Review

Weed Management in Dry Direct-Seeded Rice: A Review on Challenges and Opportunities for Sustainable Rice Production

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Abstract: Rice cultivation always remains significant for food and livelihood security. The predictions of increasing water deficiency under a changing climate and escalating labor shortages in agriculture have brought a paradigm swing in rice cultivation from conventionally flooded transplanting to direct-seeded rice (DSR). DSR cultivation can potentially address the concerns of diminishing natural resources and mounting production costs in the establishment of transplanted rice. The transition towards DSR saves water, reduces duration to maturity as well as labor required, and reduces negative environmental footprints. Despite all these recompenses, the potential yield losses through enormous weed menaces under DSR remains a challenge and may reduce yield by up to 50%. In this review, we examine the extent of weed infestation, weed shift and the losses in dry DSR (DDSR). Various regional and global scientific efforts made under DDSR have been assessed in the present and the smart weed-management strategies suggested can be adopted after scrutiny. Integration of different weed management approaches, namely prevention, cultural, mechanical, and chemical, have been discussed, which can pave the way for worldwide adoption of DDSR, especially in South Asia. In Asia, 22% of the acreage of total rice cultivation is under DSR and the region-specific integration of these weed-management approaches might reduce herbicide use in these areas by up to 50%.

Keywords: dry direct-seeded rice; establishment method; integrated weed management; herbicide-tolerant rice; weed menace; weedy rice

1. Introduction

Rice (Oryza sativa L.) is a primary food crop grown widely over 161 million hectares in more than 100 countries of the world [1]. Almost 90% of the world’s rice is produced and consumed in Asia to provide up to three-fourths of the total calories required by 520 million Asians [2]. A whopping 26% and 50% increase is demanded in global rice production to meet the requirements of the burgeoning population by 2035 and 2050, respectively [3]. China and India share 28% and 22% of the total global rice production, respectively. Several constraints involved with transplanted puddled rice (TPR), namely a huge water demand (1000–2000 mm) for puddling and maintaining continuous flooding [4]; a huge energy requirement ranging between 5630–8448 MJ ha⁻¹ [5] and almost 15–20% higher labor inputs [6] over direct-seeded rice (DSR), have made it unaffordable for many farmers, especially for small and marginal farmers in Southeast Asia [7].

Furthermore, repeated plowing for puddling breaks capillary pores, disperses clay particles, and destroys aggregate stability in the topsoil, resulting in a hardpan creation at the shallow depth [8]. Dry direct-seeded rice (DDSR) is an impending version of upland rice cultivation practiced widely to
save water, labor and energy over TPR. The rice crop is established by sowing the seeds directly in the non-puddled and non-saturated soil [9]. DDSR can be adopted both as upland rice and aerobic rice [10]. The advantages offered by DDSR, namely rapid planting, easy mechanization, less labor and water requirement, and early maturity with fewer environmental footprints have brought almost 22% of the total rice area in Asia under DSR [11,12]. In fact, DDSR is one of the oldest methods of rice establishment and before the 1950s it was very popular but was gradually replaced by TPR [13]. The traditional rain-fed systems of rice cultivation instinctively fall under DSR [14]. However, the non-conventional areas of rice cultivation like the trans-Indo Gangetic Plains (IGP) of India have also reported yield enhancement and water-saving under DDSR [15] followed by yield increment in the subsequent wheat crop also under the rice-wheat system [16].

Variable yield response and water productivity in DDSR has been reported by numerous researchers worldwide depending on location and the type of agronomic management adopted. The rice productivity over 7 t ha\(^{-1}\) under DDSR with good agronomic management was reported by International Rice Research Institute (IRRI) back in the early 1970s in the Philippines and Peru [17,18] and then from 8.4 t ha\(^{-1}\) to even 10.3 t ha\(^{-1}\) across the world [19,20].

Despite these recompenses, the major snag with practicing DDSR is the potential biotic threat posed by weeds. The yield losses under DDSR are estimated as high as 75%, which exhausts more than 30% of the total cost incurred in rice cultivation [14]. The concurrent crop and weed growth and the absence of standing water in the initial crop establishment phase aggravate weed insurgence in DDSR [21]. Under these systems, weeds could be managed by hand weeding (manual means), through herbicides or by a combination of both. However, chemical weed management is replacing manual weeding due to meagre labor availability, escalating labor costs and drudgery involved. The newer low dose high-efficacy herbicides are convenient and have made DDSR viable, especially with high-yielding short-duration varieties [22]. However, there has been grave apprehension about the solitary use of herbicides in the recent past due to the development of resistance in weeds, changes in the weed density and composition, and the emerging negative environmental footprints. Amidst these concerns, adoption of any single approach remains both insufficient and ineffective for sustainable weed management in DDSR and the present review emphasizes integrated weed management practices for DDSR. We have also attempted to identify opportunities for the plausible integration of region-specific weed management in an economic and effective way to reap the benefits offered by DSR.

2. Dry Direct-Seeded Rice (DDSR) Establishment Methods

Globally, out of the total 161 M ha under paddy cultivation, DSR is being practiced on about 33 M ha area [23]. DDSR could be practiced in rain-fed upland, lowland, and also flood-prone areas [24]. Different methods of sowing under DDSR include broadcasting of dry seeds directly, either after field preparation (conventional tillage, CT) or zero tillage (ZT), and mixed thereafter with a harrow; dibbling of sprouted seeds after seedbed preparation, especially in hilly terrain or line sowing at the rate of 70–80 kg ha\(^{-1}\) through a seed-cum-fertilizer seed drill after ZT, CT, reduced tillage or on raised beds [25]. DDSR in most Asian countries is kept aerobic through alternate wetting and drying under rain-fed upland ecosystems in place of continuous submergence or saturation. Under double DDSR, cycling dry and wet tillage is also practiced in Asia [26]; however, exclusive DDSR is practiced in the United States, Latin America, Australia, West Africa and Europe [27].

3. Weed Menace in DDSR

The aerobic soil environment in DDSR saves water, but with the absence of stagnating water and the lack of a ‘head start’ in rice seedlings over germinating weed seedlings; the weed menace in DSR is aggravated. The critical period of weed competition in DDSR remains up to 41 days after sowing (DAS), yet a weed-free situation until 70 DAS remains desirable for higher productivity [28]. Weeds, when not controlled during this period, may reduce yields from 15–100% [29]. The intense competition for water, nutrients and solar radiation posed by weeds reduces yield and grain quality. Poor weed control
is the second major yield barrier after an inadequate water supply in DDSR worldwide, the range of maximum and minimum yield losses, however, differs under varying ecologies as illustrated in Figure 1. The yield losses remain higher under DDSR over TPR. An approximate 35% yield loss has been reported in TPR [30], however, under DDSR it may reach as high as 100% [14]. Out of the total 40% yield loss in rice caused by various pests, weeds create nearly 10% of the yield loss, which under DDSR may go up to 32%. Thus, weed management shares a very high relative importance, ranking among different agronomic management options for higher productivity in DDSR [31].

Figure 1. The extent of yield losses due to weeds in major dry direct-seeded rice (DDSR) growing ecologies of the world (Source: [14]).

4. Weedy Rice Peril in DDSR

The pernicious weed, weedy (red) rice (*O. sativa* f. *spontanea*) has occupied the status of pest species on the transition from TPR to DDSR in many Asian countries and almost all rice cultivating ecologies of America and Africa [32]. Yield losses of up to 50% in DDSR due to weedy rice has been reported in Portugal and Spain [33]. Its infestation in major rice-growing countries causing quantitative and qualitative losses to rice production has been widely reported by several researchers in India, China, Sri Lanka and Korea [34], Thailand and Malaysia [35], and the Philippines [36]. Weedy rice has been a major constraint for more than five decades in Europe and the Mediterranean region [37].

The phylogenetic and evolutionary similarities, a congeneric relationship of weedy rice with cultivated rice, prolific seed production capacity, prolonged seed dormancy, high vigor, and aggressiveness have made weedy rice a voracious competitor in cultivated areas [38]. Seed dormancy for more than 10 years in soil under adverse conditions and the capability to produce high biomass along with high tillering potential and tall stature once germinated are special adaptations in weedy rice [39]. Weedy rice is capable of nutrient exhaustion from the rhizosphere due to its fine and long roots [40].

5. DDSR Adoption and Weed Shift

Initially, the weed composition in DSR may remain similar to that in TPR, but over time a noteworthy shift in the weed flora towards greater species-rich vegetation, especially grassy weeds, has been reported [15]. Generally, the weed species diversity in DDSR fields remains greater than TPR [41]. In a long-term study, total weed species, genera and families infested were 21, 18 and 13, respectively, under TPR; however, under DDSR, 50 weed species and 18 genera belonging to 22 different families were observed [42]. Alterations in agronomic management, mainly for crop establishment and irrigation under DDSR, alter the weed demographic composition and diversity. A more diverse and difficult to control grassy weed flora is seen in DDSR than in CT-TPR [41]. Southeast Asian regions, in particular, have rich weed species ecologies due to a more conducive climate for the emergence of
diverse weed flora [14]. A shift in the rice establishment method almost doubled the diversity index of weed flora in Korea [43]. A 2.5 and 4.75 times increase in the number of grassy and broadleaved weed species, respectively, was recorded from India [43]. The alteration in weed seed bank build up under DDSR depends upon the micro-environment attributed to the sowing method, i.e., with or without tillage. Tillage has an impact on weed seed distribution in soil profiles; however, under ZT, the seed prevalence, germination and emergence are from the upper soil profile only [44].

In Southeast Asia, a weed flora shift in DDSR has been reported towards more aggressive competitive grasses and sedges. In long-term field studies with DSR, initially the presence of weedy rice and Leptochloa chinensis (L.) Nees. remained very meagre but they appeared after only 2 and 4 years, respectively. Broadleaf weeds remained dominant initially under DSR, but after a decade of DSR cultivation, grassy weeds like Echinochloa crus-galli (L.) P. Beauv, L. chinensis and Ischaemum rugosum Salisb. became dominant in Malaysia [34] and Vietnam [45]. The most dominant grassy weed under DDSR was E. crus-galli, and the four most dominant sedges were Fimbristylis miliacea (L.) Vahl, Cyperus rotundus L., Cyperus iria L. and Cyperus difformis L. in the Indian subcontinent [46].

6. Weed-Management Options

The contemporaneous crop and weed growth and absence of stagnant water aggravate weed menaces under DDSR [47]. An over-reliance on chemical weed management for abundant and diverse weed flora belonging to different taxonomic classes under DDSR will be catastrophic. Use of a single herbicide for weed control targeting a single weed species like weedy rice in DDSR results in a buildup of herbicide resistance in weeds [48]. To avoid yield losses, the threshold for weed density in rice is 1–3 weeds m\(^{-2}\) [49]. Such effective weed management can never be achieved with a single approach and hence integrated weed management (IWM) aiming at the combination of at least two components remains desirable under DDSR [50].

An effective IWM strategy using weed biology in the management system protects crops from weed competition and may even suppress weeds [51]. The fundamental components of IWM include preventive, mechanical, cultural, chemical and biological control methods [52]. Various approaches of IWM involve good agronomic practices, namely stale seedbed practices, selection of cropping systems, crop rotation, use of competitive cultivars, and herbicide rotation. These practices are necessary for responding to weed shifts under DSR as illustrated in Figure 2.

Figure 2. Integration of different management approaches for effective weed control in DDSR (Source: [33]). BMFs: best management practices.
6.1. Preventive Methods of Weed Management

6.1.1. Prevention of Weed Seed Dispersal

Preventive weed-management practices aim more at minimizing weed seed banks and check the entry of new weeds in crop fields to prevent further infestation. Faulty agronomic practices often permit entry of new weed seeds in crop fields, leading to a buildup of huge weed seed banks in the soils. Preventive measures compliment curative tactics like the use of herbicides by restricting weed dispersal and preventing weed seed bank build up. The key weed species of rice are often dispersed through natural means (animal, human, mechanical, etc.). The zero weed seed rain approach is more economic and feasible than control strategies [54]. Prolific seed production, dormancy found in weed seeds and variable maturity periods make crop-weed competition more serious. For instance, a common rice weed *Caesulia axillaris* Roxb. is capable of producing mature seeds even after the removal of the crop. The existing weed seed banks exhaust due to preventive methods by induced predation, fatal germination and decay due to tillage and submergence [55].

6.1.2. Prevention of Crop Seed Contamination with Weed Seeds

The most vital and practical preventative measure for reducing the weed intensity in DDSR remains the use of clean and weed-seed free crop seeds. Many weeds like *E. colona* mature simultaneously with rice and often get mixed while harvesting and threshing [56]. The contaminated weed seeds will also spread herbicide resistance [57], besides introducing new species. An important rice weed, *L. chinesis* has reportedly been introduced in northern Italy through contaminated seeds [58]. The prevention of weed seed contamination in DSR becomes more important than in TPR as a higher seeding rate is used per unit of area under DSR.

6.2. Cultural Weed Management

6.2.1. Stale Seedbed

Stale seedbed (SSB) is a cultural method of weed management commonly practiced with tillage, but under ZT-DDSR the emerged weed seedlings are destroyed with an application of a nonselective post-emergence herbicide, either paraquat [59] or glyphosate [60]. The majority of the weed seeds remain on or close to the soil surface under DDSR, thus resulting in a higher germination percentage when induced via. irrigation [61].

SSB is a very effective weed management practice against weedy rice [62] and reduces up to 53% of weedy rice over the control [63]. A significant reduction of 25–30% in the viable seed bank of *E. colona* and *Dactyloctenium aegyptium* L. (Willd) [59], and 13–33% reductions in the overall seed bank after rice harvest have been recorded [64]. Likewise, in one year, a 2- and 1.6-fold increase in *C. rotundus* density was recorded due to SSB with glyphosate over SSB with tillage [64]. Thus, killing weeds with herbicides also reduces labor input by 30–60% [65]. Weed species, such as *Digitaria ciliaris* (Retz.) Koel., *L. chinesis* and *Eclipta prostrata* (L.) L., have small seeds which are often present in the upper soil layer. Low dormancy in seeds enables quick germination after irrigation and exposure to sunlight [66]. SSB is also effective against weeds like *Eclipta prostrata*, *C. diffornis*, *F. milieacea*, and *Euphorbia hirta* L., but species like *Amaranthus spinosus* L., *Eleusine indica* (L.) Gaertn., *Echinochloa colona* L. (Link), and *I. rugosum* need stimulation for germination [67]. Whereas, germination of seeds with hard seed coat like *Commelina benghalensis* L., *Cyperus diffusa*, *Corchorus olitorius* L., *Mimosa invisa* L. and *Mimosa pudica* L. remains difficult with SSB [68].

The high base temperature and exposure to light on the soil surface under DDSR stimulated biochemical processes for germination in weeds such as *Portulaca oleracea* L., *Cyperus iria*, *F. milieacea*, *Digitaria longifolia* (L.) Scop., *Digitaria. Ciliaris* (Retz.) Koeler, *Cyperus diformis*, *L. chinesis*, *Echinochloa colona*, *Echinochloa crus-galli*, *Eclipta prostrata*, *Chromolaena odorata* (L.) R.M. King and H. Rob., *Tridax procumbens* L., *Celosia argentea* L. Kuntze, and *Ludwigia hyssopifolia* L., which can be subsequently
killed by a false seedbed [66,69]. Practicing SSB after one and two irrigations with a successive application of herbicides reduced weed density by 44–68% and 77–85%, respectively, over a control in India [70]. Likewise, in California, a 75%, 94% and 91% reduction in the biomass of *Echinochloa* spp., *S. mucronatus* (L.) J.Jung and H.K. Choi and *C. difformis*, respectively, was recorded with SSB [71,72]. In DDSR, SSB followed by shallow plowing after two weeks resulted in an 80% and 40% reduction in the density and weed biomass, respectively [73]. The weed seed bank depletion due to SSB provides a less competitive environment for rice during the initial stage [74]. Brainard et al. (2013) [75] have also reported a decline in the density of grassy weed and *C. rotundus* by 42–67% and 22–51%, respectively, with SSB. The seed bank depletion of *E. colona* and *D. aegyptium* with SSB provides a competitive advantage to rice [15].

The SSB practice with bispyribac-sodium as a sequential post-emergence (POST) herbicide remains desirable under double DDSR; however, a short turn around period for the sowing of a succeeding rice crop may be delayed due to SSB [76].

6.2.2. Land Preparation

Tillage operations may provide a competitive advantage to crops and suppress weed emergence and growth by delivering weed-free conditions at planting by uprooting and burial of weeds [31]. Tillage may cause weed seedling mortality from the upper soil profile and induce dormancy in the buried weed seeds due to alteration in edaphic conditions, water and gaseous regimes. At the same time, tillage is also responsible for more than 85% of the total weed seed dispersal [77] and on the contrary, the absence of tillage favors predation of weed seeds lying on the surface by insects, birds and rodents. About 78% to 91% of *E. colona* seeds from the surface may be removed within two weeks through predation only [77]. The frequency, depth and timing of soil manipulations govern the emerging weed flora. Weed emergence and survival often decrease with increasing soil depth. The seedbed preparation under DDSR eliminates wet tillage (puddling), includes one or two deep plowing through disc followed by a cultivator, 2-3 harrowings, breaking up big clods and land leveling [78]. Good land preparation in DDSR followed by laser land leveling provides a weed-free seedbed, which reduces weed densities by up to 49%, saves labor for manual weeding [79] and increases herbicide use efficiency [80]. An improved crop establishment, higher nutrients, water and energy use efficiencies and overall farm profitability with laser land leveling have also been reported [81].

The lack of water stagnation under DDSR may induce dormancy in weeds like *F. miliacea* and prohibit seed bank exhaustion in the absence of puddling. Thus, stimulating weed seed germination for weeds like *F. miliacea* and *C. difformis* through irrigation and subsequent killing with tillage under SSB would reduce their density [67], while soil inversion with deep tillage inhibits the emergence of *L. chinensis* which bury its seeds beyond 5 cm soil depth [58].

Alterations in tillage practices under DDSR increased the density of annual weeds like *Echinochloa colona*, *Ludwigia octovalvis* (Jacq) P.H. Raven, *Ageratum conyzoides* L., *Eclipta prostrata*, *Eleusine indica*, *Portulaca oleracea*, *Commelina diffusa* (Burm).f., *Ischaemum rugosum*, *Leptochloa chinensis*, and *Eragrostis pilosa* (L.) P. Beauv., and sedges like *Cyperus rotundus* increase whereas *Paspalum* spp. may decrease [82,83]. The density of some perennial weeds like *Rumex crispus* L. and *Ranunculus cantoniensis* L. and weed species with aerial dispersal such as *Conyza sumatrensis* (Retz) E. Walker, *Conyza canadensis* L., *Lactuca indica* L., and *Sonchus oleraceus* L. increase under ZT-DDSR [84]. Continuous ZT in DSR systems also increases the infestation of *E. colona* and *C. iria*, which can be reduced with rotational tillage or alternate ZT and CT under DDSR [85]. In general, weed seedling emergence decreases with increased depth, especially for small-seeded species.

6.2.3. Enhancing Crop Competitiveness

Adoption of nonchemical weed-management strategies, wherein the crop is favored against weeds, such as selection of cultivars, adjusting plant geometry, seed rate and spacing, would give an initial advantage for competing against weeds [86].
Plant Type and Crop Cultivar

Weed infestation in a crop field is associated with the nature of root and shoot growth of the crop plants. The weed competitiveness in cultivars can be enhanced either by inducing tolerance or enhancing weed-suppressive ability [87]. Any rice cultivar with vigorous early growth, rapid ground cover or higher specific leaf area remains desirable for weed competitiveness [88]. Weeds offer competition for crop growth from roots and shoots, but the rice growth is more suppressed due to root competition than shoot competition and up to 55% of the reduction in rice yield is due to root competition [21]. Under DDSR, this competition becomes more severe due to simultaneous weed and crop root growth for weeds like *Echinochloa* spp. [89]. Moderately tall rice cultivars such as IR5 or IR442-2-58; Prabhat and Krishna Hamsa, under Indian IGP conditions have high seedling vigor and tillering abilities, moderately long and droopy leaves and resistance to lodging, which are suitable under DDSR [90]. The vigorous and prolific root system development leads to a better capability of absorbing the applied nutrients and water more rapidly [69]. Also, weeds like *E. colona* and *Ludwigia hyssopsifolia* G. Don. are heavy competitors for solar radiation, CO₂, space, etc., especially under DDSR.

Similarly, the shoot traits like quick initial growth, more biomass, and profuse and synchronous tillering will impart weed competitiveness [91]. Cultivars with horizontal leaf configurations increase leaf area and trap more solar radiation, minimizing weed menaces under DDSR [92].

Seed Priming

Seed priming integrated with precise seeding technology improves the speed and synchrony of seed germination by reducing germination time and improving the overall crop performance in DDSR [76]. Seed priming results in an increase in seed vigour by 50%, a higher seedling dry weight of 35–60% and resistance to various abiotic stresses [93]. Hydro-priming [94], solid matrix priming [95], spermidine, osmo-hardening with KCl, polyethylene and polyamine pre-treatment [96], and nutri-priming with phosphorus and boron [97] have been found to be very beneficial.

Plant Population Dynamics through Crop Geometry and Seed Rate

Enhancing the seed rate in DDSR from 20 to 80 kg ha⁻¹ is often useful to offer competition for weeds in various parts of Asia [98,99]. The rice yield increases as seed rates increase up to 150 kg ha⁻¹ under DSR in Malaysia [100], Latin America [101] and the United States [39]. Rice crops sown with higher seed rates also demand less herbicide. As a part of IWM programs, weed competition can be reduced by increasing plant population for better competitive ability within the crop plants. The crop competitiveness offered by narrow row spacing and higher leaf area index improves with faster canopy cover, increased light interception per unit of leaf area for crops and decreased light penetration for developing weeds [98,102].

Water and Nutrient Management

Crop establishment under DDSR is common with or without dry tillage and sowing followed by irrigation. A pre-sowing irrigation for inducing weed seed germination followed by stale seedbed, as a cultural method is often advised under DDSR to control weeds. Weed seed germination, emergence, population, growth, maturity duration and seed production are strongly influenced by water management. After early establishment, micro-irrigation, especially surface or sub-surface drip irrigation systems may help in reducing the weed menace in DDSR to a great extent. In drip-irrigated DDSR, higher grain yield and water savings (up to 42%) have been reported [103].

Appropriate nutrient management in crops as per the need helps to build up initial vigor in the plants against weeds. Under DDSR, with simultaneous crop-weed growth, weeds uptake nutrients faster during early growth stages and deprive the crop of nutrients. To increase the nutrient availability for crops, banding fertilizer and applications coinciding with crop demands would lower weed densities and biomass [104]. The variable response of weeds to applied nutrients shows that fertilizers
influence crop-weed interaction. The fertilizer doses and application methods can modify weed–crop competition by affecting weed demography, development and competitive ability [105]. The timing, rate and method of fertilizer application influence weed biology and may suppress or favor the emergence of certain weeds [106].

A higher starter dose for initial slow-growing crops may promote weeds and reduce yields [107]. Surface fertilizer applications favor the weed seeds lying on the surface or upper soil layer [108]. Surface banding of nitrogen and phosphorus as a cultural weed management method often reduces weed emergence and growth in DSR over surface broadcasting [109]. Manipulation of subsurface fertilizer placement improves growth and nutrient use-efficiency.

6.3. Interim Alternate Crop

Crops such as soybean, cotton, maize, sorghum or pastures can be taken as a break crop in traditional rice-cultivated ecologies to break the weed seed cycle where complete substitution could not be possible [110]. Therefore, interim alternate crops, not complete substitution, have been found effective for reducing weedy rice density even up to 90% in the United States, Brazil and Uruguay [111].

Promoting fatal germination for weeds with limited dormancy can be utilized by inclusion of a crop like mungbean during the fallow period between rice and wheat crops. This diversification/intensification has reduced the *D. aegyptium* in DDSR [112]. Weeds emerge due to soil disturbance undertaken for sowing summer mungbean and repeated irrigation during cropping; and emerged seedlings can then be killed through herbicides and other inexpensive weed control methods known under mung bean [113]. Likewise, intensification of the rice-wheat system by including cowpea, forage crops or *Sesbania* through relay cropping of either wheat, maize or mustard in the rotation before DDSR may suppress weeds through competition, grazing and mowing without using herbicides [114]. The summer legumes sowing in the system before DDSR should coincide with the last irrigation in winter crops (wheat, maize or mustard) to prevent delaying DDSR sowing in a narrow window under intensified systems. The legumes, after taking 1–2 pickings, can be knocked down either through cultivation or by a herbicide. This helps in meeting early N requirement, besides weed suppression in DDSR.

6.4. Residue Mulch

Crop residue retention under DDSR influences weed infestation by affecting weed seed survival, germination, emergence and development. Weed management under DDSR through crop residues (mulch or anchored residue) offers various direct and indirect advantages for microclimates in maintaining soil temperature, conserving soil moisture, suppressing weeds and adding organic matter in due time. A significant reduction in the emergence of different weed types, namely grassy, broadleaf and sedges up to 73–76%, 65–67% and 22–70%, respectively, has been reported with the application of preceding wheat residue (5 t ha$^{-1}$) retention under DDSR.

Weed suppression due to residue application depends upon the type of weed and volume of residue added. Weed species including *Echinochloa crus-galli*, *Echinochloa colona*, *D. aegyptium*, *I. rugosum*, *Eleusine indica*, *Euphorbia prostrata* Aiton, and *Murdannia nudiflora* L. Brenen may require 4–6 t ha$^{-1}$ of residues load for significant weed suppression; however, crop residues do not affect the emergence and growth of weed species such as *Trianthema portulacastrum* L., *Amaranthus viridis* L., and *Ipomoea tribola* L. [115]. The success and efficacy of crop residue use for weed management depend upon the relative position and morphology of weed seeds and residues, the volume of residue, the crop from which it is derived and environmental factors. But, some crop residues, like from *Brassica* spp., exhibit allelopathy which alters the emergence and growth of the developing weeds [45]. The self-supportive allelopathy can be explored for weed management in DDSR. The seed size disparity between small-seeded weed species and the larger size of rice seeds offers prospects for weed suppression in DDSR with residue use.

*Crotolaria juncea* or *Sesbania aculeata* co-culture with rice as brown manure and knockdown with selective herbicides (2,4-D ethyl ester or bispyribac-sodium) at 25–30 DAS reduces weed emergence
and adds biomass and fertility to the soil [21,69]. Rice-Sesbania co-culture remains more effective for both broad-leaved weeds and sedges, however, remains less effective against grassy weeds [116].

6.5. Chemical Weed Management

Various methods of weed management, including manual and mechanical weeding by hoe or hand pulling have certain constraints like intensive labor use, non-availability of laborers and difficulty in differentiation between weed and crop plants; this often remains tedious, difficult, less effective, impractical and cost-intensive [117]. Despite the apprehensions like weed shifts, poor availability of new broad-spectrum herbicides, development of herbicide resistance among weeds and environmental trade-offs, chemical weed management remains necessary for managing weeds in DDSR. The cautious use of herbicides with appropriate doses and methods should be commonly adopted for improved timeliness of weed control in DDSR [14].

Most of the weed seeds remain in the upper 2–3 cm soil layer under DDSR and any pre-emergence (PRE) herbicide application gives a satisfactory weed control for the emerging crop [25]. Also, many herbicides have been developed which effectively control various noxious weeds in rice. Important PRE herbicides are pendimethalin, oxadiazon, oxadiargyl, pretilachlor, etc., while bispyribac-sodium, penoxsulam, fenoxaprop, azimsulfuron, 2,4-D, metsulfuron-methyl, etc. are commonly used post-emergence (POST) herbicides under DDSR. The sequential application of early POST (10–12 DAS) and late POST (25–30 DAS) under DDSR remains essential under heavy weed infestation [118]. Pendimethalin or pretilachlor as PRE and early POST application of oxadiargyl, anilofos, or thiobencarb followed by POST 2,4-D offer effective control of most of the weeds. Acetolactate synthase (ALS) inhibitors, Acetyl CoA Carboxylase inhibitors and protoporphyrinogen oxidase (protox) inhibitors-based new generation POST herbicides offer a span of 7 to 25 DAS for herbicide application in DDSR. Herbicide mixtures can also be chosen as pyrazasulfuron plus bispyribac-sodium, depending on the prevalence of weed species flora in the area. A ready mixture of chlorimuron-methyl and metsulfuron-methyl remains effective for both grassy and broad-leaved weeds in DDSR. Likewise, pyrazosulfuron followed by fenoxaprop and metsulfuron plus chlorimuron stands very effective against C. rotundus [119].

Economizing weed management in DDSR with the use of herbicides should also focus on herbicide resistance prevention, management, and mitigation. For instance, oxadiazon and metolachlor are effective against weedy rice but should be applied well before sowing as they can be phytotoxic to crop emergence if heavy rain occurs immediately after herbicide application [120]. To overcome this constraint, an early POST herbicide may also be used. Also, pretilachlor when applied under a broadcasting situation should be applied along with a safener under stagnant water for at least 48 h.

The incessant use of persistent herbicides having long residual activity has caused a significant weed shift and development of herbicide resistance either slowly or rapidly [121]. For instance, the higher weed menace and over-reliance on herbicides, un-timely herbicide applications with doses higher than recommended for butachlor, anilofos and pretilachlor for the control for emerging grassy weeds have reduced the efficiency of herbicides [122]. So far, more than 30 weed species prevalent in rice have developed resistance against propanil, 2,4-D and newer sulfonylurea herbicides [123]. The success of chemical weed management depends on the presence of weed species and their dominance. Every individual herbicide has its own strength and also weakness, for example, bispyribac-sodium provides effective control of most grasses but cannot control L. chinensis, D. aegyptium and Cyperus spp. [124]. Herbicide efficacy can be enhanced with the use of proper spray techniques. A flat fan nozzle with multiple nozzle booms should be used for higher spray uniformity across the swath. Herbicide mixtures (both tank and ready-mix) should be used for broad-spectrum management of all broad-leaved, grassy weeds and sedges [125]. In practice, the dose of a narrow-spectrum herbicide often exceeds and the over-doses of herbicides, especially for PRE herbicides like oxadiazon, initially controls weeds at 15–20 DAS only and the season-long use may result in development of herbicide resistance. To avert the evolution of herbicide resistance in weed species, herbicides with dissimilar modes of action should be selected and rotated [126]. Herbicide performance and efficacy changes
with other cultural practices like tillage and irrigation, according to which PRE soil-active herbicides should be selected [44]. For example, pendimethalin does not provide good control of *C. rotundus* and *I. triloba*. The co-application of herbicide safeners with post-emergence herbicides enhance the selectivity of herbicides by protecting the crop from herbicide injury. Some safeners used to protect rice against the use of high-dose herbicides such as clomazone, organophosphate insecticide phorate and triallate-plus-phorate could be effective against weedy rice with minimal rice damage [29,127]. Likewise, application of fenclorim to rice seeds before the pre-emergence application of pretiolachlor enables selective weedy rice control without rice damage [128].

Polymeric nano-herbicides pose higher penetration and delivery efficiency which can prevent the overuse of herbicide and the chances of contaminating the environment. The precise dose would also reduce the chances of the evolution of herbicide resistance in weed biotypes. The entry and translocation of herbicide molecules encapsulated with nanoparticles aiming at a specific receptor in plant parts of targeted weeds has improved the bio-availability and herbicidal activity in atrazine [129,130]. Nano-herbicides and nano-materials for adjuvants can prove beneficial in the control of emerging perennial weeds and exhausting weed seed banks under DDSR. Alginate and chitosan nanoparticles for the encapsulation of paraquat [131] and nano-sized rice husk as a nano-carrier for 2,4-D [132] are some examples of successful nano-formulations. At the same time, nano-particles such as carboxymethyl cellulose also facilitate the easy degradation of atrazine residue in the environment [133].

### 6.6. Herbicide-Tolerant Rice (HT-Rice)

Herbicide-tolerant (HT) crops remain tolerant to a specific herbicide or a group of herbicides to which the crop is otherwise sensitive. The development of herbicide tolerance in rice was targeted for effective and selective control for enormous emerging weeds, especially weedy rice. HT rice is a feasible, economic and practical long-term solution for weeds in DSR systems. Different mechanisms for the selectivity of different herbicides have been exploited for the development of herbicide tolerance in many crops [134] and herbicides belonging to the imidazolinones group are most widely used under both transgenic and non-transgenic approaches [135]. Clearfield is a non-transgenic HT rice production technology, which has been introduced using induced mutation breeding in the United States and has been found effective against a number of herbicides [136]. During the early 21st century, a resistant line (93-AS-3510) against ALS was identified from a single surviving rice plant after chemical mutation [14]. The rice cultivars Clearfield 121 and Clearfield 141 in the United States and IRGA 422 CL in Brazil were then developed with the transference of the gene mutation G654E [137].

Imidazolinone herbicides are broad-spectrum POST herbicides and hence, their doses can be kept depending on the extent of weed infestation and repeated sprays can be done [138]. These high-efficacy low-dose herbicides are biodegradable and leave a very low quantity of herbicide released in the environment. HT rice, however, appears to be a promising alternative where all other weed suppression methods fail to give practical results. Two more transgenic HT rice lines, named Liberty Link and Roundup Ready have also been developed against glufosinate and glyphosate, respectively.

This technology offers prospects for targeted control of weedy rice, but the possibility of gene flow from HT rice to weedy rice is a major hitch for its long-term use [39,139]. The chances of natural outcrossing among rice plants in the Clearfield lines is, however, less than 1% and it is widely grown in Europe, Brazil and the United States [140], yet the gene flow may establish and spread [141]. The guidelines for growing HT rice clearly mention that the physical isolation for HT rice should be ensured, *HT rice should not be allowed to grow for two consecutive seasons. Any weedy rice plants remaining viable after the spray might exert selection pressure and hence should be immediately removed from the field* [142].

### 6.7. Monitoring, Assessing and Speculating on Weed Infestation Using Models

The identification and accurate understanding of complex crop-weed interference has become possible through technological advances made in precision weed management [143]. Crop-weed
competition is not influenced by the weed characteristics alone, but also by environmental and management factors. To capture all the genetic, management and environmental factors, many process-based simulation models have been designed to quantify crop-weed interference for prediction of yield penalty [144]. Prediction of weedy rice impacts through models addressing crop–weed combinations as integrative tools to identify the best management strategies under limited resources can be explored for developing IWM strategies [145]. The factor regulating weed population dynamics namely seedbank size, seed dormancy and germination, cropping system, water management, tillage and methods used in weed control are used in models. Some models have been specifically developed for weedy rice [146]. The empirical model developed using rectangular hyperbola is widely used to estimate yield in response to weed infestation [147,148]. The rectangular hyperbola models with independent variables describing the mixed-weed infestations for predicting economic thresholds of weeds remains desirable under DSR situations [149].

6.8. Integrated Weed Management (IWM) Strategies

An over-reliance solely on herbicides as a weed management strategy poses several economic and environmental risks. The IWM approach, including improved crop-resource management practices compatible with herbicides becomes imperative in the changing weed dynamics and crop-weed interference under DSSR. The weed management should target to deplete weed seed banks as weeds are only a symptom of the problem; the main problem is the weed seed bank. Thus, deploying a flexible IWM strategy with more emphasis on preventive and cultural methods to reduce dependence on herbicides in DSR systems remains more desirable than using individual tactics.

Various weed control methods for DDSR have been assessed, but complete reliance on one strategy fails to provide full control for weeds. A higher seed rate and fertilizer for stimulating initial growth, later on, limits the herbicide as an effective weed management approach [150]. Under DSR, stale seedbed followed by retention of crop residues followed by applications of early and late postemergence herbicides can substantially reduce weed densities. Integration of pretiachlor (PE) either with one hand weeding at 30 DAS or with brown manure through *Sesbania aculeata* or *Sesbania rostrata* provided desirable weed management during the critical growth period of DDSR under Eastern Indo-Gangetic Plains of India [151]. The stale seedbed as a cultural weed management method when integrated with penoxsulam as early post-emergence and one hand weeding at 35–45 DAS achieved 76.8% and 94.3% weed control efficiency at 30 and 60 DAS, respectively. The weed control efficiency further increased to 93% and 97% with stale seedbed and penoxsulam at 10–15 DAS followed by metsulfuron-methyl plus chlorimuron ethyl at 35–40 DAS [152]. Crop residue mulch from preceding crops of wheat at 4 t ha\(^{-1}\) in DDSR also remain effective against both grassy and broad-leaved weeds. A weed suppression of up to 54% and an increase in yield by 22% has been reported [153]. Likewise, maize mulch 5 t ha\(^{-1}\) provides weed suppression of up to 56% and increases in yield by 32% in DSR [154]. Higher nitrogen rates and pendimethalin plus bispyrribac-sodium at 20 DAS followed by one hand-weeding results in higher net returns and water productivity under DSR [155].

7. Conclusions

DDSR with appropriate agronomic interventions can produce similar yields as that of TPR and remains a feasible substitute for TPR under a labor and water shortage. Unmanaged weeds in the field are reported to reduce yield up to 75% in DDSR. A systematic weed-monitoring program for implementing successful IWM is required, wherein different weed-management approaches namely cultural weed management through stale seedbed and crop residue mulch, utilizing crop-competitiveness by growing suitable cultivars and altering seed rate, row spacing, nutrient and water management can enhance the crop competitive ability. Needs-based chemical weed management through herbicide, herbicide mixture, identification of new herbicides against a wide spectrum of weeds, and use of HT rice, would help in achieving a long-term and sustainable weed control in DDSR. The newer technologies for assessing weed losses through crop models and exploring
self-suppressive allelopathy remain desirable. These agronomic and technological innovations have made weed management very effective and economical by reducing the weed-management costs incurred in curative tactics in DDSR. Also, developing new rice cultivars suitable for direct dry sowing and short-statured ideotypes with higher initial vigor would help the wider adoption of DDSR.

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