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# Integrated weed management in rice: practical strategies for enhancing yield and production sustainability in Iranian paddy fields

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**A B S T R A C T**

Weeds are the most significant constraint on rice production in Iran, capable of causing yield losses of up to 90% under severe infestation. while herbicide application remains the predominant control method, its indiscriminate and repeated use has led to herbicide resistance in key species such as *Echinochloa crus-galli* and *Cyperus* spp. This practice has also resulted in surface water pollution, increased production costs, and environmental degradation. This article presents integrated weed management (IWM) as a sustainable, economical, and environmentally sound alternative for farmers. The IWM framework is built on five practical pillars: management of the soil seed bank through false seedbed preparation, deep plowing, and rice straw mulching; cultivation of competitive rice varieties with strong vigor and allopathic potential; increased planting density and optimized square planting patterns for rapid canopy closure; smart water management via alternate wetting and drying (AWD) irrigation to reduce water use by 20–30%; and implementation of a structured five-year herbicide rotation program incorporating varied modes of action to delay resistance evolution. The integrated application of these strategies reduces reliance on herbicides, increases yield, protects environmental health, improves farmer profitability, and ensures the long-term sustainability of rice production systems.



**Keywords**: Tillage, No-till farming, Competition, Integrated management, Transplanting

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## Introduction

Rice, a strategic crop and staple food for more than half of the world's population, plays a vital role in global food security. In Iran, rice holds significant economic and social importance, with an annual cultivation area exceeding 790,000 ha$^{-1}$ (Anynomus, 2023). However, the average rice yield in Iran (4.3 to 4.7 tons/ ha$^{-1}$) remains considerably lower than its potential yield (over 6 tons per hectare). Among the factors contributing to this gap, weeds are recognized as the primary limiting factor, accounting for a substantial portion of this disparity (Kraehmer et al., 2016). Research indicates that weeds can reduce rice yields by 30 to 90%, and in some cases, may even lead to complete crop loss. Invasive species such as *Echinochloa crus-galli* (L.) P.Beauv. (barnyard grass) and Cyperus spp. (nutsedge), which are among the most problematic weeds in Iranian rice fields, cause significant damage not only through competition for resources (light, water, and nutrients) but also through the release of allelopathic compounds and by acting as hosts for pests and diseases (Chauhan et al., 2011). While chemical control using herbicides is a common weed management method, their indiscriminate use has led to serious consequences. These include the emergence of herbicide resistance in various weed species, shifts in weed population composition, increased production costs, contamination of surface water, and adverse effects on non-target organisms. Furthermore, changing climatic patterns and successive droughts have limited access to sufficient water resources for traditional weed control methods, such as continuous flooding (Khalil Tahmasebi et al., 2024). These challenges underscore the growing need to transition toward alternative and sustainable solutions. Among them, weeds pose the most threat as they are direct natural enemies to rice plants in the field. weeds pose the most threat as they are direct natural enemies to rice plants in the field. The herbicides are effective but their curious use is suggested due to their adverse effects on human health problems and the emergence of herbicide resistant weed strains (Kaur et al., 2024) . This article provides a comprehensive review and proposes practical integrated weed management strategies for Iranian rice fields. These strategies-encompassing seed bank management, competitive and allelopathic cultivars, optimized planting, water management, crop rotation, and rational herbicide use—aim to reduce chemical reliance. By protecting the environment, they support increased yields and sustainable farmer livelihoods. Within this framework, preventive management and farm hygiene are emphasized as the primary and most effective defense, focusing on stopping the introduction, establishment, and spread of weeds.

**A**). The use of healthy, certified seeds free from weed seeds is one of the most fundamental preventive methods, as contaminated seeds are a primary source for introducing new weed species into the field (Shahmoradi et al., 2023).

**B). Irrigation management** also plays a critical role; precise control of water inflow and outflow from the field, along with the installation of appropriate filters at water inlets, can effectively block the transport of weed seeds from adjacent areas (Bagheri et al., 2021).

**C). Thoroughly cleaning agricultural implements and machinery before entering a field**, especially when moving from infested areas, is essential to prevent the mechanical transmission of seeds.

**D). Managing field borders and irrigation canals is another crucial preventive focus**, as these areas can act as primary sources of infestation. Controlling weeds in these zones prevents seeds from entering the main field (Rahmani & Ghorbani, 2021).

E). **Management of plant residues and organic amendments** must be considered. Animal manures should be properly composted to avoid introducing weed seeds, and appropriate handling of crop residues helps prevent the augmentation of the weed seed bank (Mousavi et al., 2023). Understanding the concept of the soil weed seed bank – as a reservoir of viable weed seeds – is vital for appreciating the necessity of these preventive measures. This bank is formed through the accumulation of seeds from various species over time and is responsible for replenishing more than 90% of the annual weed population. A single weed plant can produce thousands of seeds capable of persisting for future years. the longevity of these seeds varies from two to over five years depending on the species and environmental conditions, highlighting the persistent, long-term challenge of weed control (Davis, 2023). Even a single period of inadequate control can, due to the persistence of seeds in this bank, lead to increased field infestation in the long term.

**Strategies for Depleting the Weed Seed Bank**

Various methods have been proposed to reduce the weed seed bank in soil:

A) **Preventing Seed Production:** Timely weed control before flowering to minimize seed set (Buhler et al., 1997).

B) **Anaerobic/Aerobic Tillage Rotation:** Alternating between flooded (anaerobic) and dry (aerobic) conditions, particularly effective for species dependent on aerobic conditions, such as weedy rice *Echinochloa crus-galli* (L.) P.Beauv. (Chauhan and Johnson, 2011).

C) **Occasional Deep Plowing:** Periodic deep tillage to bury seeds into deeper soil layers, thereby removing them from the germination zone (Mohler, 2011).

D) **Adoption of Reduced or No-Tillage Systems:** These systems offer a strategic advantage, as weed seeds remaining on the soil surface are exposed to depletion factors such as predation by soil organisms and decay induced by unfavorable environmental conditions (Westerman et al., 2003).

E) **Crop Rotation:** Implementing rotations with crops like wheat and canola, which establish under different germination and growth conditions compared to rice, can disrupt the life cycle of rice-associated weeds (Liebman and Dyck, 1993).

F) **Use of Mulch or Rice Straw:** Applying mulch or rice straw suppresses seed germination by limiting light penetration and moderating soil temperature fluctuations (Teasdale and Mohler, 2000).

G) **Physical Effects:** A layer of residue significantly delays and reduces weed emergence by preventing light from reaching the soil surface (essential for germination of many weed species), dampening diurnal temperature fluctuations, and creating a physical barrier that impedes seedling emergence.

H) **Chemical Effects (Allelopathy):** Plant residues may release specific chemical compounds (e.g., allelochemicals or microbial decomposition products) that can inhibit the germination and growth of weeds (Jabran, 2015).

I) **False Seedbed Technique:** This involves stimulating weed germination through light irrigation or rainfall before sowing the main crop. The emerged weed seedlings are then eliminated using non-selective herbicides (e.g., glyphosate) or shallow tillage (e.g., disking) before crop establishment. This method leads to a significant reduction in the weed seed bank and initial field infestation (Bond and Grundy, 2001).

## 1. The Role of Rice Cultivars in Weed Management: Competitive and Allelopathic Approaches

The selection of rice cultivars possessing desirable competitive and allelopathic traits has gained attention as a complementary strategy within integrated weed management systems. By reducing reliance on chemical herbicides, these cultivars offer the potential to realize more sustainable agricultural systems.

### Cultivars with Superior Competitive Traits

Studies indicate that rice cultivars characterized by strong seedling vigor, particularly in upland and direct-seeded systems, exhibit a highly competitive ability for suppressing weeds. Research has demonstrated a significant positive correlation between traits such as culm length and seedling vigor index with this competitive ability (Kanbar et al., 2006). The most critical of these traits include rapid canopy establishment, high tillering capacity, substantial initial biomass production, and the development of a high leaf area index.

### The Role of Allelopathy in Rice Cultivars for Weed Management

Rice, a vital global cereal crop, possesses a remarkable natural ability known as "allelopathy" for managing weeds (Khawar, 2017). This defense mechanism, which functions through the release of chemical compounds from intact roots, inhibits the growth of major weeds such as barnyard grass (*E. crus-galli*). Compounds like phenolics and momilactones not only exert an effect on weeds (Kong et al., 2011) but also enhance the activity of beneficial soil microorganisms (Khawar, 2017). Research indicates that allelopathy contributes approximately 34% to the overall competitive ability of rice. This potential has been widely confirmed worldwide; for instance, studies in Australia, India, Korea, Iran, and Sri Lanka have identified cultivars capable of reducing weed growth by 50 to 90 percent (Table 1). In Iran, for example, studies demonstrated that the cultivars Dinorado, Domsiah, and Dalar exhibited the highest allelopathic potential, respectively (Modarres Sanavy et al., 2015). The concurrent optimization of this trait with other competitive characteristics is key to developing cultivars with superior weed-suppressing ability for sustainable agriculture (Ranagalage and Wattalagala, 2015; Sadat Asilan et al., 2013).

**Table 1.** Rice varieties or genotypes with reported allelopathic activity from different regions of the world.

| Allelopathic Rice Variety/Genotype | Target Weed Species | Country | Reference |
|---|---|---|---|
| STG06L-35-061 | *Echinochloa crus-galli* (L.) P.Beauv. | USA | Gealy et al. (2013b) |
| Tuna Bria, Hungary No. 1 | *Damasonium minus (R.Br.) Buchenau* | Australia | Seal and Pratley (2010) |
| Amaroo, Giza 176, Ratna, Takanishiki, Italpatna | *Echinochloa crus-galli (L.) P.Beauv.* | Australia | Seal and Pratley (2010) |
| PI312777, Hagan-1 | *E. crus-galli*, *Echinochloa colona* (L.) Link, *Cyperus difformis* L. | China | Kong et al. (2011) |
| Hagan-3 | *E. crus-galli*, *Echinochloa prostrate*, *Cyperus difformis* L. | China | Kong et al. (2011) |
| Jianliangyou 527, Ziyashui 417, Zhongzu 14, Ganxin 203, Zhongzhao 22 | *Lactuca sativa* L. | China | Ma et al. (2014) |
| PI312777 | *E. crus-galli* | China | Fang et al. (2015) |
| IAC165, Taichung Native 1 | *E. crus-galli* | China, Philippines | Bi et al. (2007) |
| Kouketsumochi | *E. crus-galli* | China | Guo et al. (2009) |
| Jangahnbyeo | Not Specified | Republic of Korea | Chung et al. (2006) |
| Donganbyeobongji, Daengbyeo | *E. crus-galli* | Republic of Korea | Chung et al. (2006) |
| Daechangjeong, Kasarwala, Mundara, Damagang, Daegado | *E. crus-galli* | Republic of Korea | Chung et al. (2006) |
| Nowindari, Baekna, Baekkwanguk | *Bulbostylis junciformis* (Kunth) C.B.Clarke Roxb., *Eleocharis kuroguwai* Ohwi, *Echinochloa crus-galli*, *Pontederia vaginalis* Burm.f.(Burm.f.) C. Presl | Republic of Korea | Chung et al. (2006) |
| Sathi, AC1423, PI312777 | *E. crus-galli*, *Monochoria vaginalis* (Burm.f.) C.Presl | Republic of Korea | Lee et al. (2005) |

| | | | |
|---|---|---|---|
| AC1423, Taichung Native 1, Tang Gan, Sathi | *E. crus-galli* | Republic of Korea | Lee et al. (2005) |
| Sathi | *E. crus-galli* | Republic of Korea | Junaedi et al. (2007) |
| Taichung Native 1 | *Echinochloa* spp., *Trianthema portulacastrum* L. | Republic of Korea, Taiwan | Kim et al. (2005) |
| Super Basmati | Wheat (*Triticum aestivum* L.), Berseem Clover (*Trifolium alexandrinum* L.), Oat (*Avena sativa* L.), Barley (*Hordeum vulgare* L.), Mung Bean, *Vigna radiata* (L.) R.Wilczek | Pakistan | Javaid et al. (2009) |
| BR17 | *Echinochloa* spp. | Bangladesh | Salam et al. (2009) |
| Karthik Shail | *Echinochloa* spp., *Lolium multiflorum* Lam., *Digitaria sanguinalis* (L.) Scop. | Bangladesh | Kato-Noguchi et al. (2011) |
| BR26, WITA3, WITA12, BRRI, Dular | *Spinacia oleracea* L. | Bangladesh | Kabir et al. (2010) |
| Goria, Birun, Karthiksail, Boteshwar | *Echinochloa* spp. | Bangladesh | Masum et al. (2016) |
| Ld356, Ld368, Ld365, Ld408 | *E. crus-galli* | Sri Lanka | Ranagalag and Wattagala (2015) |
| Bw400, Ld355, Ld368, Bw364 | *E. crus-galli* | Sri Lanka | Ranagalag and Wattagala (2015 |
| HKR126, IR64, Jaya, Haryana Basmati-1 | *Phalaris minor* Retz. | India | Junaedi et al. (2007) |
| Sorkheh, Anbarboo, Yousen, Dasht, Dular, Neda, Dinorado | *E. crus-galli* | Iran | Berendji et al. (2008) |
| Dinorado, Neda | *Sagittaria platyphylla* (Engelm.) J.G. Sm. | Iran | Berendji et al. (2011) |
| Giza179 | *E. crus-galli* | Egypt | El Shamey et al. (2015) |

## 2. The Role of Planting Density and Row Spacing in Weed Management of Rice

### 2–1. Importance of Planting Density:

Planting density serves as a strategic tool for weed management in rice fields. Increased plant density accelerates canopy closure, thereby reducing light availability for light-dependent weeds such as *E. crus-galli* (barnyard grass). Research indicates that enhancing planting density can suppress weed biomass by up to 59% while simultaneously increasing crop yield significantly (Chauhan et al., 2011). This approach is particularly effective in low-input and organic systems, which often face challenges with herbicide resistance. However, determining the optimal density that balances effective weed control with the prevention of intraspecific competition is essential for each specific cultivar and region. For high-yielding cultivars like "Hashemi" and "Gilaneh," a density of 30–35 plants per square meter is recommended. In contrast, for short-statured and high-tillering cultivars such as Sepidrood, a higher density of approximately 40–45 plants per square meter have demonstrated greater efficacy in suppressing weeds.

## 2-2. The Role of Planting Pattern

Linear or square planting patterns (with spacings of 20 × 20 cm or 25 × 25 cm), compared to scattered planting, lead to a more uniform distribution of plants and faster canopy closure. Furthermore, the critical period for weed control is shorter in narrower rows (15 cm) than in wider rows (30 cm), which facilitates weed management (Chauhan et al., 2011). Another study also indicated that weeds in 20 cm rows, compared to 30 cm rows, exhibit lower aerial biomass and seed production (Chauhan et al., 2011).

## 3. Effect of Planting Date on Weed Establishment

Planting time is one of the most critical factors determining the severity of weed infestation and the yield of rice.

## 3–1. Delayed Planting

Research in Guilan Province has demonstrated that delaying rice transplanting from mid-May to early June leads to a 40–60% reduction in the density of barnyardgrass (*E. crus-galli*). This is attributed to the fact that the seeds of this weed exhibit higher germination rates under the higher temperatures and longer days of June. Consequently, with delayed planting, the rice crop loses the opportunity for early growth and canopy development, which would otherwise suppress weeds. However, it is important to note that excessive delay (e.g., beyond June 10) may result in reduced rice yield due to a shorter growing season and increased damage from pests and diseases (Mahdavi-Damghani et al., 2020).

## 3–2. Early Planting

Early planting (early May) generally allows rice to pass through its sensitive growth stages without facing intense competition from weeds. A study conducted in Mazandaran Province indicated that planting rice on April 30 led to a 25% reduction in the density of purple nutsedge (*Cyperus rotundus*) and increased rice yield by 1.2 tons per hectare compared to planting on May 26 (Yousefi et al., 2021).

## 3–3. Regional Examples

In Guilan, the optimal planting window for the 'Hashemi' cultivar is typically reported to be between May 5 and May 20. In Mazandaran, earlier planting (early May) for cultivars such as 'Shiroodi' and 'Khazar' has yielded better results in reducing weed competition. Conversely, in Khuzestan (for summer rice cultivation), delayed planting has been associated with an increased density of barnyardgrass.

## 4. Water Management and Its Role in Weed Control

Water management serves as a key ecological tool for controlling weeds in Iran's paddy fields, which are predominantly cultivated under flooded conditions. Research indicates that maintaining a continuous flood depth of 5 to 7 cm can reduce the density of major weeds such as barnyardgrass (*Echinochloa crus-galli* (L.) P.Beauv. and purple nutsedge (*Cyperus rotundus* L.) by up to 75% and 62%, respectively (Abdollahi et al., 2023). However, due to water resource limitations, intermittent flooding systems, which achieve 20-30% water savings, are being adopted. It should be noted that if mismanaged, this alternative system can lead to an increase in weed density. The impact of water management varies among different weed species; for instance, barnyardgrass growth can be 2 to 3 times greater under intermittent flooding conditions, while semi-aquatic species like purple nutsedge can survive even under continuous flooding (Norouzi & Mirzakhani, 2022).

## 5. Crop Rotation and Cover Crops in Weed Management

## 5-1. Importance of Crop Rotation

Crop rotation is considered one of the most effective methods for the ecological management of weeds in rice paddy systems. By altering the cultivated crop, the germination patterns and growth cycles of weeds are disrupted, thereby reducing competitive pressure on the rice crop. In northern Iran, a rice-wheat rotation has been demonstrated to reduce the density of barnyardgrass and purple nutsedge by 40-50% in the subsequent year

(Chauhan et al., 2011). The primary reason for this reduction is the alteration of soil conditions and the alternation between flooded and dry periods, which are incompatible with the life cycles of these specific weeds. Overall, combining crop rotation with integrated nutrient management effectively reduced both weed density and biomass through various mechanisms inherent to the system. The incorporation of an offseason green manure crop, especially in conventional systems, proved effective for weed control. Furthermore, including sunhemp within organic fertilization regimes significantly lowered grass weed biomass, playing a key role in altering weed community composition (Wickramasinghe et al., 2023). In Iranian rice cultivation systems, crop rotation has been recognized as a classic and effective strategy for breaking the life cycle of rice-specific weeds (such as barnyardgrass and sprangletop). Research indicates that replacing rice with crops such as winter cereals (wheat and barley), forage plants (clover), or row crops (corn and soybean) within a rotation system significantly reduces weed density and diversity. This reduction is attributed to changes in soil moisture, planting timing, and ecological competition (Ranjbar et al., 2019).

### 5-2. Utilization of Cover Crops

In addition to preventing soil erosion, cover crops play a significant role in competing with weeds and reducing the weed seed bank. Common species include beans (*Phaseolus vulgaris* L.), clover (*Trifolium pratense* L.), and rye (*Secale cereale* L.). Soil coverage by these plants reduces light penetration, inhibits the germination of barnyardgrass and ryegrass seeds, and enhances the activity of soil microorganisms, which contribute to seed decay. Cover crops play a key role by covering the ground with a substantial amount of biomass. This suppresses weeds through competition and, upon termination, contributes to nutrient release for the subsequent crop (Didon et al., 2014). The use of cover crops, such as clover (Trifolium spp.), and common vetch (Vicia sativa L.) during fallow periods or between main rice cultivations is being increasingly adopted as an integrated weed management strategy in northern and some western regions of Iran. Field studies have confirmed that soil coverage with these plants suppresses weed germination and growth through competition for light, water, and nutrients, as well as through the release of allelochemicals (Karimi & Mousavi, 2020).

## 6. The Role of Chemical Management in Rice Weed Control

Herbicides are considered a key component within integrated weed management systems for rice. The rational and scientific use of these compounds, alongside other management practices, can provide effective control against weed populations. Selecting an appropriate herbicide should be based on the dominant weed species, the growth stage of the crop, climatic conditions, and the type of cropping system (Khakzad et al., 2016). Herbicide application must be accompanied by adherence to resistance management principles. Rotating herbicides with different modes of action and using herbicide mixtures can prevent the emergence and spread of resistant biotypes. Correct timing of herbicide application is also particularly crucial, as application during the early growth stages of weeds is generally more effective. The development of selective herbicides with suitable spectra of control and reduced environmental impact is among the recent research achievements in this field. The use of new formulations with higher efficacy and lower active ingredient usage can be more economical while simultaneously reducing the environmental pollution load. Furthermore, the adoption of precise herbicide application methods utilizing modern technologies can prevent the unnecessary dispersion of these compounds.

Table 2. List of Recommended Herbicides and Their Weed Control Spectrum for Rice Fields in Iran (Zand et al., 2019)

| Common Name | Trade Name | Site of Action | Formulation | Application Rate per Hectare | Application Timing and Weed Control Spectrum |
|---|---|---|---|---|---|
| Oxadiazon | Ronstar | PPO Inhibitor | 12% SL | 4-3.5 L | Pre-emergence, before 2-leaf stage of barnyardgrass (*Echinochloa crus-galli*), smartweed (*Persicaria* spp.), arrowhead (*Sagittaria* spp.), water plantain (*Alisma* spp.), and annual sedge (*Cyperus* spp.). |
| Molinate | Ordram | Fatty Acid Inhibitor | 72% EC | 5-6 L | 5 to 12 days after transplanting; controls barnyardgrass. |
| Bentazone* | Basagran | PSII Inhibitor | 48% SL | 3-5 L | 3 to 5 weeks after transplanting; controls arrowhead, water plantain, duckweed (*Lemna minor* L.), false pimpernel (*Lindernia* spp.), ammania (*Ammania* spp.), toothcup (*Rotala* spp.), hygrophila (*Hygrophila* spp.), false foxglove (*Adenosma* spp.), common rush (*Juncus bufonius* L.), goosegrass (*Eleusine indica (L.) Gaertn* ., small-flowered nutsedge, annual sedge, and water clover (*Marsilea* spp.). |
| Thiobencarb | Saturn | Fatty Acid Inhibitor | 50% EC | 5-6 L | Before 2-leaf stage of barnyardgrass (barnyardgrass, common rush, goosegrass). |
| Bispyribac-sodium* | Nominee | ALS Inhibitor | 10% SC | 250 mL | 2 to 5-leaf stage of weeds: barnyardgrass, arrowhead, water plantain, Ludwigia spp., false pimpernel, ammania, toothcup, false foxglove, barnyardgrass, small-flowered nutsedge, annual sedge, perennial sedge, sprangletop (*Leptochloa* spp.), and purple nutsedge. |
| Bispyribac-sodium* | Clean Weed | ALS Inhibitor | 40% SC | 250 mL | 2 to 5-leaf stage of weeds: barnyardgrass, arrowhead, water plantain, Ludwigia spp., false pimpernel, ammania, toothcup, false foxgun, barnyardgrass, small-flowered nutsedge, annual sedge, perennial sedge, sprangletop, and purple nutsedge. |
| Bensulfuron-methyl* | Londax | ALS Inhibitor | 60% DF | 50-75 g | 7 to 12 days after transplanting; controls arrowhead, monochoria (*Monochoria* spp.), water plantain, Ludwigia spp., duckweed, false pimpernel, ammania, toothcup, rotala, hygrophila, false foxglove, common rush, goosegrass, small-flowered nutsedge, perennial sedge, alkali weed (*Aloecuris* spp.), sprangletop, purple nutsedge, water clover, salvinia (*Salvinia* spp.), and azolla (*Azolla* spp.). |
| Cyhalofop-butyl** | Stet | ALS Inhibitor | 20% WG | 100-150 g | 7 to 12 days after transplanting; controls arrowhead, monochoria, water plantain, Ludwigia spp., duckweed, false pimpernel, ammania, toothcup, rotala, hygrophila, and false foxglove. |
| Pretilachlor* | Rifit | Fatty Acid Inhibitor | 50% EC | 2 L | 5 to 7 days after transplanting; barnyardgrass at 2-leaf stage, arrowhead, water plantain, common rush, goosegrass, small-flowered nutsedge, and annual sedge. |

| | | | | | |
|---|---|---|---|---|---|
| Anilofos + Ethoxysulfuron** | Sun Rice Plus | Cell Division Inhibitor + ALS Inhibitor | 31.5% SC | 3 L | 4 to 7 days after transplanting; controls arrowhead, duckweed, false pimpernel, ammania, toothcup, rotala, hygrophila, and false foxglove. |
| 2,4-D + MCPA | U46 Kombi-fluid | Synthetic Auxin | 72% SL | 1.5 L | Late tillering to first node stage; controls arrowhead, monochoria, water plantain, Ludwigia spp., duckweed, false pimpernel, ammania, toothcup, rotala, hygrophila, and false foxglove. |
| Oxadiargyl** | Topstar | PPO Inhibitor | 80% WG / 30% EC | 125-150 g / 3-3.5 L | Pre-emergence up to 7 days after transplanting; controls arrowhead, barnyardgrass, and annual sedge. |
| Penoxsulam | Rizal | ALS Inhibitor | 40% SC | 150 mL | 3 to 7 days after transplanting; controls arrowhead, water plantain, Ludwigia spp., false pimpernel, ammania, toothcup, false foxglove, barnyardgrass, small-flowered nutsedge, annual sedge, perennial sedge, sprangletop, purple nutsedge, water clover, salvinia, and azolla. |
| Ethoxysulfuron + Triafamone* | Council | ALS Inhibitor | 30.6% WG | 100-150 g | Before 2-leaf stage of weeds: arrowhead, water plantain, Ludwigia spp., false pimpernel, ammania, toothcup, false foxglove, barnyardgrass, common rush, small-flowered nutsedge, annual sedge, perennial sedge, sprangletop, purple nutsedge, water clover, salvinia, and azolla. |
| Flucetosulfuron* | Ziclor | ALS Inhibitor | 10% WG | 300 g | Before 2-leaf stage of weeds: barnyardgrass, arrowhead, water plantain, Ludwigia spp., false pimpernel, ammania, toothcup, false foxglove, barnyardgrass, small-flowered nutsedge, annual sedge, perennial sedge, sprangletop, purple nutsedge, water clover, salvinia, and azolla. |

* Demonstrates better efficacy in simultaneously controlling all three major weed groups (grasses, sedges, broadleaves). ** Obsolete internationally.

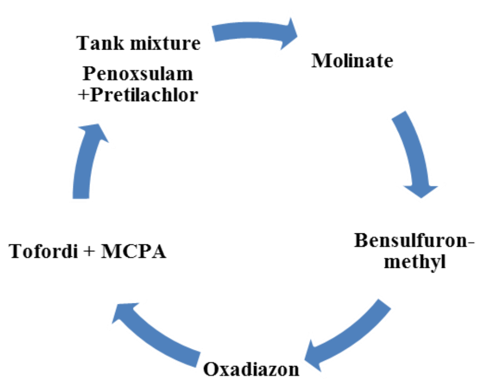


Figure 1. **A multi-faceted, cyclical framework for managing and delaying herbicide resistance in weeds in rice crops.** This model emphasizes the strategic application of herbicides (chemical control) as its foundation, with the primary aim of reducing selection pressure for resistance.

## 7. Integrated Management

In conclusion, integrating herbicides with other management methods -such as competitive cultivars, cultural practices, and biological control-can greatly support the development of sustainable rice production systems. This integrated weed management strategy provides effective control while simultaneously reducing herbicide reliance and minimizing environmental impact (Table 3).

Table 3. Management and damage reduction strategies for weeds in rice cultivation

| Strategy Category | Specific Method | Mechanism of Action | Considerations & Applications |
|---|---|---|---|
| Reducing the Seed Bank | Enhancing Seed Predation by Soil Organisms | Increases seed mortality of weeds through consumption by insects, earthworms, rodents, and birds. | Avoid burning crop residues and field borders; pile residues to create shelter and food for predators; use cover crops in rotation. |
| | False Seedbed Technique | Stimulates weed seed germination with light irrigation, followed by their destruction before sowing the main crop. | Use of non-selective herbicides (e.g., glyphosate) or shallow tillage; highly effective for photoblastic species like crabgrass and goosefoot; requires sufficient time interval between cultivation cycles. |
| Tillage and Residue Management | No-Till/Reduced-Till System | Maintains a greater proportion of weed seeds on the soil surface, exposing them to mortality factors (predation, decay). | Results in slower germination and weaker growth of weeds; suitable for species like ryegrass; requires effective residue management. |
| | Deep Moldboard Plowing | Buries a large volume of the weed seed bank at depths greater than 10 cm (exceeding emergence depth). | An emergency strategy when the surface seed bank is highly enriched; studies indicate performing this once every 5 years can control problems with weeds like green foxtail. |
| | Use of Plant Residue Mulch (Straw) | Physically and chemically suppresses weed seed germination and growth. | Creates a physical barrier, prevents light penetration, reduces fluctuations in temperature and moisture, and releases allelopathic compounds; requires specific seeders (e.g., turbo) for planting under heavy residue conditions. |
| Use of Competitive Varieties | Varieties with Superior Morphological Traits | Competes for light, water, and nutrients through rapid canopy closure and shading. | Varieties with strong seedling vigor, rapid early growth, high tillering capacity, high Leaf Area Index (LAI), and droopy leaves; highly effective in dryland and direct-seeded systems. |
| | Allelopathic Varieties | Release inhibitory chemical compounds from roots that suppress the germination and growth of adjacent weeds. | Can contribute up to 34% to the overall competitive ability of rice; still primarily in the research phase and requires further development for practical application. |
| | Varieties Tolerant to Anaerobic/Waterlogged Conditions | Enables the creation of waterlogged conditions to suppress non-tolerant weeds. | Allows for flooding immediately after planting in direct-seeded systems; currently, limited varieties are available (under research at IRRI). |
| Planting Management | Increasing Seeding Rate | Enhances crop competitiveness by establishing a denser plant population and promoting faster canopy closure. | Reduces space and resources available for weeds; studies show increasing the seeding rate from 25 to 100 kg/ha reduced weed biomass by 47-59%. |
| | Reducing Row Spacing | Promotes faster closure of inter-row spaces, reducing light penetration to the soil surface. | Shortens the critical period for weed control; studies indicate 20 cm row spacing resulted in lower weed incidence compared to 30 cm spacing. |

## conclusion

In conclusion, achieving sustainable and productive rice cultivation in Iranian paddy fields necessitates a paradigm shift from over-reliance on herbicides to a sophisticated, multi-component Integrated Weed Management (IWM) strategy. This holistic approach synergistically combines preventive sanitation, strategic seed bank depletion through tillage and false seedbeds, the deployment of competitive and allelopathic cultivars, optimized planting density and geometry, smart water management via Alternate Wetting and Drying, and structured crop rotations. When underpinned by a disciplined, science-based herbicide rotation program, this integrated framework effectively suppresses weed populations, delays resistance evolution, enhances yield potential, conserves vital water resources, and safeguards environmental and economic sustainability for future generations.

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