen the sustainability and resilience of drip-irrigated rice production systems.

CONCLUSIONS

This study evaluated the effectiveness of different herbicide programs in managing weeds and sustaining grain yield in drip-irrigated rice cultivation in Bilecik Province, Türkiye. Initial approaches relying on herbigation and a single post-emergence application proved insufficient, resulting in severe weed resurgence and a notable yield decline - approximately 20% below the national average.

Following methodological revisions, including the integration of pre-emergence herbicide treatments and two sequential post-emergence applications, weed control efficacy improved markedly. Programs 6 [500 g/L Pretilachlor (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (16-20 DAT), 250 g/L Quinclorac (35-40 DAT), 7 (300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 160 g/L Cyhalofop-butyl + 12 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT), and 10 (300 g/L Pretilachlor + 20 g/L Pyribenzoxim (16-20 DAT), 250 g/L Quinclorac (16-20 DAT), 20 g/L Penoxsulam + 12.5 g/L Florpyrauxifen-benzyl (16-20 DAT), 200 g/L Cyhalofop-butyl (18-20 DAT), 250 g/L Quinclorac (35-40 DAT)] consistently achieved over 90% control of key weed species such as *Amaranthus retroflexus*, *Cyperus rotundus*, and *Convolvulus arvensis*, leading to the highest recorded yields of 6,540, 6,330, and 6,300 kg/ha, respectively. In contrast, untreated plots exhibited drastic yield reductions, down to 280 kg/ha.

The findings clearly underscore the necessity of implementing structured herbicide programs tailored to the specific conditions of drip-irrigated rice systems. A management regime consisting of a pre-emergence application followed by two well-timed post-emergence treatments proved critical for effective weed suppression and yield stability.

This research highlights the distinct weed management challenges associated with drip irrigation compared to traditional flood systems. The proposed herbicide strategy offers a practical and effective solution for farmers, contributing both to enhanced crop productivity and sustainable water resource use. Further studies are recommended to evaluate long-term sustainability aspects, including herbicide resistance dynamics and the integration of chemical control with cultural and mechanical weed management practices.

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