Weed Diversity in Rice Ecosystems: Taxonomy, Ecology, Identification, and Integrated Management Strategies

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Abstract—**Rice production systems worldwide are challenged by diverse weed communities that compete aggressively for nutrients, water, light, and space, causing substantial yield losses and increasing production costs. Weed interference remains one of the most important biological constraints to rice productivity, particularly in direct-seeded rice systems where crop–weed competition begins immediately after emergence. This review synthesizes current knowledge on the taxonomy, morphology, ecology, economic significance, and management of major weed species occurring in rice ecosystems. Particular emphasis is given to dominant grass weeds including *Echinochloa crus-galli*, *Echinochloa colona*, and *Leptochloa chinensis*; sedges such as *Cyperus rotundus*, *Cyperus difformis*, and *Fimbristylis miliacea*; and broadleaved weeds including *Eclipta prostrata*, *Ammannia baccifera*, and *Acalypha indica*. Diagnostic morphological traits useful for field identification are discussed alongside ecological adaptations that contribute to weed persistence and competitiveness. The review further evaluates integrated weed management strategies encompassing cultural, mechanical, biological, and chemical approaches. Special attention is given to herbicide resistance evolution, precision weed management technologies, artificial intelligence-assisted weed recognition systems, and emerging bioherbicide-based solutions. Sustainable rice production will increasingly depend on integrated and knowledge-intensive weed management programs that combine accurate species identification, diversified control tactics, and advanced decision-support technologies.**

Index Terms—**rice weeds; *Echinochloa*; *Cyperus*; weed identification; integrated weed management; herbicide resistance; direct-seeded rice**

I. INTRODUCTION

Rice (*Oryza sativa* L.) is the principal staple food for more than half of the global population, cultivated across more than 160 million hectares annually and representing a cornerstone of food security, nutrition, and rural livelihoods, especially across Asia where over 90% of global rice production occurs (Negi et al. 2024). Rice agroecosystems encompass a remarkable breadth of production environments—irrigated lowlands, rainfed uplands, flood-prone lowlands, and deep-water systems—each supporting distinct ecological communities and presenting unique management challenges.

Among biotic constraints affecting rice productivity, weeds consistently cause greater yield losses than insects, diseases, or other pests under unmanaged conditions. Weed infestation reduces crop growth through direct competition for nutrients, water, light, and physical space while simultaneously increasing the incidence of insect pests, nematodes, and phytopathogens. Yield reductions attributable to uncontrolled weeds range from 15% to over 80%, with complete crop failure reported under severe infestations in direct-seeded rice systems (Rao et al. 2024; Hashim et al. 2024).

The agronomic transition from traditional puddled transplanted rice to direct-seeded rice (DSR) systems—driven by labor shortages, declining water availability, and rising production costs—has markedly intensified weed management challenges. Under DSR, crop and weed seedlings emerge simultaneously, eliminating the competitive advantage that transplanted seedlings enjoy. Studies report water savings of 13–23% and substantial reductions in labor inputs under DSR, yet yield losses from poorly managed weed populations can exceed 80–90% in these systems (Negi et al. 2024; Jehangir et al. 2024).

The composition of rice weed communities is dominated by three functional groups: grass weeds (Poaceae), sedge weeds (Cyperaceae), and broadleaved weeds from numerous dicotyledonous families. Among these, species of *Echinochloa* are universally recognized as the most troublesome because of their aggressive growth, prolific seed production, mimicry of rice morphology, and rapidly evolving herbicide resistance. Sedges such as *Cyperus rotundus*, *C. difformis*, and *Fimbristylis miliacea* thrive under flooded conditions and exhibit reproductive strategies that make eradication extremely difficult. Broadleaved weeds contribute additional management complexity through diverse life-history strategies and varying herbicide susceptibilities (Vulchi et al. 2024; Rao et al. 2024).

The rapid evolution of herbicide resistance represents a particularly acute threat to sustainable rice production. Resistance to acetolactate synthase (ALS) inhibitors, acetyl-CoA carboxylase (ACCase) inhibitors, and several other herbicide groups has been documented across Asia, North America, and Australia (Vulchi et al. 2024; Heap 2024). Cross-resistance and multiple-resistance mechanisms are increasingly prevalent, severely limiting chemical control options and underscoring the need for diversified management frameworks.

Integrated Weed Management (IWM) has emerged as the most scientifically supported framework for sustainable weed suppression, combining cultural, mechanical, biological, and chemical approaches to maintain weed populations below economically damaging thresholds. Simultaneously, digital agriculture technologies—including artificial intelligence (AI), unmanned aerial vehicles (UAVs), machine learning, and hyperspectral imaging—are opening new possibilities for early weed detection, species-specific management, and precision herbicide application (Li et al. 2024; Guo et al. 2024; Adhinata et al. 2024).

Accurate species identification remains the indispensable foundation of effective weed management. The similarity among rice weeds during seedling stages frequently causes misidentification, resulting in inappropriate herbicide selection, reduced efficacy, economic losses, and accelerated resistance development. This review therefore aims to: (i) document the diversity and taxonomy of major rice-associated weeds; (ii) provide diagnostic morphological characteristics for accurate field identification; (iii) examine ecological adaptations and economic significance; (iv) evaluate current integrated management strategies; and (v) discuss emerging technologies that are reshaping sustainable weed management in rice ecosystems.

II. CLASSIFICATION AND DIVERSITY OF MAJOR WEED FLORA IN RICE ECOSYSTEMS

Rice ecosystems support more than 1,800 weed species globally, of which approximately 350–400 are considered economically important in tropical and subtropical Asia (Negi et al. 2024). Weed community composition is highly dynamic, reflecting interactions among climatic conditions, soil characteristics, water regime, crop establishment method, tillage practices, fertilizer management, and weed control strategies (Chauhan et al. 2017; Rao et al. 2024). Three major functional groups—grasses (Poaceae), sedges (Cyperaceae), and broadleaved weeds—account for the majority of yield losses, each differing substantially in morphology, physiology, ecology, and herbicide susceptibility.

The relative abundance of each group differs according to production environment. In transplanted lowland rice, sedges and aquatic broadleaved weeds are frequently dominant due to prolonged flooding. In direct-seeded systems, aggressive grass weeds—particularly *Echinochloa* spp., *Leptochloa* spp., and weedy rice—dominate because shallow water depths and simultaneous emergence confer competitive advantages. Aerobic and upland rice ecosystems frequently harbor the greatest weed diversity, supporting mixtures of aquatic and terrestrial species (Hashim et al. 2024). The major weed flora associated with rice ecosystems can be broadly classified into grasses, sedges, and broadleaved weeds, each differing in morphology, ecology, and management requirements (Table 1).

2.1. Grass Weeds (Family: Poaceae)

Grass weeds represent the most economically damaging weed group in rice ecosystems worldwide. As monocotyledonous plants with fibrous root systems, hollow cylindrical stems, alternate parallel-veined leaves, and spikelet-bearing inflorescences, they are morphologically similar to rice during early growth stages, complicating management timing. Their rapid growth rates, high tillering capacity, prolific seed production, and ecological plasticity enable adaptation across flooded, moist, and aerobic environments. In direct-seeded rice systems throughout South and Southeast Asia, grass weeds account for approximately 40–50% of total weed biomass (Rao et al. 2024).

Table 1. Classification of major weed flora in rice ecosystems.

Weed Group	Scientific Name	Family	Common Name
Grass	*Echinochloa crus-galli*	Poaceae	Barnyard grass
Grass	*Echinochloa colona*	Poaceae	Jungle rice
Grass	*Leptochloa chinensis*	Poaceae	Chinese sprangletop
Sedge	*Cyperus rotundus*	Cyperaceae	Purple nutsedge
Sedge	*Cyperus difformis*	Cyperaceae	Smallflower umbrella sedge
Sedge	*Fimbristylis miliacea*	Cyperaceae	Globe fringerush
Broadleaf	*Eclipta prostrata*	Asteraceae	False daisy
Broadleaf	*Ammannia baccifera*	Lythraceae	Blistering ammannia
Broadleaf	*Acalypha indica*	Euphorbiaceae	Indian copperleaf

Source: Holm et al. (1997), Rao (2000), Moody (1989), Chauhan et al. (2017)

2.2. Sedge Weeds (Family: Cyperaceae)

Sedges constitute the second most important weed group in rice. Distinguished from grasses by their characteristic triangular stems, three-ranked leaf arrangement (the mnemonic "sedges have edges" remains a useful diagnostic aid), and distinctive inflorescence structures, sedges are particularly successful in flooded and poorly drained environments. The perennial *Cyperus rotundus* reproduces vegetatively through extensive networks of underground tubers and rhizomes, rendering it one of the most persistent weeds in agricultural systems globally. Annual sedges such as *C. difformis* and *F. miliacea* rely on prolific seed production and rapid colonization of disturbed habitats.

2.3. Broadleaved Weeds (Dicotyledonous Species)

Broadleaved weeds form a diverse assemblage of dicotyledonous species from numerous plant families, characterized by broad leaves with reticulate venation, branched stems, differentiated floral structures, and taproot or branched root systems. Although generally producing less total biomass than dominant grass weeds, several species are major competitors in flooded lowland environments. Common representatives include *Eclipta prostrata*, *Ammannia baccifera*, *Acalypha indica*, *Monochoria vaginalis*, *Ludwigia parviflora*, and *Sphenoclea zeylanica*. Many also serve as alternate hosts for insect pests and phytopathogens, increasing their agricultural significance (Moody 1989; Rao 2000).

III. MAJOR GRASS WEEDS (FAMILY: POACEAE)

Grass weeds constitute the most economically important and yield-limiting weed group in rice production worldwide. Their significance arises from morphological similarity to rice during early growth, rapid growth rates, prolific seed production, efficient nutrient acquisition, and strong competitive ability. The increasing adoption of direct-seeded rice has further intensified grass weed importance because crop and weed seedlings emerge simultaneously, creating severe competition during the critical weed-free period (Chauhan et al. 2017; Rao et al. 2024). Among numerous grass species, *Echinochloa crus-galli*, *E. colona*, and *Leptochloa chinensis* are considered the most destructive and widely distributed throughout tropical and subtropical rice-growing regions.

3.1. Echinochloa crus-galli (L.) P. Beauv. (Barnyard Grass)

3.1.1. Taxonomy and Morphology

Echinochloa crus-galli (family Poaceae, tribe Paniceae) derives its generic name from the Greek *echinos* (hedgehog) and *chloa* (grass), reflecting the bristly inflorescence. The species epithet *crus-galli* ("cock's foot") describes the characteristic panicle branching. Plants are robust annuals reaching 30–150 cm, erect and tufted, with fibrous root systems and flat smooth leaves 10–40 cm long and 6–18 mm wide. The most important diagnostic feature is the complete absence of a ligule at the leaf blade–sheath junction, distinguishing it from many co-occurring grasses. The terminal panicle (8–20 cm) bears densely packed spikelets with stiff awns up to 15 mm long, imparting a rough, bristly appearance. Seeds are broadly ovate, pale to dark brown at maturity, and exhibit dormancy that contributes to persistent soil seedbanks.

3.1.2. Ecology and Distribution

E. crus-galli occurs in more than 60 countries across temperate, subtropical, and tropical regions. It thrives between 25–35°C and tolerates a wide range of moisture regimes, establishing readily in moist soils and shallowly flooded paddies. Its capacity to mimic rice morphology during early growth further enhances survival by reducing detection during manual weeding. A single plant may produce 40,000–60,000 seeds, remaining viable for several years and contributing substantially to long-term seedbank persistence. Significant phenotypic plasticity among populations permits adaptation to changing management systems and climatic conditions.

3.1.3. Economic Importance and Management

Yield reductions of 35–70% are commonly reported in transplanted rice, and losses may exceed 80% in direct-seeded systems where weed emergence coincides with crop establishment. Competition is particularly severe during the first 20–40 days after sowing, the critical weed-free period for rice. Additional impacts include reduced grain quality, interference with harvesting, increased grain moisture, and lodging. Effective integrated management combines stale seedbed preparation, competitive cultivars, optimum planting density, water management, mechanical weeding, and chemical control. Pre-emergence herbicides (butachlor, pretilachlor, pendimethalin) followed by post-emergence applications of bispyribac-sodium, penoxsulam, or cyhalofop-butyl are widely used, though widespread resistance to ALS inhibitors, ACCase inhibitors, and PSII inhibitors necessitates herbicide rotation strategies (Vulchi et al. 2024; Heap 2024).

3.2. Echinochloa colona (L.) Link (Jungle Rice)

3.2.1. Taxonomy and Morphology

E. colona is generally smaller and more slender than *E. crus-galli*, reaching heights of 15–80 cm. Plants possess narrow leaves (2–8 mm wide), smooth stems, and lack a ligule. The panicle is shorter and more compact (3–10 cm) and usually lacks prominent awns. Leaf sheaths often exhibit purplish-green coloration, a useful field identification aid. The compact inflorescence of clustered racemes distinguishes the species from the rougher, bristly panicle of *E. crus-galli*.

3.2.2. Ecology, Economic Significance, and Management

The species thrives under warm, moist conditions and can complete its life cycle within 45–60 days, permitting multiple generations per cropping season. Yield losses ranging from 20% to 60% are reported depending on weed density and timing of emergence. Increasing herbicide resistance in *E. colona* populations has become a major concern in rice-growing regions of Asia and Australia. Integrated management combines competitive cultivars, stale seedbed practices, timely hand weeding, and appropriate herbicide programs incorporating resistance monitoring.

3.3. Leptochloa chinensis (L.) Nees (Chinese Sprangletop)

3.3.1. Taxonomy and Morphology

L. chinensis is an important annual grass of irrigated and wet-seeded rice systems throughout tropical Asia. The most reliable diagnostic feature is a short membranous ligule (1–2 mm), clearly differentiating the species from *Echinochloa* weeds. Plants are slender and erect (30–100 cm), with narrow leaves (2–5 mm wide). The inflorescence is a highly branched panicle bearing numerous slender racemes. Seeds are small, flattened, and reddish-brown, produced in large numbers.

3.3.2. Ecology, Economic Importance, and Management

The species prefers saturated soils and shallowly flooded environments. Although less tolerant of prolonged flooding than *Echinochloa* spp., it performs exceptionally well under wet-seeded rice conditions. Yield losses ranging from 15% to 45% have been documented under heavy infestation. Effective management includes maintaining appropriate water depth, crop competition, and selective herbicides such as penoxsulam and cyhalofop-butyl.

Important diagnostic characteristics of the dominant grass weeds occurring in rice ecosystems are summarized in Table 2. highlighting differences in ligule presence, panicle structure, habitat preference, and yield-loss potential.

Table 2. *Comparative identification characteristics of major grass weeds in rice ecosystems.*

Character	E. crus-galli	E. colona	L. chinensis
Ligule	Absent	Absent	Present (1–2 mm)
Plant height	30–150 cm	15–80 cm	30–100 cm
Panicle type	Rough, bristly, awned	Compact, awnless	Branched, slender
Seed size	Medium	Small	Very small
Preferred habitat	Flooded and moist soils	Aerobic/DSR systems	Wet-seeded rice
Competitive ability	Very high	High	Moderate–high
Yield loss potential (%)	35–80	20–60	15–45

Source: Rao et al. (2017), Chauhan et al. (2017).

IV. MAJOR SEDGE WEEDS (FAMILY: CYPERACEAE)

Sedges (Cyperaceae, comprising over 5,500 species across ~100 genera) constitute one of the most important weed groups affecting rice production worldwide. Distinguished from grasses by their triangular stems, three-ranked leaf arrangement, generally absent ligules, and umbel-type inflorescences, sedges are uniquely adapted to the flooded, waterlogged, and periodically saturated environments characteristic of rice agroecosystems. Among sedge species, *Cyperus rotundus*, *C. difformis*, and *Fimbristylis miliacea* are the most economically important, differing substantially in life cycle, reproductive biology, and management requirements (Holm et al. 1997; Chauhan et al. 2017).

4.1. Cyperus rotundus L. (Purple Nutsedge)

4.1.1. Taxonomy and Morphology

C. rotundus is a perennial sedge reported in over 90 countries and infesting more than 50 crop species, frequently ranked as the world's most troublesome weed (Holm et al. 1997). Plants grow 10–55 cm tall, with erect triangular stems arising from a complex underground system of rhizomes, bulbs, and tubers—the primary organs of persistence and vegetative propagation (Rao 2000; Rao and Nagamani 2017). Leaves are narrow, dark green, and glossy. The inflorescence is an open umbel bearing reddish-brown to purple spikelets. Tubers are arranged in chains connected by rhizomes at depths of 5–30 cm, are ovoid, brown to black, and rich in stored carbohydrates supporting regrowth following mechanical or chemical injury.

4.1.2. Ecology, Persistence, and Economic Importance

Purple nutsedge reproduces predominantly through vegetative structures. Under favorable conditions, a single plant may produce hundreds of shoots and thousands of tubers within six months (Holm et al. 1997; Chauhan et al. 2017). Several mechanisms contribute to persistence: (i) tubers at depths exceeding 20 cm escape tillage and herbicide exposure; (ii) tuber dormancy enables populations to survive adverse conditions; (iii) mechanical cultivation fragments rhizomes and stimulates new plant formation; (iv) allelopathic compounds released by *C. rotundus* suppress crop germination and early seedling development. Continuous flooding suppresses growth in lowland rice, but the species remains highly problematic in upland, aerobic, and direct-seeded systems. Yield losses of 25–60% have been reported in upland and aerobic rice (Rao and Nagamani 2017; Negi et al. 2024). Successful management requires deep tillage to disrupt rhizome networks, repeated cultivation to exhaust carbohydrate reserves, flooding, directed glyphosate applications, sedge-selective herbicides (halosulfuron-methyl), and soil solarization during fallow periods.

4.2. Cyperus difformis L. (Smallflower Umbrella Sedge)

C. difformis is an annual sedge widely distributed in tropical and subtropical lowland irrigated rice systems characterized by prolonged flooding and high soil moisture. Plants range from 10–60 cm tall with soft, slender triangular stems and pale green, narrow leaves. The inflorescence is a compact umbrella-like cluster of numerous small spikelets on short rays—a reliable field identification feature. Unlike *C. rotundus*, the species reproduces exclusively through seeds, yet prolific output (thousands of seeds per plant) allows rapid population expansion. Seeds germinate readily under shallow water, and the short life cycle enables multiple generations per season. Yield losses of 20–50% are reported under severe infestations. Resistance to ALS-inhibiting herbicides (bensulfuron-methyl, pyrazosulfuron-ethyl) through target-site mutations and enhanced metabolic detoxification has been documented in several Asian rice-growing regions. Integrated management includes early flooding, competitive cultivars, herbicide rotation, and penoxsulam- or halosulfuron-based programs where resistance is absent.

4.3. Fimbristylis miliacea (L.) Vahl (Globe Fringerush)

F. miliacea is among the most widespread annual sedges in lowland rice throughout South and Southeast Asia, increasingly important in direct-seeded rice where fluctuating water levels favor establishment. Plants are tufted annuals reaching 15–60 cm with slender triangular stems and narrow grass-like leaves. The characteristic globular or button-like spikelet clusters in loose inflorescences provide the most reliable diagnostic feature. Although lacking underground tubers, the species compensates through prolific seed production, extended germination periods, large soil seedbanks, and effective seed dispersal through irrigation water. Individual plants may produce thousands of seeds viable for several years. Yield losses of 15–40% are reported under moderate to severe infestations. Emerging resistance to ALS-inhibiting herbicides has been documented in several regions, emphasizing the importance of herbicide rotation, water-level management, and integrated weed control programs.

Comparative morphological and ecological characteristics of the major sedge weeds are presented in Table 3, facilitating rapid field identification and management decisions.

Table 3. *Comparative characteristics of major sedge weeds in rice ecosystems.*

Character	C. rotundus	C. difformis	F. miliacea
Life cycle	Perennial	Annual	Annual
Stem shape	Triangular	Triangular	Triangular
Reproduction	Tubers + seeds	Seeds only	Seeds only
Underground organs	Extensive tubers and rhizomes	None	None
Flood tolerance	Moderate	High	High
Preferred habitat	Upland and aerobic rice	Flooded rice	Flooded rice
Yield loss (%)	25–60	20–50	15–40
Resistance risk	Moderate	High	Increasing
Management difficulty	Very high	Moderate	Moderate

Source: Holm et al. (1997), Rao (2000), Rao and Nagamani (2017)

V. MAJOR BROADLEAVED WEEDS IN RICE ECOSYSTEMS

Broadleaved weeds represent a diverse and ecologically important component of rice weed communities. Their significance has increased in recent years as long-term herbicide programs targeting grasses and sedges have altered community composition, promoting shifts toward broadleaved weed dominance (Chauhan et al. 2017; Rao et al. 2024). Beyond direct competition, many species serve as alternate hosts for insect pests, nematodes, and phytopathogens, and produce large quantities of long-viable seeds that sustain persistent infestations (Moody 1989; Rao 2000).

5.1. Eclipta prostrata (L.) L. (False Daisy)

E. prostrata (Asteraceae) is one of the most common broadleaved weeds in lowland rice ecosystems throughout tropical, subtropical, and warm temperate regions. Plants are annual or short-lived perennial herbs reaching 15–60 cm, with opposite lanceolate leaves, branched stems covered with fine hairs, and characteristic small white capitula (6–8 mm diameter)—the most reliable diagnostic feature. The species thrives in moist and flooded conditions, reproducing exclusively through seeds dispersed by irrigation water and field operations. Dense infestations compete strongly for nutrients and light during early rice development (Rao et al. 2017).

Management integrates timely hand weeding, water management, competitive crop stands, and selective herbicides including metsulfuron-methyl and bispyribac-sodium.

5.2. Ammannia baccifera L. (Blistering Ammannia)

A. baccifera (Lythraceae) is among the most troublesome broadleaved weeds in transplanted and direct-seeded rice systems throughout South and Southeast Asia (Moody 1989). Plants are erect annual herbs growing 20–80 cm, with characteristic reddish or purplish, highly branched stems and opposite narrow sessile leaves. Small pink to purple flowers emerge from leaf axils, followed by capsule fruits containing numerous seeds. The species is particularly adapted to flooded conditions, and seedlings emerge repeatedly throughout the growing season. Yield reductions of 15–35% are reported under severe infestations (Rao et al. 2017). Management relies on integrated approaches incorporating water regulation, crop competition, hand weeding, and herbicide programs.

5.3. Acalypha indica L. (Indian Copperleaf)

A. indica (Euphorbiaceae) occurs widely throughout tropical Asia, more commonly in upland and partially drained rice environments. Plants are erect annual herbs ranging 20–70 cm, with ovate serrated leaves on long petioles and greenish inflorescences in elongated axillary spikes. The species exhibits rapid growth and substantial seed production, enabling rapid colonization of disturbed sites under moist but not permanently flooded conditions. Management relies on early-season cultivation, hand weeding, crop competition, and broad-spectrum herbicides.

5.4. Monochoria vaginalis (Burm. f.) C. Presl (Pickerel Weed)

M. vaginalis (Pontederiaceae) is one of the most important aquatic broadleaved weeds in flooded rice ecosystems, distributed across Asia, Australia, and parts of Africa (Chauhan et al. 2017). Plants possess broad ovate leaves with long petioles and striking violet-blue flowers arranged in terminal clusters—a distinctive diagnostic feature. Young plants may be mistaken for beneficial aquatic vegetation, allowing infestations to establish before control is initiated. The species forms dense stands under flooded conditions that shade rice seedlings severely. Recent reports document evolving resistance to ALS-inhibiting herbicides in several rice-growing regions (Vulchi et al. 2024). Management includes water-level manipulation, mechanical removal, herbicide rotation, and prevention of seed production.

5.5. Ludwigia parviflora Roxb. (Water Primrose)

L. parviflora (Onagraceae) is a common weed of wetland rice, recognizable by its narrow leaves, yellow flowers, and elongated capsules. Mature plants may exceed 1 m in height under favorable conditions. The species thrives in saturated soils and shallowly flooded conditions, exhibiting rapid growth and high reproductive output. Early intervention is essential because mature plants become difficult to control mechanically or chemically.

5.6. Sphenoclea zeylanica Gaertn. (Gooseweed)

S. zeylanica (Sphenocleaceae) is an annual aquatic broadleaved weed widely distributed in tropical rice regions, frequently dominant in poorly managed flooded fields. Plants are succulent and erect (30–100 cm), with fleshy lanceolate leaves and a characteristic cylindrical flowering spike—an important diagnostic feature. The species completes its life cycle rapidly, produces large quantities of seeds that disperse readily through water, and competes strongly for nutrients and light. Integrated weed management programs incorporating water management, crop competition, and timely herbicide application provide the most effective long-term control.

The major broadleaved weeds of rice ecosystems differ considerably in habitat preference, reproductive biology, and competitive ability, as summarized in Table 4.

Table 4. Comparative characteristics of major broadleaved weeds in rice ecosystems.

Species	Family	Habitat	Reproduction	Yield Loss (%)
Eclipta prostrata	Asteraceae	Flooded/moist soils	Seeds	10–30
Ammannia baccifera	Lythraceae	Flooded rice	Seeds	15–35
Acalypha indica	Euphorbiaceae	Moist upland rice	Seeds	10–25
Monochoria vaginalis	Pontederiaceae	Flooded rice	Seeds	20–50
Ludwigia parviflora	Onagraceae	Wetland rice	Seeds	15–40
Sphenoclea zeylanica	Sphenocleaceae	Flooded rice	Seeds	15–45

Source: Holm et al. (1997), Rao (2000), Rao et al. (2017), Chauhan et al. 2017.

VI. COMPARATIVE WEED IDENTIFICATION AND DIAGNOSTIC KEYS

Accurate species identification is the cornerstone of effective weed management in rice ecosystems. The success of cultural, mechanical, biological, and chemical control strategies depends on correct recognition of target weed species. Misidentification results in inappropriate herbicide selection, reduced efficacy, increased production costs, and accelerated herbicide resistance (Rao 2000; Chauhan et al. 2017). Rice-associated weeds exhibit considerable morphological similarity during seedling stages; reliable diagnostic characteristics and systematic identification keys are therefore essential tools for researchers, extension personnel, and farmers.

6.1. Key Morphological Diagnostic Characters

Grasses (Poaceae) are identified by round or cylindrical stems, parallel leaf venation, two-ranked leaf arrangement, fibrous roots, and spikelet-bearing inflorescences. Sedges (Cyperaceae) are distinguished by triangular stems, three-ranked leaf arrangement, absent ligules, and umbel-type inflorescences. Broadleaved weeds (dicots) are recognized by broad leaves with reticulate venation, branched stems, differentiated floral structures, and taproot or branched root systems. Among grass weeds, the single most important identification character is the ligule—absent in *Echinochloa* spp. and present (short, membranous) in *L. chinensis*. Panicle architecture (bristly and awned vs. compact and awnless) further differentiates *E. crus-galli* from *E. colona*. For sedges, the presence of underground tubers immediately identifies *C. rotundus*, while compact umbels distinguish *C. difformis* from the globular spikelet clusters of *F. miliacea*. Broadleaved weeds are most readily distinguished by floral characteristics—violet-blue flowers in *M. vaginalis*, white daisy-like capitula in *E. prostrata*, reddish stems and pink-purple axillary flowers in *A. baccifera*, and the cylindrical flowering spike of *S. zeylanica*.

6.2. Dichotomous Identification Key for Major Rice Weeds

Step 1.
1a. Leaves broad with reticulate venation .... Go to Step 2
1b. Leaves narrow with parallel venation .... Go to Step 5
Step 2.
2a. Flowers violet-blue .... *Monochoria vaginalis*
2b. Flowers not violet-blue .... Go to Step 3
Step 3.
3a. White daisy-like flower heads .... *Eclipta prostrata*
3b. Flowers pink, purple, yellow, or green .... Go to Step 4
Step 4.
4a. Stem reddish; flowers pink-purple .... *Ammannia baccifera*
4b. Leaves serrated; green inflorescence spikes .... *Acalypha indica*
4c. Yellow flowers .... *Ludwigia parviflora*
4d. Cylindrical flowering spike .... *Sphenoclea zeylanica*
Step 5.
5a. Stem triangular .... Go to Step 6
5b. Stem round or cylindrical .... Go to Step 8
Step 6.
6a. Underground tubers present .... *Cyperus rotundus*
6b. Tubers absent .... Go to Step 7
Step 7.
7a. Umbrella-like compact inflorescence .... *Cyperus difformis*
7b. Globular spikelet clusters .... *Fimbristylis miliacea*
Step 8.

8a. Short membranous ligule present .... *Leptochloa chinensis*
8b. Ligule absent .... Go to Step 9
Step 9.
9a. Large rough panicle with bristly awns .... *Echinochloa crus-galli*
9b. Compact panicle without prominent awns .... *Echinochloa colona*

Key diagnostic features useful for distinguishing major rice weed species are presented in Table 5 and can be used alongside the dichotomous identification key.

Table 5. Comparative identification characteristics of major rice weed species.

Species	Group	Stem Shape	Ligule	Leaf Venation	Tubers	Flower Color	Habitat
E. crus-galli	Grass	Round	Absent	Parallel	No	Green/purple	Flooded & aerobic
E. colona	Grass	Round	Absent	Parallel	No	Green	Aerobic/DSR
L. chinensis	Grass	Round	Present	Parallel	No	Green	Wet-seeded rice
C. rotundus	Sedge	Triangular	Absent	Parallel	Yes	Purple-brown	Upland & moist
C. difformis	Sedge	Triangular	Absent	Parallel	No	Green	Flooded rice
F. miliacea	Sedge	Triangular	Absent	Parallel	No	Brown	Flooded rice
E. prostrata	Broadleaf	Branched	N/A	Reticulate	No	White	Wetland/moist
A. baccifera	Broadleaf	Branched	N/A	Reticulate	No	Pink-purple	Flooded rice
M. vaginalis	Broadleaf	Succulent	N/A	Reticulate	No	Violet-blue	Aquatic/flooded

Source: Holm et al. (1997), Rao (2000), Rao et al. (2017), Chauhan et al. 2017.

6.3. Emerging Digital Tools for Weed Identification

Recent advances in artificial intelligence, computer vision, hyperspectral imaging, and unmanned aerial vehicles are transforming weed identification in rice ecosystems. Deep-learning convolutional neural networks trained on large labeled field image datasets now distinguish morphologically similar weed species with accuracies exceeding 90%, approaching operational deployment for practical farm use (Li et al. 2024). UAV-mounted multispectral cameras combined with machine learning algorithms enable large-scale weed mapping and site-specific herbicide application, reducing costs and environmental impacts (Guo et al. 2024; Adhinata et al. 2024). Smartphone-based diagnostic applications leveraging these models offer transformative potential for farmer-level weed identification and management decision support, particularly in resource-limited settings.

VII. ECONOMIC IMPORTANCE, CROP LOSSES, AND ECOLOGICAL IMPACT OF RICE WEEDS

Weed infestation remains one of the most significant biological constraints limiting rice productivity worldwide. Uncontrolled weeds frequently cause greater yield reductions than insect pests, diseases, or nematodes combined. Global yield loss estimates from weeds in rice range from 15% to 90%, with direct-seeded systems experiencing greater losses due to simultaneous weed and crop emergence (Rao et al. 2024; Hashim et al. 2024).
Reported yield losses associated with major rice weeds under uncontrolled conditions are shown in Table 6, illustrating the substantial economic consequences of weed interference.

Table 6. Yield losses caused by major rice weed species under uncontrolled conditions.

Weed Species	Common Name	Reported Yield Loss (%)
Echinochloa crus-galli	Barnyard grass	35–80
Echinochloa colona	Jungle rice	20–60
Leptochloa chinensis	Chinese sprangletop	15–45
Cyperus rotundus	Purple nutsedge	25–60
Cyperus difformis	Smallflower umbrella sedge	20–50
Fimbristylis miliacea	Globe fringerush	15–40
Monochoria vaginalis	Pickerel weed	20–50
Sphenoclea zeylanica	Gooseweed	15–45
Mixed weed flora	Multiple species	30–90

Source: Rao et al. (2017), Chauhan et al. 2017, Rao et al. (2024).

Weeds reduce rice productivity through direct competition for light, nutrients, water, and physical space. Competition for light is particularly severe from tall-growing species such as *E. crus-galli* and *S. zeylanica*, which intercept sunlight and suppress photosynthesis, tillering, and biomass accumulation. Dense weed infestations may remove substantial quantities of nitrogen, phosphorus, and potassium from the soil, reducing fertilizer-use efficiency and the economic return on nutrient inputs (Rao et al. 2017). Economic losses beyond yield reduction include increased labor requirements, herbicide costs, reduced grain quality, harvesting difficulties, increased grain moisture content, and reduced input-use efficiency. In direct-seeded rice systems, weed management may account for 15–30% of total production costs (Negi et al. 2024).

7.1. Critical Period of Weed Competition

The critical period of weed competition—the interval during which weeds must be controlled to prevent economically significant yield losses—spans approximately the first 20–45 days after sowing or transplanting. Failure to maintain a weed-free environment during this period causes irreversible suppression of tillering, root development, nutrient uptake, and panicle formation. The exact duration of the critical period varies according to rice variety, weed flora composition, and production system, but represents the primary intervention window for management strategies (Rao et al. 2017; Chauhan et al. 2017).

7.2. Ecological Consequences of Weed Infestation

Beyond direct economic impacts, weeds significantly influence rice agroecosystem functioning. Dominant weed species can alter plant community composition and reduce local biodiversity. Many species serve as alternate hosts for insect pests, plant pathogenic fungi, bacterial pathogens, and nematodes, thereby amplifying disease and pest pressure within rice fields. Perennial weeds with extensive underground root and rhizome systems alter soil physical properties, nutrient cycling, and organic matter dynamics. Long-term weed infestations therefore have cascading ecological consequences that extend beyond the immediate crop season.

VIII. INTEGRATED WEED MANAGEMENT STRATEGIES

Integrated Weed Management (IWM) represents the most scientifically accepted framework for sustainable rice weed suppression. Rather than relying exclusively on herbicides, IWM integrates preventive, cultural, mechanical, biological, and chemical methods to maintain weed populations below economically damaging thresholds while minimizing environmental impact and resistance selection pressure. Recent studies demonstrate that IWM strategies improve productivity, profitability, and resource-use efficiency while reducing weed seedbank accumulation in rice-based cropping systems (Padhan et al. 2026; Jabran and Chauhan 2022).

8.1. Preventive Measures

Prevention is the most cost-effective component of IWM. Key preventive strategies include: (i) using certified weed-free seed to prevent introduction of new weed species and weedy rice; (ii) cleaning machinery and irrigation infrastructure to minimize weed propagule dispersal; (iii) preventing weed seed production in field margins and irrigation channels; and (iv) monitoring fields for early detection of invasive or herbicide-resistant weed populations.

8.2. Cultural Weed Management

Cultural practices that enhance crop competitiveness and disrupt weed life cycles are foundational to IWM. Competitive rice cultivars with rapid early vigor, greater tillering capacity, taller plant stature, and broad leaf area suppress weed growth through shading and resource competition. Optimum plant density improves canopy closure and reduces light availability to weeds. Narrow row spacing accelerates canopy development and reduces weed establishment. Crop rotation (rice–wheat, rice–maize, rice–legume systems) disrupts weed life cycles and reduces dominance of species adapted to flooded environments. The stale seedbed technique—stimulating weed germination before planting, then eliminating emerged weeds through shallow tillage or non-selective herbicides—can substantially reduce early-season weed pressure (Mahajan et al. 2021).

8.3. Mechanical Weed Control

Mechanical control remains an important IWM component, particularly in labor-adequate regions. Hand weeding provides broad-spectrum control of grasses, sedges, and broadleaved weeds but is constrained by increasing labor costs. Mechanical weeders (rotary, cono, power, and inter-row cultivators) improve soil aeration while reducing weed populations. Tillage practices influence weed emergence and seed distribution within the soil profile through destruction of emerged weeds, burial of weed seeds, and disruption of vegetative propagules. Water management—particularly maintaining standing water in lowland rice—is one of the most effective physical weed suppression strategies, suppressing many grass weeds and reducing emergence of upland species, although aquatic weeds such as *M. vaginalis* may thrive under prolonged flooding.

8.4. Biological Weed Control

Biological control employs living organisms and their metabolites to suppress weed populations. Insect biocontrol agents have been investigated for invasive aquatic weeds. Fungal pathogens—including *Colletotrichum*, *Alternaria*, *Phoma*, and *Fusarium* spp.—represent promising candidates because of their host specificity and environmental compatibility. Mycoherbicides (formulations of plant-pathogenic fungi) offer environmentally friendly alternatives to synthetic herbicides, with advantages including target specificity, reduced environmental contamination, compatibility with IWM programs, and lower resistance risk. Advances in formulation technology (microencapsulation, wettable granules) have improved field performance and shelf life (Singh and Pandey, 2023; 2024). Combination products pairing bioherbicides with reduced doses of synthetic herbicides may provide synergistic control while reducing selection pressure (Kumar and Ladha 2011).

8.5. Chemical Weed Control

Herbicides remain the cornerstone of rice weed management because of their effectiveness, speed, and scalability. Pre-emergence herbicides (pretilachlor, butachlor, pendimethalin, oxadiargyl, pyrazosulfuron-ethyl) suppress weeds during early establishment stages when crop competition is weakest. Early post-emergence herbicides (penoxsulam, bispyribac-sodium, fenoxaprop-p-ethyl,

cyhalofop-butyl) target emerged weeds during the critical weed-free period. Post-emergence herbicides (2,4-D, metsulfuron-methyl, halosulfuron-methyl) provide targeted control of late-emerging weeds. Herbicide tank mixtures and premix formulations broaden the control spectrum and reduce resistance selection pressure. Rotation of herbicides with different modes of action is essential for managing resistance in intensive rice systems.
Commonly used herbicides for rice weed management, their application timing, and primary target weed groups are listed in Table 7.

Table 7. Major herbicides used in rice weed management, timing of application, and primary target weed groups.

Herbicide	Application Timing	Major Target Weeds
Pretilachlor	Pre-emergence	Grasses, sedges
Butachlor	Pre-emergence	Annual grasses
Pendimethalin	Pre-emergence	Grasses and broadleaves
Penoxsulam	Early post-emergence	Grasses, sedges, broadleaves
Bispyribac-sodium	Post-emergence	*Echinochloa* spp., sedges
Cyhalofop-butyl	Post-emergence	Grass weeds
Halosulfuron-methyl	Post-emergence	Sedges
2,4-D	Post-emergence	Broadleaved weeds

Source: Chauhan et al. 2017, Mahajan et al. (2021), Jabran and Chauhan (2022)

8.6. Precision and Smart Weed Management
Emerging digital technologies are transforming weed management in rice systems. UAV-based multispectral imagery enables early weed detection, spatial weed mapping, and variable-rate herbicide application, with studies reporting herbicide use reductions of 20–40% through site-specific management (Rao and Nagamani 2017). Deep-learning algorithms trained on hyperspectral field images achieve over 90% accuracy in classifying *Echinochloa* from rice at the three-leaf stage, approaching operational deployment (Li et al. 2024; Guo et al. 2024). Smart sprayers equipped with optical sensors allow real-time detection and targeted herbicide application, reducing costs and environmental contamination. Agricultural robotics platforms for autonomous mechanical weeding represent a further frontier for reducing herbicide dependence (Duckett et al. 2023).

IX. HERBICIDE RESISTANCE IN RICE WEEDS: MECHANISMS, GLOBAL STATUS, AND MANAGEMENT

Herbicide resistance is defined as the inherited ability of a weed biotype to survive and reproduce following exposure to a herbicide dose lethal to the wild-type population (Heap 2024). Resistance evolves through natural selection: rare individuals possessing genetic resistance traits reproduce and gradually dominate populations under continuous herbicide selection pressure (Powles and Yu 2010). Rice ecosystems are particularly vulnerable because weed management programs often depend on a limited number of herbicide groups. The widespread adoption of direct-seeded rice and labor-saving technologies has further increased herbicide dependence, intensifying selection pressure (Chauhan et al. 2017).

9.1. Mechanisms of Herbicide Resistance

Resistance mechanisms are classified as target-site resistance (TSR) or non-target-site resistance (NTSR). TSR occurs when mutations alter the herbicide target enzyme (ALS, ACCase, or EPSPS), reducing binding affinity and herbicide effectiveness—the predominant mechanism for ALS-inhibiting herbicide resistance, which is widely documented in rice weeds (Yu and Powles 2014). NTSR involves mechanisms that reduce herbicide concentration at the target site, including enhanced metabolic detoxification, reduced absorption, reduced translocation, and herbicide sequestration. NTSR is particularly concerning because it may confer cross-resistance to multiple herbicide classes simultaneously, limiting management options (Gaines et al. 2020).

9.2. Major Herbicide-Resistant Weed Species

E. crus-galli is among the most problematic resistant weeds globally, with resistance documented to ALS inhibitors, ACCase inhibitors, quinclorac, propanil, and multiple herbicide combinations across Asia, North America, and Europe (Heap 2024). Resistance in *E. colona* to glyphosate, ALS inhibitors, and ACCase inhibitors has expanded rapidly in Asian and Australian rice systems. *L. chinensis* has developed resistance to cyhalofop-butyl, penoxsulam, and ALS inhibitors in direct-seeded rice systems. *C. difformis* has evolved resistance primarily to ALS-inhibiting sulfonylurea herbicides through prolonged selection. ALS-resistant *M. vaginalis* populations have been reported in continuously flooded rice systems in several Asian countries, while emerging resistance in *F. miliacea* is increasingly documented (Vulchi et al. 2024; Heap 2024).

Herbicide-resistant weed species reported from rice ecosystems and their associated resistance mechanisms are summarized in Table 8.

Table 8. Major herbicide-resistant weed species in rice ecosystems.

Weed Species	Herbicide Group(s)	Resistance Type
Echinochloa crus-galli	ALS, ACCase, quinclorac	Multiple
Echinochloa colona	Glyphosate, ALS, ACCase	Multiple

Leptochloa chinensis	ALS, ACCase, cyhalofop-butyl	Multiple
Cyperus difformis	ALS inhibitors	Target-site
Monochoria vaginalis	ALS inhibitors	Target-site
Fimbristylis miliacea	ALS inhibitors	Emerging

Source: Heap (2024), Beckie et al. (2023), Vulchi et al. (2024).

9.3. Resistance Management Strategies

Effective resistance management integrates multiple complementary strategies: (i) herbicide rotation between different modes of action to reduce selection pressure; (ii) herbicide mixtures combining compounds with different target sites; (iii) IWM incorporating crop rotation, water management, mechanical control, competitive cultivars, and biological control to reduce herbicide dependence; (iv) prevention of seed production by resistant plants to limit population expansion and dispersal; and (v) regular resistance monitoring through field scouting and bioassays to enable early detection and timely management intervention (Beckie et al. 2023; Heap 2024). Economic losses attributable to herbicide resistance may exceed billions of dollars annually when resistant populations become established in major agricultural systems, underscoring the urgency of proactive management (Beckie et al. 2023).

X. FUTURE PERSPECTIVES

Several transformative technologies and research priorities will shape the future of weed management in rice ecosystems. Precision and digital agriculture platforms—particularly UAVs equipped with multispectral cameras for sub-meter resolution weed mapping enabling variable-rate herbicide application with 20–40% use reductions—are approaching commercial deployment (Rao and Nagamani 2017; Guo et al. 2024). Machine learning algorithms trained on hyperspectral imagery achieving over 90% accuracy for *Echinochloa*-rice discrimination at the three-leaf stage represent near-operational capabilities.

AI-assisted weed identification through deep-learning convolutional neural networks trained on large labelled field image datasets, deployed via smartphone-based diagnostic applications, offers transformative potential for farmer-level decision support in resource-limited settings (Li et al. 2024). Advanced bioherbicide formulations—microencapsulation and wettable granule technologies extending shelf life and improving field performance—combined with reduced-dose synthetic herbicide combinations, may provide synergistic weed control while reducing resistance selection pressure (Singh and Pandey 2024; Kumar and Ladha 2011).

RNA interference (RNAi)-based weed management—topically applied double-stranded RNA molecules targeting essential weed-specific genes—represents a novel, highly specific class of management tools currently under development, with proof-of-concept demonstrated against *C.*

rotundus in controlled environments (Rao and Nagamani 2017). Robotics platforms for autonomous mechanical weeding offer additional pathways to reduce herbicide dependence (Duckett et al. 2023). Nanotechnology-based herbicide delivery systems offer improved target specificity and reduced environmental persistence (Kah et al. 2023). Climate-smart weed management frameworks integrating predictive modelling of weed community responses to rising temperatures, altered precipitation, and elevated CO_2 concentrations will be essential for maintaining weed management efficacy under changing agricultural environments (Datta et al. 2023; FAO 2023).

XI. CONCLUSION

Rice ecosystems harbor a highly diverse and ecologically dynamic weed flora that continues to pose one of the greatest biological constraints to sustainable rice production worldwide. The twelve major species reviewed—*Echinochloa crus-galli*, *E. colona*, *Leptochloa chinensis*, *Cyperus rotundus*, *C. difformis*, *Fimbristylis miliacea*, *Eclipta prostrata*, *Ammannia baccifera*, *Acalypha indica*, *Monochoria vaginalis*, *Ludwigia parviflora*, and *Sphenoclea zeylanica*—exhibit remarkable ecological adaptability, reproductive plasticity, and competitive ability, enabling persistence across diverse production systems and contributing substantially to yield losses, reduced grain quality, and increased production costs.

Accurate early-stage identification remains the cornerstone of effective management. The diagnostic descriptions, comparative identification tables, dichotomous key, and morphological characteristics presented in this review provide practical tools for researchers, extension personnel, agronomists, and farmers to improve field-level weed recognition. The increasing prevalence of herbicide-resistant populations across all three major weed groups underscores the limitations of herbicide-dependent management and the critical necessity of diversified IWM approaches that reduce selection pressure and enhance agroecosystem resilience.

Emerging technologies in artificial intelligence, machine learning, remote sensing, UAVs, smart sprayers, robotics, molecular diagnostics, bioherbicides, and nanotechnology are enabling earlier detection, species-specific management, and more efficient use of control inputs. Future research should prioritize integrated, climate-resilient management strategies combining ecological knowledge with technological innovation, with emphasis on monitoring herbicide resistance evolution, improving biological control technologies, and strengthening interdisciplinary collaboration to address the increasingly complex weed management challenges of twenty-first-century rice production.

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