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REVIEW ARTICLE

Weed management in direct wet-seeded rice - A comprehensive review to higher productivity

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Abstract

This review examines various weed control strategies for Direct Seeded Rice systems. The diverse weed flora in DSR includes grasses (*Echinochloa colona*), sedges (*Cyperus iria*) and broadleaf weeds (*Ludwigia parviflora*) being prevalent. Integrated weed management combining cultural, mechanical, biological and chemical methods is recommended for sustainable control. Cultural practices such as stale seedbed techniques, crop rotations and flooding help suppress the growth of weeds. Mechanical methods, including hand weeding and the use of weeders, are effective but labour-intensive. Chemical control via pre-emergence (pretilachlor) and post-emergence (bispyribac-sodium) herbicides has shown promising results optimally. This review highlights that an integrated approach utilizing multiple complementary weed management tactics is essential for effective and sustainable weed control in direct-seeded rice. The proper timing of interventions, combinations of methods, and consideration of local conditions are essential factors. Although chemical herbicides are still valuable tools, there is a growing emphasis on reducing their use by integrating alternative methods. Overall, continued review of innovative biological and ecological approaches can further enhance the existing options for weed management in DSR systems.

Keywords

allelopathy; bispyribac sodium; herbicide tolerance; integrated weed management; pretilachlor

Introduction

Rice (*Oryza sativa* L.) is a major cereal crop worldwide, and its consumption is projected to reach 590 million tonnes by 2040. In India, rice accounts for 45% of total food grain production (1). DSR is an agricultural practice where rice seeds are sown directly into the field, as opposed to the traditional method where rice is first grown in nurseries and then transplanted into puddled fields. Compared with conventional transplanting, DSR is an increasingly important cultivation method with advantages such as reduced labour requirements and lower water usage (2). DSR uses 12-35% less water and labour, significantly lowers methane emissions by 10-90%, enhances soil physical conditions and reduces manual effort and production costs while delivering yields comparable to traditional methods. However, weed management remains a critical challenge in DSR systems, as the absence of standing water during crop establishment creates favourable conditions for weed growth (3).

DSR is emerging as a viable alternative, offering benefits such as higher water use efficiency, fewer labour requirements, lower costs and reduced soil disturbance. However, DSR faces significant weed management challenges, with potential yield losses of up to 100% due to weed infestation. Key problematic weed species include *Cyperus rotundus*, *Echinochloa crusgalli* and *Leptochloa mucronata*. These weeds compete with rice for nutrients, water and light, necessitating effective management strategies (3-5).

Integrated weed management approaches, which combine cultural, mechanical, chemical and biological methods, have shown promise in addressing this challenge (4). Cultural practices such as stale seedbed techniques and optimal water management can suppress weed growth. Chemical control *via* pre and post-emergence herbicides remains a crucial component of weed management in DSR (5). Additionally, emerging strategies such as using allelopathic rice cultivars (6) and herbicide-tolerant varieties (7) offer new possibilities for weed control.

This review aims to comprehensively examine various weed management strategies for direct wet-seeded rice, evaluating their efficacy, sustainability and potential for integration into IWM systems. The main objectives of this paper are to review studies and reports that provide reliable information on more effective and sustainable weed management practices in DSR cultivation. This study also addresses the importance of combining herbicides with hand weeding.

Methodology for Bibliometric analysis

Bibliographic information about weed and weed management, herbicide and direct seeded rice studies for 20 years (2006-2024) was downloaded from the Scopus database (Fig. 1. and Fig. 2.).

Review of direct-wet seeded rice

DSR, the oldest rice crop method, is established in the field directly instead of transplanting seedlings from a nursery. Based on land preparation, seedbed conditions, the seed environment and the sowing type, DSR can be classified into wet-DSR, dry-DSR and both wet-DSR and dry-DSR (8). DSR is the best alternative methodology to avoid limitations in transplanting methods, including transplanting shock (9). In dry DSR, seeds are broadcast into dry soil, whereas in wet DSR, seeds are broadcast in wet soil. Compared with transplanted rice, the DSR methodology increases productivity by 5-10% (10). The DSR method is more economical, as the cost of cultivation for DSR is lower than that of the transplanting method (9). However, DSR results in a low yield in the case of improper or poor establishment of crops and increases spikelet sterility due to the unavailability of the required quantity of water (11). Row seeding of germinated seeds can also be performed, but it is practiced on a limited scale because of the cost and difficulty in obtaining implementation.

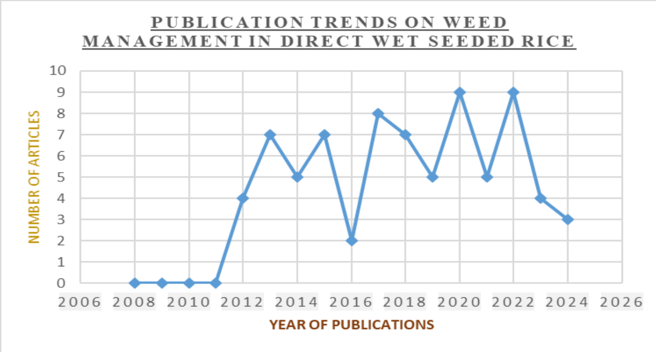

Fig. 2. Number of articles related to weed management in direct-wet seeded rice per year between 2006 and 2024; source: Scopus database document search portal accessed on March 15, 2024.

Weed flora associated with direct-seeded rice

Direct seeding leads to a shift in the distribution of weed species, especially *Echinochloa* spp., *Ishemum rugosum, Fimbristylis miliacea* and *Cyperus*, which differ from the specific environmental conditions associated with direct-seeded rice cultivation (12). Grasses such as *Echinochloa crusgalli, Echinochloa colonum* and *Cynodon dactylon* were the predominant weed flora observed in direct-seeded rice fields. Sedges such as *Cyperus iria, Cyperus rotundus* and *Fimbristylis*

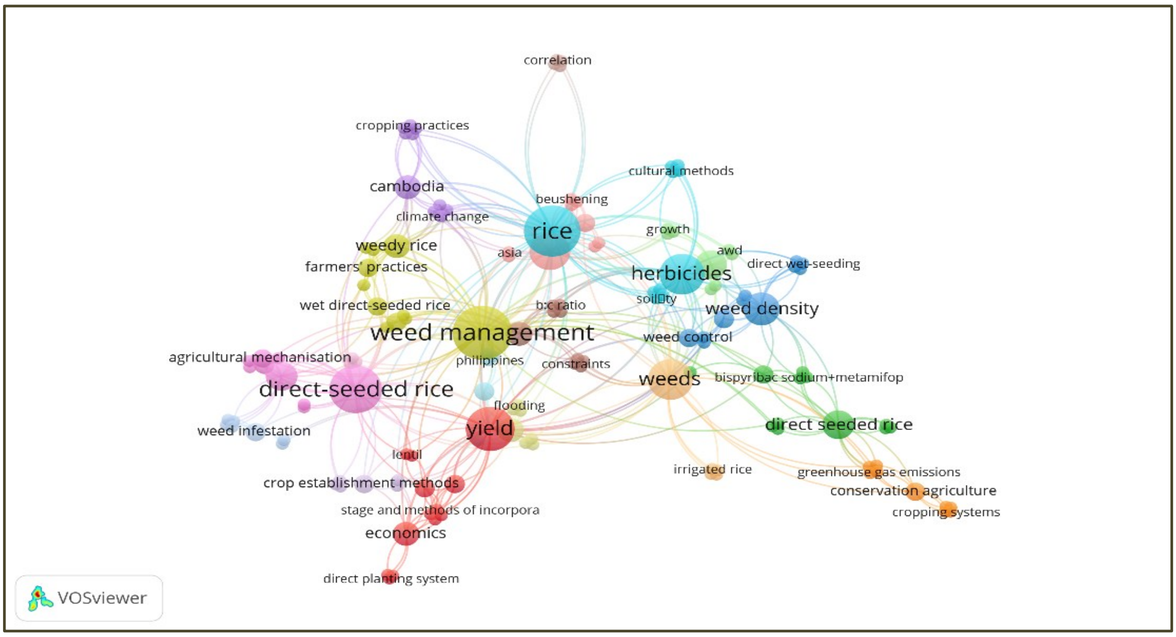

Fig. 1. Bibliographic analysis focused on weed management strategies and direct wet-seeded rice via author keywords. Co-occurrence analysis was performed with a minimum threshold of one occurrence, identifying 172 keywords that met this criterion.

miliacea were also commonly found in these areas. Additionally, broad-leaved weeds, such as *Caesulia axillaris* and *Eclipta alba,* were identified in the same agricultural context (13). The weed flora in DSR comprises grasses (*Echinochloa crusgalli, E. colona, Eluesine indicia, Leptochloa chinensis, Dactyloctenium Egyptian*), sedges (*C. iria, C. rotundus*) and broad-leaved weed (*Trianthema portulacastrum, Portulaca oleracea, Ipomoea aquatic*) (14).

With different crop establishment and weed control methods, significant variation occurs in the dominance of the abundant weed species (15). When rice is switched from transplanting rice to directly sowing it, there are variations in the amount of different weed species in the vegetation. Among the major weeds observed at 30 days post-transplantation, sedges such as *C. iria* and *F. miliacea* dominated, accounting for 47.0% of the total weed population. This was followed by broadleaf weeds such as *Sphenochlea zeylanica, Ludwigia parviflora and Commelina benghalensis,* which constituted 36.1% of the weed population and grasses, particularly *E. crusgalli*, which made up 16.9% of the total. However, during direct seeded rice (DSR) cultivation in Cuttack or Orissa, a different trend was observed, where broad leaf weeds, including *Ludwigia parviflora, Sphenochlea zeylanica, L. chinensis, Aeschynomene indica, Monochoria vaginalis, Limnophila heterophylla, Cleome viscosa* and *Melochia corchrifolia,* accounted for 43.2% of the weed population. This percentage was higher than the percentages of sedges (*C. iria, F. miliacea and Scirpus articulates*) (32.6%) and grasses (*E. colona and Panicum repens*) (24.2%) (16). Broad-leaved weeds (BLW), grasses and sedges comprise the diverse weed flora infecting direct-seeded rice farms. In terms of relative density, the majority of weed species found in DSR were *E. colona* (86.12%), followed by *F. miliaceae* (7.93%) and *L. chinensis* (3.28%). DSR promotes *E. colona* proliferation in *L. chinensis* (15).

Cultural methods for weed control

Weed growth is influenced by soil moisture, nutrients and pH, which create good weed growth conditions. Since DSR lacks continuous flooding, weeds can spread more efficiently than traditional rice. Temperature, light and plant spacing also affect how well weeds grow, as some species thrive better under specific conditions. Low crop density and poorly timed sowing or herbicide use can give weeds an advantage. The weed seed bank in the soil, built up from past farming practices, also affects how many weeds emerge in DSR fields.

Tillage and culture practices

Crop and weed competitiveness for aboveground and belowground resources is greatly influenced by cultural practices, which may influence weed control strategies (17). There are other cultural weed management techniques, such as levelling the field. By creating a weed-free seedbed for seeding, efficient land preparation can lower weed densities. The field must be levelled before any crops are sown to achieve a consistent crop stand. Using global positioning systems (GPSs) and/or laser-guided instrumentation, large tractors and soil movers can precisely modify the slope or level of the soil through cutting or filling. Laser ground levelling greatly improves crop establishment (18) and more effective use of herbicides and accurate water regulation could also be achieved (3).

Stale Seed Bed technique (SSB)

Before planting any crop, the stale seedbed (SSB) technique is another essential cultural management strategy used to reduce the weed seed bank. Weeds are encouraged to sprout in SSB by light irrigation or following a downpour. Nonselective herbicides such as glyphosate, shallow tillage, or flooding are subsequently used to destroy emerging weed seedlings. This technique reduces the number of weed seeds in the soil seed bank and inhibits weed emergence, also referred to as the soil weed seed bank (12). The preparation of the seedbed, removal of emerged weeds, types of weeds present, and duration of the stale seedbed period are all crucial factors that influence the effectiveness of the stale seedbed technique (19). Environmental conditions, such as temperature during the stale seedbed period, also play a significant role. Owing to their poor seed dormancy and restricted ability to emerge from depths above 1 cm, weed species are more susceptible to the stale seedbed approach (20).

Crop rotation

Crop rotation does several things, such as disrupting the cycle of weed seeds and making it easier to identify weedy rice, which leads to better control strategies. The efficacy of weedy rice management can be increased by rotating rice crops because it makes it possible to apply alternate pesticides and cultural treatments that are impractical for rice farming alone (21). In addition to suppressing weeds, sesbania co-culture has other benefits, such as fixing nitrogen in the atmosphere and assisting in crop emergence, especially in areas where problems with soil crust development are common (22). Sesbania co-culture was less effective against sedges and broadleaf weeds (BLW) than grasses. Pendimethalin is recommended for use in crop rotation to combat the problem of grassy weeds (2). In direct-seeded rice production, immersion is by far the most effective herbicide. Every type of weed has a maximum soil moisture content at which it cannot thrive. Hence, critical factors in suppressing weeds are the timing, depth and duration of flooding. Immersion inhibits weed germination and decreases the number of weeds that germinate. Problem weeds such as *L. chinensis* are suppressed in their emergence and growth by early and continuous flooding down to a shallow depth of 2 cm (23). Weed densities were higher in monoculture rice systems than in rice-maize rotations, especially during the early growth stages across all input systems. In organic systems, weed densities during the later stages of crop growth were similar to those in conventional and integrated systems. Overall, crop rotation combined with integrated nutrient management effectively suppressed weed density and biomass, utilizing various mechanisms within the system. Including an inter-season green manure crop in the rotation, particularly in conventional systems, effectively controlled weeds. Additionally, the inclusion of sunhemp in organic nutrient management systems significantly reduced grass biomass, contributing to weed compositional changes (24).

Chemical Weed Management in Direct Wet-Seeded Rice

Pre-emergence herbicides

During the past few decades, pretilachlor has been widely utilized for DSR weed management (25). Pre-emergence pretilachlor at 0.45 kg/ha at 5 DAS followed by manual weeding at 45 DAS and a post-emergence mixture of fenoxaprop + ethoxysulfuron at 45-60 g/ha + 10-18 g/ha were the most promising herbicides for aerobic rice (26).

The application of triasulfuron + pretilachlor (9 + 500 g/ha) during the rainy season in clay loam soil produced the maximum weed control efficacy (95.1%)(27). The application of the pre-emergence herbicide pretilachlor + safener @1 litre ha^{-1} followed by one-hand weeding at 30 DAS considerably increased the grain yield (5333 kg ha^{-1}) of rice (28). In the Philippines, weeds were successfully controlled under regulated irrigation via pretilachlor + safener applied at 0.3 kg a.i./ha and butachlor + safener applied at 0.75 kg a.i. ha^{-1} at 3 DAS. The rice crop exhibited the maximum uptake of nitrogen and phosphorus when triasulfuron + pretilachlor (0.009 + 0.5 kg/ha) was applied (29). Pretilachlor was used at a rate of 300 g ha^{-1} to suppress weeds from the grass, BLW and sedge groups (30). Additionally, it improved grain quality and decreased the biomass and number of weedy rice panicles (20-69%) and 15-26% (31). An effective and reasonably priced weed control strategy involves the use of pretilachlor as a pre-emergent and bispyribac sodium as a post-emergent. This suggests that the use of pretilachlor (the active ingredient) at 750 g a.i./ha on day 8 after sowing (DAS) and bispyribac sodium at 25 g a.i./ha on day 30 DAS for direct-sown drum-seeded rice could improve the effectiveness of weed control (26). It effectively combats a wide range of both annual and perennial weeds. It is a systemic herbicide for rice that acts pre- and early post-emergence (32). Using ethyl pyrazosulfuron@ 20 or 25 g/ha at 3 or 10 DAT significantly decreased the weed density and dry matter. Applying pyrazosulfuron ethyl @ 20 g/ha significantly increased the grain yield (4.45 t/ha) (33).

Post-emergence herbicides

Chemical weed management in direct wet-seeded rice plays a primary role in controlling weeds and helps increase crop yield (34, 35). Later management is closely related to weed control and decreases the phytotoxicity effect in rice (36). The increased toxicity of chemicals may lead to sterility in weeds. Farmers are searching for alternatives to manual weeding due to manpower shortages, increased labour costs and the pressing need to increase yields and maintain profitability in dwindling land resources. Effective weed control strategies are essential for DSR cultivation and herbicide treatment seems to be crucial (37). It has been reported that compared with weedicides, two-way hand weeding resulted in a lower weed density (38). In direct-seeded rice, ethoxysulfuron, cyhalofop-butyl, chlorimuron, metsulfuron, bispyribac sodium and penoxsulam have proven to be efficient post-emergence herbicides for controlling weeds (39). The application of Bispyribac two times, at 21 and 40 days after the completion of sowing, at a rate of 250 ml ha^{-1} or 200 g ha^{-1}, effectively controls weeds (such as grasses, BLW and sedges) in DSR and significantly increases the paddy yield (40). Although the differences were not always statistically significant among post-emergence herbicides such as bispyribac, penoxsulam and azimsulfuron, which generally reduce the density and dry weight of BLW and sedges at the 15 DAS stage compared with the 25 DAS stage of all herbicides, bispyribac 25 g ha^{-1} had the greatest effect on controlling *E. crus-galli* (41). *L. chinensis* is not effectively controlled by bispyribac-sodium, although it is quite effective against sedges and BLW, such as *E. crusgalli*, *Paspalum distichum* and *A. philoxeroides*. When barnyard grass is at the 3-5-leaf stage, applying 10% bispyribac-sodium SC at 225-450 ml/hm^2 with 450 L/hm^2 water is advised. Thiobencarb or fenoxaprop-p-ethyl should also occasionally be used to reduce *L. chinensis* (42).

Except for *L. chinensis,* early post-emergence application of bispyribac sodium at a rate of 20-40 g a.i./ha efficiently controls a wide range of weeds (43). It also enhances the water productivity and financial returns of directly planted rice (44). The most effective herbicidal treatment, bispyribac @ 25 g/ha administered at 15 or 25 DAT, was determined to produce a 41% increase in rice grain production over the weedy check. Furthermore, bispyribac did not exhibit phytotoxicity to rice or residual toxicity to a subsequent wheat crop (45). The highest weed control efficiency (85.7%), crop resistance index, herbicide efficiency index and lowest weed index were obtained with bispyribac sodium @ 30 g ha^{-1}. *D. sanguinalis, Commelina banghalensis and C. iria* were all successfully managed by bispyribac. In DSR, the application of bispyribac sodium + metamifop @ 90 g/ha as a post-emergence herbicide yielded the best net returns (Rs. 86238/ha), maximum grain yield (8051 kg/ha) and highest weed control efficacy (96.62%) (46).

In rice fields, weeds such as perennial grasses, annuals, sedges and BLW are effectively controlled by Bispyribac-sodium, a pyrimidinyl carboxy herbicide (47). The most effective weed-killing solution was bispyribac-sodium (20 and 25 g/ha), which was applied either at the 1-3-leaf or 4-6-leaf stage, when the weeds presented the lowest biomass and density (48). Using pendimethalin at 1.0 kg ha^{-1} before applying bispyribac sodium at 25 g/ha + pyrazosulfuron at 25 g/ha post-emergence produced the best results in terms of weed control efficiency (91.8%), weed control index (88.0%) and herbicide efficiency index (23.65%). The weed index obtained the lowest yield (1.20%) (49). During the reproductive stage of the crop, early post-emergence (EPOE) treatment with bispyribac sodium (10% SC, 40 g/ha) reduced weed density, increased weed control efficacy. It yielded a substantial amount of grain (5058 kg/ha) (50).

Herbicide tolerance

Herbicide-tolerant (HT) crops exhibit tolerance to a specific herbicide or a group of herbicides that would otherwise impact the crop. Any viable weedy rice plants that survive herbicide treatment should be promptly removed from the field to prevent selection pressure (51). The focus of developing herbicide tolerance in rice is to effectively and selectively control the emergence of large quantities of weeds, particularly weedy rice. In the context of DSR systems, HT rice has proven to be a viable, economical and practical long-term solution for weed management. Several crops have utilized different mechanisms to exploit the selectivity of various herbicides to develop HTs (7). The imidazolinone group of herbicides is extensively used in transgenic and non-transgenic approaches (52). Clearfield, a non-transgenic HT rice production technology, has been successfully introduced through induced mutation breeding in the United States, effectively countering numerous herbicides (53).

In the early 21st century, a resistant line (93-AS-3510) against acetolactate synthase (ALS) was discovered in a single surviving rice plant after a chemical mutation (54). The rice cultivars Clearfield 121 and Clearfield 141 in the United States and IRGA 422 CL in Brazil were subsequently developed by transferring the gene mutation G654E (55). In India, herbicide-tolerant (HT) rice varieties have not yet been widely commercialized, although research and development in this area have been progressing. The situation around herbicide tolerance in rice, primarily genetically modified (GM) crops, is nuanced and has both regulatory and scientific dimensions. Imidazolinone herbicides are broad-spectrum POST herbicides, allowing for flexible dosages depending on the extent of weed infestation and multiple applications can be performed (56). These herbicides are highly effective at low doses and are easily decomposable, resulting in minimal release of herbicides into the environment. However, when conventional weed suppression methods fail to yield practical results, HT rice has emerged as a promising alternative. Two additional transgenic HT rice lines, Liberty Link and Roundup Ready, have also been developed to combat glufosinate and glyphosate. This technology offers the potential for targeted control of weedy rice. However, the possibility of gene flow from HT rice to weedy rice poses a significant obstacle to its long-term use. Although the likelihood of natural outcrossing among rice plants in Clearfield lines is less than 1%, and it is extensively cultivated in Europe, Brazil and the United States (57), gene flow may still occur and propagate (58).

Mechanical Weed Management in DSR

Effective weed management for direct wet-seeded rice is possible by adopting various strategies, including mechanical management, chemical management, biocontrol agents and cultural methods. Among these techniques, machinery effectively controls and suppresses weed growth in direct wet-seeded rice fields. By using machines, such as rotary weeders and mechanical seeders, farmers can effectively control weed growth without relying solely on labour-intensive manual weeding (3), which saves time and labour costs. Weeds within rows are not controlled by mechanical weeders, which are used for weed control between rows. Enough moisture in the soil during weeding is essential to improve the effectiveness of mechanical weeders. Hand-pushed cono-weeders take much time and effort, yet they are still widely used in many eastern Indian locations. Using rice power weeders that run on gasoline or diesel, farmers in east India have recently expressed interest in robotic weeding. In DSR fields, a two-row rice power weeder can finish weeding an acre in two to three hours, depending on the density of the weeds. Additionally, mechanical weed management can help reduce the reliance on herbicides, addressing concerns about herbicide resistance and environmental impact. Furthermore, incorporating mechanical weed management into direct wet-seeded rice cultivation systems can improve weed control and increase crop yields (59).

Mechanical weed control and hoeing can potentially inhibit the growth of weeds and increase the grain yield in DSR (12). Manual pulling and mechanical hoeing have demonstrated superior weed suppression and yield improvement compared to herbicides. Manual pulling resulted in a significant 30% increase in grain yield compared with the control, whereas mechanical hoeing achieved a 25% increase. Hand weeding (HW) is the most effective approach for managing annual and certain perennial weeds that do not typically regenerate from underground parts (60). Typically, 2-3 manual weeding sessions at appropriate stages have proven to be effective in achieving the desired level of weed control in DSR. The initial weeding should be conducted at 20-25 DAS for dry-seeded rice and 25-30 DAS for wet-seeded rice, followed by a second weeding at 45-50 DAS. Additional weeding sessions may be needed depending on the specific field conditions. In areas with high rainfall, three weeding sessions at 15, 30, and 60 DAS presented comparable grain yields to those obtained from a weed-free crop throughout the season. Two weeding sessions at 15 or 30 DAS, or 15 and 45 DAS, yielded relatively high net returns (61). In India, under lowland conditions, hand weeding in a DSR field typically takes approximately 200-250 hours per hectare, depending on the extent of weed infestation (62).

Advanced Weed Management Strategies for DSR

Biological control

Biological weed management in rice cultivation involves using natural mechanisms, such as beneficial organisms and ecological practices, to control weed populations while promoting crop growth. This approach is part of integrated weed management (IWM) and seeks to minimize the use of synthetic herbicides (63). In the United States, *Puccinia canaliculata*, a rust fungus, is currently being developed and commercialized to suppress yellow nut sedge (64). The irrigated lowland rice-fish farming system effectively suppressed *F. miliacea, C. iria* and *S. maritimus* when it included both common carp and grass carp (65). Herbivorous fish species, such as carp and tilapia, feed on young, tender aquatic plants, including many weed species that may compete with rice. By consuming these weeds, fish help reduce their biomass and prevent them from establishing and proliferating. Selective grazing behaviour of fish can selectively graze on specific weed species while leaving rice plants unharmed, especially if the rice plants are larger and more established than the weeds (66).

The beneficial fungi *Exserohilum monocerus* and *Cocholiobolus lunatus* have also been effective in barnyard grass biocontrol (67). In addition to traditional methods, the biological process of weed control offers an environmentally benign approach. It entails intentionally applying bacteria, fungi, nematodes, insects, or other bioagents that suppress weed growth. In certain countries, various herbivorous bioagents, such as fish, tadpoles, shrimp, ducks and pigs, are employed to manage weeds in irrigated lowland rice. Research is currently being conducted on using mycoherbicides for weed management to reduce reliance on herbicides. *E. monocerus* and *Cochliobolus lunatus* are the most promising fungi for barnyard grass biocontrol. Moreover, *L. chinensis* may be successfully controlled by *Setosphaeria* sp. *Cf. rostrata* without endangering the rice plants (68). The improvement in yield-related components may result from reduced weed competition for these factors during the crop growth period. This is because early -emerging weeds are controlled before sowing through pre-emergence herbicide application and late-emerging weeds are controlled through hand weeding and post-emergence herbicide application.

Allelopathy

Allelopathy is the term used to describe a plants' ability to either stimulate or inhibit another plant by releasing chemicals into the environment (69). This concept has potential application in agriculture as a substitute for synthetic herbicides since it was introduced nearly a century ago (6). Using allelopathy as a weed management approach to increase a crops ability to compete with nearby plants is a promising strategy to reduce production losses caused by weeds in rice and other crops. In both natural and agricultural settings, various processes release allelochemicals from plant parts, including volatilization from leaves, secretion from roots, drainage from leaves or ground debris and residue breakdown (70). Allelochemicals can alter the rhizospheres soil properties by altering the microbial community or inhibiting the germination, development, and establishment of nearby plants once released (71). The development, yield and characteristics of plants belonging to a shared crop family may be influenced by the allelochemicals generated by a specific crop species (72). Allelopathy is a trait observed in herbs, grasses, and important crops that belong to the Poaceae family. This phenomenon seems to represent a more effective and enduring approach to ensuring the protection of the area (73). Allelochemicals synthesized by rice varieties are anticipated to impact the nitrogen absorption of adjacent plants, thereby modifying the shoot length growth of the plants under investigation. Allelopathy is the ability of some plant species to synthesize and exude specialized metabolites into the soil that prevent surrounding plants from germinating or growing, which might be viewed as a chemical arms race.

To effectively manage weeds in crop fields, allelopathy must meet three key requirements. Initially, at naturally secreted concentrations, allelochemicals must exhibit a potent selective inhibitory effect on the target plant or weed species (74). Second, crop plants need to tolerate or resist allelochemicals. Third, soil-based allelochemicals should not have broader effects on the environment, such as harming a variety of non-target species, such as fungi, insects, or small animals (75,76). Traditionally, studies on allelopathy have concentrated on determining the phytotoxic potential of plant leftovers or unrefined extracts (77). The allelopathic impact of rice species results in low germination of barnyard grass when treated with allelopathic rice accessions. These effects may be caused by the allelochemicals released from the rice variety, which affected both the germination and the growth of the roots of the barnyard grass *E. crusgalli* by more than 75%. Moreover, the root exudates of allelopathic rice accessions presented the greatest inhibitory effects on certain traits of barnyard grass seedlings.

Types and Effects of Allelochemicals

Bacteria create allelochemicals during decomposition or by plants as secondary metabolites. On the basis of their molecular similarity, allelochemicals can be divided into 14 types (78). Straight-chain alcohols, aliphatic aldehydes, ketones and other organic compounds, such as simple unsaturated lactones, polyacetylenes, benzoquinone and anthraquinone, as well as more intricate substances, such as complex quinones, simple phenols, benzoic acid derivatives, coumarin, cinnamic acid, flavonoids, tannins, terpenoids, steroids, amino acids, peptides, alkaloids, cyanohydrins, sulfides, glucosinolates, purines and nucleosides, represent a selection of solutes that exhibit water solubility within the 14 specified categories (79). Allosteric substances include gibberellic acid, ethylene and salicylic acid, which are known to inhibit plant development. The efficacy, absorption and mechanism of action of allelochemicals differ (80).

Many of the described allelochemicals still have unknown mechanisms of action. Numerous allelochemicals possess mechanisms not found in synthetic herbicides, which can lead researchers to new avenues of action (81). Although many allelochemicals have low or unknown efficacy and selectivity (82), they are suitable substitutes for synthetic herbicides (56). Rice allelopathy may be used more extensively for weed management if more research is conducted on the extraction of allelochemicals from allelopathic rice cultivars and a comprehensive analysis of their mechanism of action. Researchers discovered 191 rice accessions with clearly noticeable allelopathic activity in a field experiment in which 5,000 rice accessions were used for allelopathic activity on duck salad (83). According to (84), 45 out of the 1,000 examined rice cultivars exhibited allelopathic activity against monochorea (*Monochoria vaginalis (Burm. f.) C. Presl*). According to the "evaluation of 749 rice cultivars' allelopathic capabilities, the japonica rice cultivar had a greater ability to inhibit the root growth of barnyard grass". Rice extracts have been shown to contain numerous phytotoxic chemicals from various chemical classes, including fatty acids, benzoxazinoids, indoles, phenolic acids, phenylalkanoic acids and terpenoids (85). Momilactone B and tricin are the main allelochemicals in allelopathic rice cultivars (86). Rice residues under wet conditions contain several phenolic acids, including p-hydroxybenzoic, vanillic, ferulic, o-hydroxy phenylacetic and syringic acids (87).

Integrated Weed Management (IWM)

Realizing the shortcomings of chemical-based weed management techniques led to the idea of Integrated Weed Management. To sustainably manage weeds in rice fields, IWM combines chemical, mechanical, biological and cultural methods (88). Weed communities are highly susceptible to management techniques and environmental factors, making combining diverse technologies essential for successful weed control (4). However, not all agronomic instruments could work

Table 1. Diverse weed flora prevailing in the rice ecosystem

Weed type	Weed species	References
Grasses	*E. colona* (L.), *E. crus-galli* (L.) *P. Beauv., Leptochloa chinensis* (L.) *Nees, Oryza sativa L. f. spontanea Roshev, Ischaemum rugosum Salisb, C. dactylon, Panicum repens, Leersia hexandra, Digitaria ciliaris* and *Barcheria ramose*	(5) (12)
Sedges	*C. iria* (L.), *C. difformis* (L.), *Schoenoplectus juncoides (Roxb.) Palla, C. rotundus,* and *F. miliacea*	(15)
Broadleaf weed	*Ludwigia hyssopifolia, Ludwigia linifolia*, *Spheoclea zeylanica Gaertner, Ageratum houstonianum, Monochoria vaginalis, Borrelia articularis, Eclipta prostrate* (L.), *C. axillaris, E. alba, A. sessilis, Ammannia baccifera, Caesulia argentia, Cleome viscosa, Comelina beghalensis C.communis, Cyanotis axillaris* and *Digera arvensis*	(13) (15) (12)

equally well with every type of weed or crop. Increased seeding rates, spring fertilizer applications and carefully timed herbicide applications proved to be an effective weed control method that preserved high yields. This coordinated strategy maintained ideal crop productivity while successfully controlling weeds (89).

Future progress in weed management should focus on Precision Agriculture Technologies, such as Remote Sensing and Variable Rate Technology (VRT). Using satellite imagery and drone technology enables farmers to accurately monitor weed populations, identify weed hotspots and assess the effectiveness of management practices, facilitating targeted interventions. VRT allows for the precise application of herbicides based on specific weed pressure in different field areas, reducing overall chemical use while ensuring effective control (90).

Conclusion

Weeds lead to significant reductions in rice yields and increased cultivation costs. Grasses, sedges and broadleaf weeds make up the diverse weed flora in direct wet-seeded rice. The species include E. colona, C. iria and Ludwigia parviflora. Integrated weed management combining cultural, mechanical, biological and chemical methods is essential for sustainable and effective control. This balances the weed community and reduces reliance on chemicals.

Promising new strategies include using allelopathic rice cultivars that suppress weeds through released chemicals. Herbicide-tolerant varieties also allow better control of weedy rice. Biological control with herbivorous fish and fungi offers environmental benefits. Effective options exist for chemical weed management in direct wet-seeded rice.

The herbicides found effective include bispyribac-sodium, pyrazosulfuron-ethyl and pretilachlor. Timing of application and combinations are important considerations. Cultural practices like stale seedbed techniques, crop rotations and flooding help suppress weeds. Mechanical weeders and manual weeding also play a crucial role despite labour requirements and costs.

In conclusion, an integrated approach with multiple weed management strategies is required for effective and sustainable control of direct wet-seeded rice. Further research on novel biological methods can enhance existing options for weed control.

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Authors' contributions

TV and PG conceived the idea for this manuscript. TV conducted the literature review and drafted the initial manuscript. SM, GM, BV, PP, TK and MV provided critical feedback and revisions to the manuscript. TV and PG prepared the final version of the manuscript. All authors read and approved the final manuscript for submission.

Compliance with ethical standards

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