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Planting Geometry and Herbicides for Weed Control in Rice: Implications and Challenges

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Abstract

Weeds are one of the major biological threats to higher rice productivity worldwide. Various cultural, biological, physical and chemical practices affect the composition and intensity of weeds in rice fields. Generally, weeds can be controlled through herbicides; nevertheless, chemical weed control is not a sustainable option on a long term. Various agronomic practices such as the use of tolerant cultivars, adjusting sowing time, tillage permutations and plant geometry may reduce the weed pressure in rice. Integrated approaches for weed management, emphasizing on the combination of management practices and scientific knowledge, may reduce the economic costs and improve weed control owing to the complexity of the weed community. The present chapter reveals the role of planting geometry and herbicides as weed management strategies in rice, and discusses the issue of herbicide resistance associated with chemical weed control. Moreover, the research and knowledge gaps in rice weed management through planting geometry and herbicides were also highlighted.

Keywords: rice, planting geometry, herbicidal sprays, weed management, yield

1. Introduction

To declare a plant as a weed means to narrate it with the human environment. Their presence in crops, pastures, lawns, gardens, rangelands, along roads or thoroughfares, parks, recreational areas and other natural lands, interferes with human intentions by changing the native flora/natural vegetation of a region. Hence, human intentions are directly linked

to define a weed and their activities endorse weed establishment and dissemination while weed persistence over a period, its type and density, emergence time and its interference period with the crop are directly related to the weed-related losses in crop yields [1]. Both ecological and biological factors of a specific region affect weed composition, distribution and propagation as well as its diversification and occupancy in that region. Interference to the environment often led to multiplication and colonization of plants in open space whose biological activities predispose them. Most of the weed species in annual cropping systems are those which rapidly colonized under disturbed environment [2]. Weed interference and species composition of an area are affected by various environmental and biological factors like soil type, soil moisture, pH, light intensity, temperature, precipitation patterns, crop type, crop competitiveness, crop-weed interference and other flora and fauna of that area. Further, weed interference, its competitive ability and population dynamics changes with weed species composition which further affected by human efforts to control them.

Weeds being the most serious pests in agriculture have the ability to compete with the crop for nutrients through rapid growth and development. Competitive abilities of weeds developed through natural selection make them more vigorous even under severe conditions [3]. Weeds uptake available nutrients and compete with rice plants for water, light and space. Weeds under adverse conditions negatively affect plant growth cycle, plant developmental pattern, leaf architecture, tillering ability, as well as yield and yield attributes of rice [4]. Out of the other factors, poor weed management is also responsible for reduction in rice yield depending on weed type and their infestation [5]. Further, weed management in rice is one of the major causes that affect its crop yield. Normally the decrease in yield due to weeds ranges between 15 and 20%, however; under severe conditions the losses may raise up to 50% or more depending upon the weeds species, types, pressure and intensity [3]. For example, up to 76% reduction in rice grown under puddle conditions is caused due to uncontrolled weeds [6]. The most problematic and common weeds in rice especially in Asia are *Cyperus iria*, *Cyperus maritimus*, *Echinochloa glabrescens*, *Cyperus rotundus*, *Cyperus difformis*, *Paspalum distichum*, *Echinochloa colona*, *Echinochloa crus-galli*, and *Marsilea minuta* [7–9].

Weed control in rice crop is always remaining a difficult task for successful crop production as their presence in the field cause severe reduction in yield and quality of crops and increase the cost of production [10]. The use of herbicides to control weeds is just in the introductory stage in most of the developing and under developed countries and farmers of these regions also behave rationally in herbicide usage. Among all the weed control methods, chemical weed control is commonly used to overcome weeds infestation which is easy, quick, time saving, cost effective and the most reliable method to control weeds in rice. There are diverse weed communities and types in rice fields. Hence the use of a single herbicide cannot give satisfactory and cost-effective results of weed control [11]. The use of herbicides gives effective control of weeds; hence care must be taken in the selection of herbicide that should be based on the target weed species in addition to their broader category of grass, sedge and broadleaf for planning of an effective weed control program for successful rice production [12]. No doubt, manual weed control is efficient method to control weeds but difficult to apply due to scarcity and rising wages of labor and its dependence on the prevailing weather conditions [13]. Azmi et al. [14] stated that use of herbicides seems a crucial part to control and manage weed infestation in rice. An effective and feasible weed management program is essential to overcome various

types of weeds throughout the growing period of crop as manual control of weeds is not a quick method. It requires lot of time and labor as well whilst herbicides offer easy, economical and quick control of weeds if applied in proper dose and at a proper stage of the crop [15].

Not only the weeds pressure, but also the sub-optimal plant population also favors weeds to grow profusely which can be managed by spatial arrangement of crops [4]. The growth, development and the yield of rice as well as the intensity of weed infestation are greatly affected by plant spacing. Planting density in rice strongly influences the growth and development due to its inter-specific competition which affects grain yield [16]. Dense plant population may lead to intra-plant competition whereas lower plant population provides the space for off-types to grow easily [17]. Hossain et al. [18] reported that in too dense populated rice fields, inter-specific competition starts which may cause lodging and gradual shading and results in yield penalty. Hence, it is necessary to adjust suitable plant spacing and plant population as a weed management tool and to get better economic returns.

Integrated weed management is the best option to control weeds whereas cultural weed control is a key component of it [19, 20]. By manipulating the different weed management strategies, the competitive ability of crop over weeds for above and below ground resources can be enhanced [20–24]. This review comprehends the role of planting geometry and herbicide application as a viable tool for weed management in rice.

2. Weed dynamics and control in rice

Weeds are serious problem to rice production. It accounts for one third of the total crop yield losses due to various biotic factors. Simply, plants that compete and interfere with the desirable crop plants and compete with its growth and development are known as weeds [25]. Weeds are one of the main factors which are responsible for low production of field crops [26–28]. Weeds compete with crops for available resources like light, space, water as well as nutrients. During early growth stages weeds compete with crop plants vigorously than later growth stages and ultimately cause substantial reduction in growth and yield [29]. For instance, 16–48% grain yield of transplanted rice is reduced due to the occurrence of weed flora in rice field [4]. This weed infestation in rice disturbs the rice growth badly and may result in complete crop failure [30]. So to minimize the weed density, various weed control strategies have been evaluated in rice crop to get maximum output [20, 30]. Moreover, weed competition is more severe in direct seeded than in transplanted rice [13, 31–33]. Reduction in grain yield of direct seeded rice (DSR), wet seeded rice (WSR) and transplanted rice due to uncontrolled weeds was 75.8, 70.6 and 62.6% respectively [31]. Wet seeded rice refers to the use of pre-germinated seeds as a planting material.

There are about 50 weed species found in rice field causing severe losses in productivity all over the world [33]. Asian sprangletop (*Leptochloa chinensis* L.) and barnyard grass (*Echinochloa crus-galli*) quickly establish formal in a very short duration especially where rice is produced by direct seeding [34]. *Echinochloa colona* L., known as a Jungle rice, grows vigorously in direct seeded rice whilst predominantly found in both direct-seeded and transplanted rice [13, 35, 36].

Sr. No.	Family	Category	Weed species
1	Poaceae	Grass	<i>Paspalum distichum</i> , <i>Echinochloa colona</i> , <i>Leptochloa chinensis</i> , <i>Echinochloa crus-galli</i> , <i>Oryza sativa</i> (weedy rice), <i>Digitaria setigera</i> , <i>Digitaria ciliaris</i> , <i>Eleusine indica</i> , <i>Ischaemum rugosum</i> , and <i>Digitaria ciliaris</i>
2	Cyperaceae	Sedge	<i>Cyperus rotundus</i> , <i>Fimbristylis lismiliacea</i> , <i>Cyperus difformis</i> , and <i>Cyperus iria</i>
3	Commelinaceae	Broadleaved	<i>Commelina benghalensis</i>
4	Pontederiaceae		<i>Monochoria vaginalis</i>
5	Asteraceae		<i>Eclipta prostrata</i>
6	Convolvulaceae		<i>Ipomoea aquatica</i>
7	Onagraceae		<i>Ludwigia octovalvis</i>
8	Sphenocleaceae		<i>Sphenoclea zeylanica</i>
9	Onagraceae		<i>Ludwigia adscendens</i>

Source: [37]

Table 1. The most common weed species in rice.

Juraimi et al. [37] observed that dominance of weed species vary significantly with weed control and different crop establishment methods and reported that *E. crus-galli* and *E. colona* are the most problematic weeds found in rice. Moreover, in the upland rice field, *Cynodon dactylon* and *Cyperus rotundus* are also serious weeds of rice. The list of most common weeds infesting rice fields are presented in **Table 1**.

Singh et al. [38, 39] reported a reduction of 12–98% in rice yield due to weed infestation. Threshold levels of *Cyperus iria* and *Echinochloa crus-galli* were estimated about 30 and 20 plants m⁻² in transplanted rice [40, 41]. A competition study of *C. iria* in transplanted rice showed that 30 days competition caused 12.9% while a 40 day competition caused 43.5% yield loss in rice [42]. Similarly, about 25 kg ha⁻¹ yield is reduced in direct seeded rice for every day delay in weeding [43]. According to the same study, 35.2% yield reduction was recorded by delaying the removal *C. iria* for a period of 30–40 days after tillering. At the seedling stage, *E. colona* and *E. crus-galli* are closely related to rice plant and may be called as “crop mimicry” that need to control in time [44]. While checking the efficacy of different weed control strategies, Cherati et al. [45] found weed control through herbicides as the best method followed by mechanical weeding without engine, three hand weeding and power mechanical weeding. Chemical and manual weed control measures resulted in similar effect under puddled rice [46]. Anaya [47] and Remington and Posner [43] reported that lack of weed control in fields shared about 12% of total waste production and suggested hand weeding, chemical or mechanical weeding or their combinations for better weed control.

3. Planting geometry: role in weed management and rice yield

In most crops, narrower row spacing can increase the competitiveness of a crop [48] whilst reduced crop spacing has also been found to favor the crop development at the expense of weeds.

Weeds are the serious pest in rice production but these can be managed effectively by maintaining the critical periods of weed competition [11] as growth of the rice is greatly influenced by all the competition periods [49]. Chemical weed control is the most popular weed control method, however herbicide resistance, limited amount of available herbicides, weed population shifts and expensive herbicide products may limit its application in the future [50, 51]. To control weeds more effectively and to minimize the complete reliance on herbicides, adoption of cultural approaches in integrated pest management by farmers has been increasing [14].

Weeds can be suppressed by enhancing the crop competitive ability [52]. Hand weeding is a cultural approach to control weeds but it is a very tedious, labor intensive and slow method [53]. Weed control through herbicides is effective but total dependence on chemical weed control with extensive use of hazardous farm chemicals has necessitated the new approaches to tackle the weeds problems [54]. In addition, the use of herbicides on a large scale has resulted serious ecological threats such as shifts in weed population and dominance of minor weeds [55].

Both yield and yield components of rice are affected by plant spacings as well as planting density [56]. Optimum plant density is necessary to obtain higher yields in rice [57]. The effect of both varied planting patterns and herbicides on weed dynamics in rice is presented

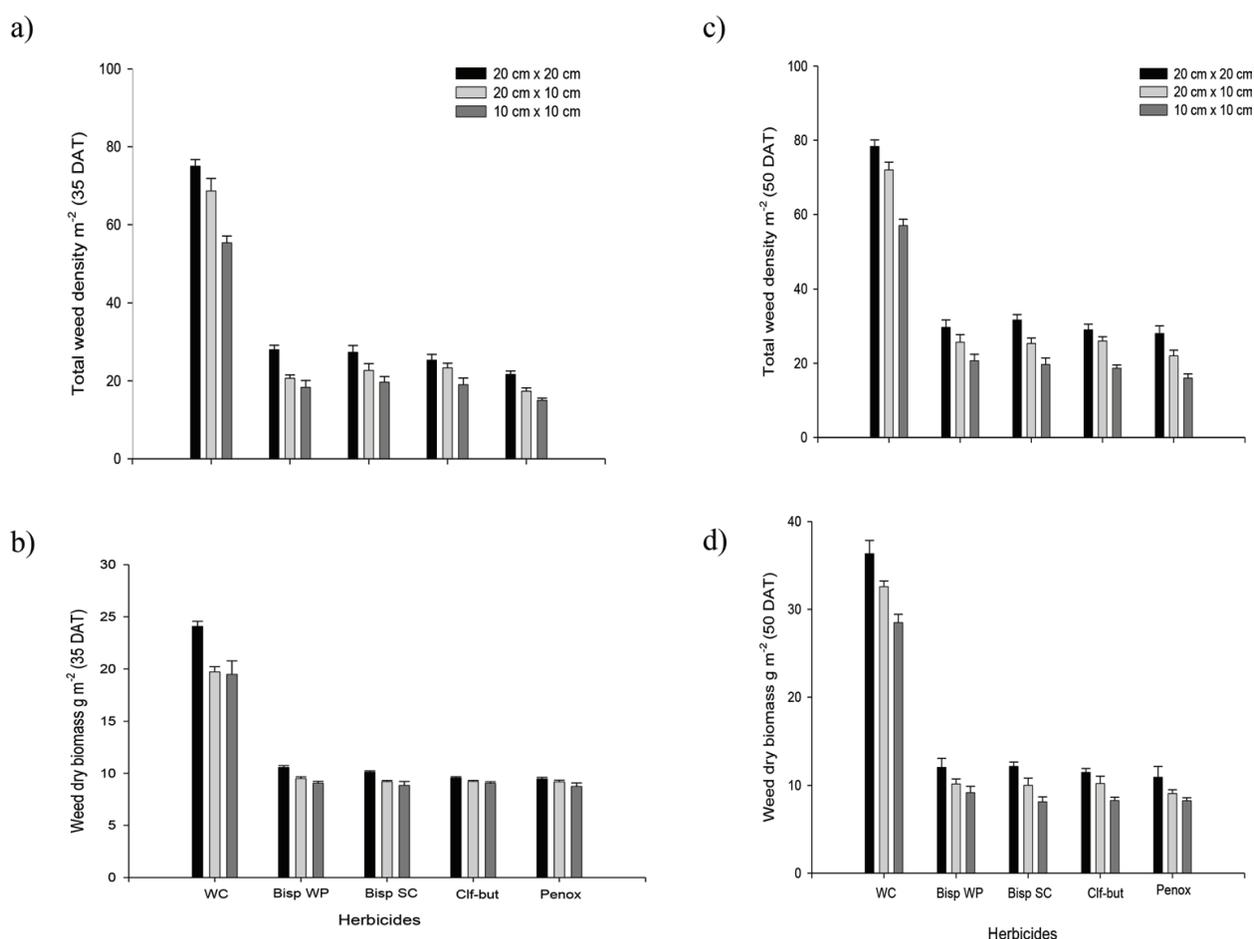


Figure 1. Effect of different planting patterns and early post emergence herbicides on total weed density, and weed dry biomass at 35 and 50 days after transplanting (DAT) (a-d). Bars above means represent S.E. of three replicates. WC: weedy check; Bisp WP: Bispyribac sodium 20% WP at 39.50 g a.i. ha⁻¹; Bisp SC: Bispyribac sodium 100 SC at 39.50 g a.i. ha⁻¹; Clf-but: Cyhalofop-butyle 10% EC at 49.50 g a.i. ha⁻¹; Penox: Penoxulam 240 EC at 15 g a.i. ha⁻¹ [64].

Sr. No.	Rice establishment method	Widest spacing	Narrowest spacing	Remarks	References
1	DSR	20 × 20 cm	10 × 10 cm	Under weed free conditions, yield was 29% higher in the plot with 10 cm row spacing than 20 cm whereas grain yield 87–88% higher than uncontrolled weedy plots.	[3]
2	TR	20 × 20 cm	15 × 15 cm	24.31% higher yield was recorded in widest spacing of 20 × 20 cm compared with narrow spacing of 15 × 15 cm. whilst 36.63% increase in paddy yield was observed in weed free treatment compared with weedy check.	[4]
3	TR	20 × 10 cm	30 × 20 cm	Among the spacing, the widest spacing gave maximum weed control efficiency (55.30%) at 30 DAT and lowest weed control efficiency (62.03%) at 60 DAT.	[17]
4	TR	20 × 10 cm	20 × 10 cm	Adoption of 20 × 10 cm spacing and pre emergence application of anilofos 2, 4-D at 6 days after transplanted supplemented with 2, 4-D Na salt at 20 days after transplanted generally enhanced rice yield from 58.13 to 70.41%.	[29]
5	DSR	10 × 10 cm	30 × 30 cm	Rice spacing determines rice-weed competition and can play a decisive role to minimize weed pressure. Closer spacing could be considered as a vital tool in integrated weed management program for aerobic rice. 51.79 and 70.68% increase in weed dry biomass was observed for 10 × 10 cm and 30 × 30 cm, respectively. Up to 50% increase in rice yield was recorded for narrow spacing compared with wide spacing	[60]
6	TR	20 × 20 cm	15 × 15 cm	The maximum weed density and dry biomass was found in widest spacing, nevertheless, the yield was also remained higher in widest spacing with 19.55% more than the closest.	[4]
7	DSR	30 × 30 cm	20 × 20 cm	The weed population especially <i>E. colona</i> and <i>E. crus-galli</i> was 29% more in widely spaced crop than narrow spacing whilst 18.68 and 23.45% higher grain yield was recorded in narrowest spacing than wide spacing for <i>E. colona</i> and <i>E. crus-galli</i> , respectively.	[61]
8	DSR	30 × 30 cm	15 × 15 cm	Rice grown in 30 cm row spacing has 32–35% greater weed biomass and 38–50% less yield as compared with 15 cm.	[62]
9	TR	25 × 10cm	20 × 10 cm	Short duration of 'aman' rice transplanted at 25 × 15 cm with three hand weedings gives 193% total dry matter than 20 × 10 cm with weedy control.	[63]

Sr. No.	Rice establishment method	Widest spacing	Narrowest spacing	Remarks	References
10	TR	10 × 10 cm	10 × 10 cm	Grain yield was remained lower up to 25% in narrowest plant spacing than widest spacing. Lower grain yield could be due to intra specific competition in rice.	[64]
11	DSR & TR	25 × 15 cm	20 × 10 cm	Narrow row spacing in both DSR and TR resulted in higher grain productivity from 4.7 to 12.2% with reduced weed density.	[65]
12	SRI	30 × 30 cm	25 × 25 cm	The rice yield in closer spacing was 19.50% more than wider. Further, weed control through anilophos at 0.4 kh ha ⁻¹ gave higher yield than weedy check.	[66]

DSR: Direct seeded rice, TR: Transplanted rice, SRI: System of rice intensification

Table 2. Planting geometry-induced changes in weed density and yield of direct seeded and transplanted rice.

in **Figure 1**. According to Awan et al. [58], the yield of rice was much higher where nursery was transplanted in lines as compared to randomly transplanting. Bozorgi et al. [59] studied three levels of plant spacings i.e., 15 × 15, 20 × 20, and 25 × 25 cm in interaction with number of seedlings per hill and found the highest grain yield from 15 × 15 cm. Furthermore, narrow plant spacing in rice significantly reduced weed pressure and weed dry biomass [60]. Hence, plant spacing in rice determines rice-weed competition and has a crucial role in reducing weed intensity and rice yield (**Table 2**). Among the three plant spacings (20 × 10, 25 × 15, 30 × 20 cm), the efficiency of weed control was the highest (62.03%) in 20 × 10 cm at 30 days after transplanting (DAT), while the lowest (55.03%) at 60 DAT [17]. Ehsanullah et al. [16] studied four rice sowing methods and concluded that the highest grain yield (3.06 t ha⁻¹) was obtained from 20 × 20 cm spacing while the lowest of 2.52 t ha⁻¹ from direct seeding by broadcasting the seeds in the standing water. Rasool et al. [67] estimated the impacts of three plant spacings (15 × 15, 15 × 20, 20 × 20 cm) on yield and yield components of rice and observed maximum plant height, total number of tillers, leaf area index (LAI) and total dry matter accumulation from 15 × 15 cm which provided 8.97% higher yield than the 20 × 20 cm spacing. Similarly higher grain yield was obtained in 50 hills m⁻² and the paddy yield record obtained due to high planting density over 16.7, 22.2, 25 and 33.3 hills m⁻² were 4.0, 9.5, 4.8 and 6.0%, respectively [68]. Moreover, number of panicle per plant and straw yield of rice increased significantly by raising planting density in rice [69]. Tari et al. [70] concluded that rice sown at the spacing of 20 × 20 cm and the application fertilizer (138 kg N ha⁻¹) gave maximum yield. Out of three spacings investigated (5 × 15, 15 × 20 and 15 × 25 cm), the highest yield and harvest index were recorded for rice from 15 × 20 cm [71]. Sultana et al. [72] evaluated the effect of five hill to hill spacings viz. 2.5, 5, 10, 15 and 20 cm and two row spacings viz. 20 and 25 cm where the highest grain yield was recorded at 25 × 15 cm and the lowest at 20 × 2.5 cm spacing. Further studies using four row spacings (10 × 25, 15 × 25, 20 × 25, and 25 × 25 cm) resulted in significant improvements in rice yield and related components from 15 × 25 cm spacing with two seedlings per hill with four levels of seedlings per hill were assessed by Alam et al. [73]. In addition, vigorous growth and better yield of rice was harvested from the

spacing of $22.5 \times 22.5 \text{ cm}^2$ compared to that of $20 \times 20 \text{ cm}^2$ and $25 \times 25 \text{ cm}^2$ [74]. The yield of rice was found higher in widest plant spacing i.e., $20 \times 20 \text{ cm}$ than the narrow plant spacings i.e., $20 \times 15 \text{ cm}$ and $10 \times 10 \text{ cm}$.

The performance of rice established under different planting geometries was investigated by Ashraf et al. [4] where a maximum yield of 5.87 t ha^{-1} was obtained using Machete 5G and GGR-6 under plant spacing $20 \times 20 \text{ cm}$. Furthermore, Jacob et al. [75] concluded that $20 \times 10 \text{ cm}$ spacing with the application of anilofos+2, 4-DEE (ready mix) $0.40 + 0.53 \text{ kg ha}^{-1}$ supplemented with 2, 4-D sodium salt 1 kg ha^{-1} provided the maximum grain yield and minimum weed competition. Hence, spatial arrangement of crop plants is the best cultural practice to reduce weed competition and raise rice yield.

4. Weed control in rice using herbicides

Herbicides are chemicals that either kill or inhibit growth of plants. They can be classified in numerous ways viz; by crop (e.g., a soybean herbicide), by their application timing (e.g., pre- or post- emergence to the crop or weeds), by their chemical family (e.g., sulfonylureas, dinitroanilines), by their path of mobility in the plant (e.g., translocation by phloem, xylem, or both), and by their mode of action (MOA) (e.g., photosystem II inhibitors, ALS inhibitors). In the context of herbicide resistance in crops and weeds, MOA is the most relevant classifier because it best describes the means by which the herbicide imposes selection pressure on weeds, and its manipulation can be used for herbicide resistant weed management. More than 200 active ingredients are registered as herbicides around the world, and this estimate does not include compounds that are used exclusively as crop growth regulators or crop desiccants. There are, however, only 29 major mechanisms of herbicide action, including a group of herbicides for which the MOA is unknown [76]. The herbicides are very specific for their mode of action and differ in their weed control efficacy (**Table 3**).

Chemical weed control is becoming priority for farmers due to mainly shortage of labor for hand weeding [77]. Rising wages of labor and their non-availability at peak time discourage hand weeding and make it necessary to use alternative methods of weed control including herbicides [13, 33, 78]. Hence, the importance of herbicides cannot be ignored as it is the most effective, time saving and reliable weed control technology available today [79]. Weedicides can suppress weeds effectively and may provide a weed free environment if applied at proper stage and time [80]. Chemical weed control has an edge over cultural weed control as it is quick, cost effective and saves labor, time and money. So, it may be regarded as an economical method of weed control [81].

The doses of registered herbicides under changing weed composition and density as well as different growth stages may be overestimated to get maximum weed control [82]. Manufacturers recommend higher doses of herbicides than the optimum dose which controls the weed population at satisfactory level [83]. The rate of herbicide to be applied depends on the type of weed flora, the density of weed population, phenological development of both the weed and the crops and the prevailing environmental conditions of the location. Keeping the

Sr No.	Herbicide Class	Herbicide name	Mode of action	Weed efficacy	References
1	Post emergence	Pyrazosulfuron ethyl	ALS inhibitor	An increase of 87–188% was recorded in rice yield in herbicide treated plots than weedy check (control).	[3]
2	Pre emergence	Pretilachlor	Selective	Among all treatments, 79.53% weed control was obtained by application of pretichlor at 30 DAT.	[17]
3	Pre emergence	Butachlor	Selective, systemic herbicide.	Weed dry biomass was 56.92% less in treatment having machete (butachlor) application over weedy check.	[4]
		Ethoxysulfuron	ALS inhibitor		
	Post emergence	Penoxsulam	ALS inhibiting		
	Early emergence and post emergence	Cyhalofop-butyl	Contact and translocated		
4	Pre+Post emergence	Pendimethalin-followed by- bispyribac-sodium + azimsulfuron	ALS inhibitor	Application of these herbicide provided 85% weed control over other herbicides with minimum weed dry biomass.	[63]
5	Post emergence	Penoxsulam	ALS inhibiting	Penoxsulam gives excellent control of <i>Echinochloa</i> spp resulting 19–40% increase in rice yield.	[97]
6	Pre and post emergence	Isoproturon + 2, 4-D	Selective systemic herbicide	Rice yield was 11–15% higher and 0.19 more B:C ratio (net monetary return) than weedy control	[109]
7	Pre emergence	Butachlor	Selective, systemic herbicide	All the herbicides reduced more than 80% weed density and 74–87%	[110]
		Pretilachlor	Selective		
		Pendimethlane	Microtubule assembly inhibition		
8	Pre emergence	Pretilachlor	Selective	Rotational use of pretilachlor with butachlor reduces sedges population and increased paddy yield by 3–5%.	[111]
9	Pre emergence	Pendimethlane	Microtubule assembly inhibition	Highest yield attributes and grain yield 62.8% (q ha ⁻¹) were recorded in treated plots. Uncontrolled weed caused 98.64% reductions in grain yield.	[112]
	Pre emergence	Pretilachlor	Selective		
	Post emergence	Quinclorac	Synthetic Auxin		

Sr No.	Herbicide Class	Herbicide name	Mode of action	Weed efficacy	References
10	Post emergence	Penoxsulam	ALS inhibiting	In herbicide treated plots grain yield was 75–88% and 81–93% better weed control as compared to other treatments	[113]
11	Early emergence and post emergence	Cyhalofop-butyl	Contact , translocated	In herbicide treated plots 27–41% higher grain yield was obtained as compared to control providing 75–93% weed control	[113]

Table 3. Herbicides differ for their class, name, mode of action and weed control efficacy.

weed density below the threshold level instead complete removal is considered best as it is also an ecological approach of weed management [84]. Various herbicides give satisfactory weed control without reducing yield and increasing weed population pressure even if applied at lower rates [85–88]. Weed control efficiency at reduced dose of herbicide tend to be lower than recommended doses, although in many cases it may be 60–100% and acceptable commercially [82]. Application of both pre and post emergence herbicides at proper dose suppress weed flora effectively, however, the use of a single herbicide rarely gives an effective weed control in rice [78].

Rao et al. [13] suggested various herbicides packages like penoxsulam, bensulfuron, carfentrazone, molinate, bentazone, clomazone, pyrazosulfuron, fenoxaprop, propanil, bispyribac-sodium and cyhalofop-butyl control weeds in rice. Further, Pacanoski and Glatkova [89] reported that herbicides i.e., propanil + bentazon, mefenacet + bensulfuron-methyl, penoxsulam, and azimsulfuron + adjuvant controlled *Cyperus rotundus*, *Echinochloa crus-galli* effectively in rice. Similarly, Kawana [90] indicated that weeds such as *L. chinensis* and *I. rugosum* can were effectively controlled using cyhalofop-butyl and bispyribac-sodium, respectively. Herbicide treatments applied with bispyribac-sodium substantially suppressed dry weight and density of weeds as compared to penoxsulam and resulted in maximum marginal rate of return [91]. Bispyribac-sodium is the most effective to the small and actively growing weeds especially against barnyard grass (alligator weed) when applied as an early post emergence herbicide applied at the 3-leaf stage of rice [92]. Both bispyribac-sodium and penoxsulam herbicides in suspension concentrate (SC) formulation were applied in combination with ethoxysulfuron as post emergence and found that bispyribac-sodium + ethoxysulfuron gave better weed control in rice [93]. Saini et al. [94] found that cyhalofop-butyl at 90 g ha⁻¹ caused significant reduction in dry matter accumulation and growth of weeds. Post-emergence application of bispyribac-sodium with metsulfuron methyl after pre-emergence application of oxyfluorfen gave the highest weed control index in fine rice [95]. Application of pendimethalin followed by bispyribac-sodium and penoxsulam reduced weed density up to 80% in rice [91], whereas application of cyhalofop-butyl at 80 g ha⁻¹ effectively controlled *Echinochloa colona* [96]. On the other hand, post emergence application of penoxsulam effectively controlled barnyard grass (*Echinochloa crus-galli*) but was inefficient in controlling broadleaf

weeds. In contrary, the combination of penoxsulam and cyhalofop-butyl was ineffective in controlling grassy weeds [97]. Moreover, the total weed density was significantly reduced using bispyribac-sodium and cyhalofop butyl herbicides although the former caused a slight recoverable injury to the rice plant [98]. Bispyribac sodium at 30 g a.i. ha⁻¹ reduced the density and biomass of weeds by up to 75 and 80%, respectively; hence, its application as a post emergence herbicide proved as a viable strategy of weed control in rice [99]. In direct seeded rice, the lowest weed dry biomass was recorded using the combination of bispyribac-sodium and pretilachlor [100]. The use of bispyribac-sodium at 30 g a.i. ha⁻¹ suppressed various types of weeds which includes broad leaf weeds, grasses and sedges; hence enhanced the grain and straw yield of rice by up to 17.45 and 12.30%, respectively compared to the weedy check [101]. Application of herbicide mixtures proved better regarding weed control than single herbicide application at critical weed competition periods [102].

Chauhan et al. [103] evaluated the efficacy of different post emergence herbicides viz. penoxsulam + cyhalofop, fenoxaprop + ethoxy sulfuron (in combination) and bispyribac-sodium (alone) on four different types of weeds i.e., *E. colona*, *Digitaria ciliaris*, *Leptochloa chinensis* and *E. crus-galli* by applying it at four, six and eight-leaf stages. Fenoxaprop + ethoxy sulfuron gave more than 97% weed control in all weed species under study. Moreover, early application of post emergence herbicides provided high weed control than late application whilst fenoxaprop + ethoxy sulfuron controlled *Digitaria ciliaris* and *Leptochloa chinensis*, penoxsulam + cyhalofop controlled *Leptochloa chinensis* and bispyribac-sodium controlled *E. colona* effectively. Furthermore, both bispyribac-sodium and anilophos were effective against broadleaf and narrow leaf weeds. Bispyribac-sodium reduced the density of *Alternanthera philoxeroides*, *Ammannia* sp., *Commelina diffusa*, *C. difformis*, *C. iria*, and *D. junceum* while anilophos controlled *Cyperus difformis*, *C. sanguinolentus*, and *C. iria* effectively. However, high weed density led to significant reductions in tiller production and grain yield in rice [104]. Application of bensulfuron, bispyribac-sodium and cyhalofop-butyl at early growth stage followed by Bentazon/2-methyl-4-chlorophenoxyacetic acid (MCPA) at mid growth stage control weeds effectively with increased productivity of rice [105]. Different herbicides viz. ethoxy sulfuron, cyhalofop-butyl, chlorimuron, metsulfuron, bispyribac-sodium and penoxsulam controlled different types of weeds effectively in dry seeded rice [37, 106, 107]. Hussain et al. [108] reported that bispyribac-sodium and ethoxy sulfuron were efficient with 90 and 87% weed control efficiency, respectively in rice. They further reported that maximum paddy yield and net benefits were obtained where bispyribac-sodium was applied followed by ethoxysulfuron while the lowest were recorded from weedy check.

Herbicides such as penoxsulam, ethoxysulfuron and butachlor, ethoxysulfuron were considered the most efficient with 93% reduction in weed density in rice [109]. Bispyribac-sodium and penoxsulam at 25 g ha⁻¹ controlled weeds effectively in rice [107]. Penoxsulam (15 g a.i. ha⁻¹) as post emergence was better in suppressing weed density and biomass than pendimethalin (825 g a.i. ha⁻¹) as pre-emergence in rice [110].

On the other hand, the study by Khaliq et al. [91] using five pre- and post-emergence herbicides resulted in unexpected outcome. In this case, not only the germination rate of the two dominant weeds i.e., jungle rice and purple nut sedge were significantly reduced but also the

germination and root-shoot growth of rice were negatively affected. This shows that these herbicides caused seedling mortality to both the weed and the crop irrespective of the time of application as a pre-emergence or post emergence.

Khaliq et al. [93] studied the efficacy of tank mixed pre- and post-emergence herbicides on weed control in rice. In this case, pendimethalin herbicide was tank mixed with ethoxy sulfuron ethyl at 1137 and 30 g a.i. ha⁻¹ and applied as pre-emergence, respectively. Similarly, pyrazosulfuron ethyl, penoxsulam and bispyribac-sodium at 30, 15, 30 g a.i. ha⁻¹ were also tank mixed with ethoxysulfuron ethyl at the same concentration, respectively and applied as post emergence. The findings of this work showed that the weed control was higher for ethoxy sulfuron with bispyribac-sodium combination than all other combinations. In general, different herbicide mixtures can be used for better weed control in rice.

5. Weed resistance to herbicides

Herbicide resistance is the heritable capacity for plants to grow and reproduce after herbicide treatment that would have been fatal to all but one or a very few progenitors in an antecedent population. Herbicide resistant weeds occur in both herbicide-resistant crops and conventional crops in response to selection pressure from a specific herbicide. A herbicide selects plants with natural genetic resistance to that MOA. The mechanism of herbicide MOA has been depicted in **Figure 2**. Those plants survive and reproduce, and if selection by the herbicide continues for several generations, the population of the resistant weed biotype increases until there is a noticeable population of weeds that herbicide will no longer control that biotype. On the other hand, both transgenic and non-transgenic herbicide-resistant crop cultivars are resistant to specific herbicides because they have been bred to survive the action of herbicide. Therefore, susceptible crop genotypes are killed by a specific herbicide while the resistant cultivars survive. When the identity of a conventional cultivar is mistaken for a resistant cultivar in the field, the conventional cultivar is killed or severely injured by the herbicide that the resistant cultivar resists without adverse effects.

Resistance of weeds to various herbicides is a well-known phenomenon but not as much focused as resistance to insecticides or fungicides [111]. Most often it is misunderstood that resistance is a problem caused by a particular active ingredient but it results from agronomic systems which totally depend on herbicides to control weeds [76]. Herbicides commonly used in rice mostly relate to acetyl co-enzyme A carboxylase (ACCase) inhibitors, acetolactate synthase (ALS), thiocarbamates, synthetic auxins and amides due to which herbicide resistance has become a serious problem in many regions [112]. Zein et al. [111] observed the evolutionary resistance of *Echinochloa colonum* during the years 2005–2007 against bispyribac-sodium when applied to both susceptible and resistant biotypes of *Echinochloa colonum*. Riar et al. [44] found some resistant populations of *Echinochloa crus-galli* to bispyribac-sodium and penoxsulam. El-Nady et al. [113] investigated the physiological and anatomical differences between the susceptible and resistant biotypes of *Echinochloa colonum* and resulted that GR₅₀ of resistant biotype was 10.2 times greater than susceptible biotype of *Echinochloa colonum* where bispyribac-sodium was applied. Rahman et al. [114] tested cyhalofop-butyl, quinclorac and propanil against 10 populations of *Echinochloa*

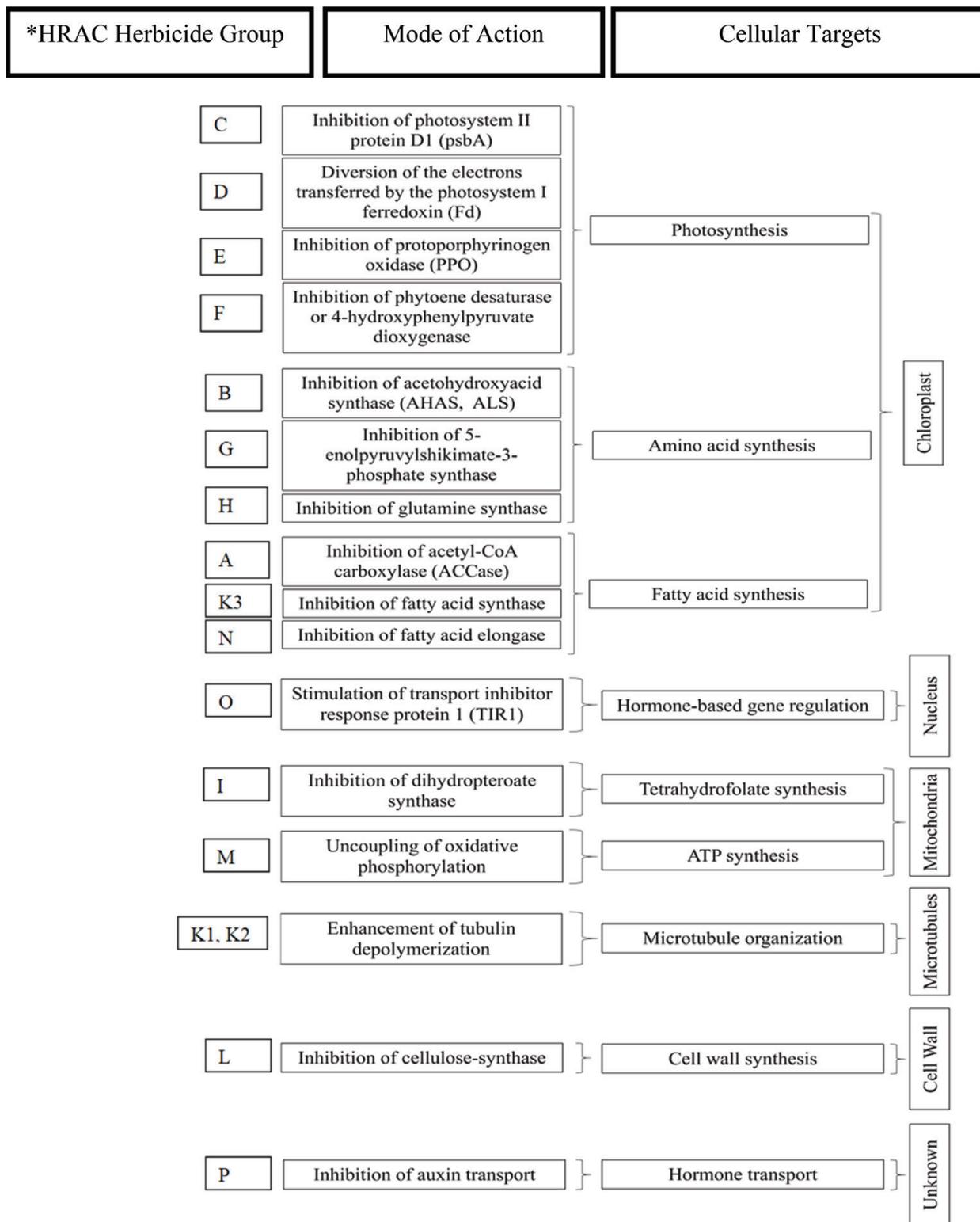


Figure 2. Herbicide class and its mode of action as defined by Herbicide Resistance Action Committee (HRAC; <http://www.hracglobal.com>). Herbicides target different cellular structures and functions and are very specific in their mechanism of action in plants. Source: [115].

crus-galli which were collected from rice field. They concluded from the ED50 values from the dose-response experiment that resistant biotypes were 4, 10 and 17 times resistant to propanil, quinclorac and cyhalofop-butyl, respectively. Regular monitoring and early

detection of the evolution and mechanism of herbicide resistance and by adopting some suitable management strategies usefulness of herbicides may be enhanced otherwise weed control through herbicides might be at a high risk in future [116, 117].

6. Conclusions and future needs

Weeds being the most serious pests in agriculture have the ability to compete with the crop for available resources through rapid growth and development. Competitive abilities of weeds developed through natural selection make them more vigorous even under severe conditions. Weed control in rice crop is always remaining a difficult task for successful crop production as their presence causes severe reduction in yield and quality of crops thus increasing the cost of production. Among all the weed control methods, chemical weed control is commonly used to overcome weed infestation which is easy, quick, time saving, cost effective and the most reliable method to control weeds. There are diverse weed communities and types in rice fields. Hence, the use of a single herbicide cannot give satisfactory and cost-effective results of weed control. Not only the weeds pressure, but also the sub-optimal plant population favors weeds to grow profusely. Planting density significantly influences the growth and development as well as grain yield of rice due to its inter-specific competition. Dense plant population may lead to intra-plant competition whereas low plant population provides the space for off-types to grow easily. Integrated weed management is the best option to control weeds. By manipulating diverse weed management strategies, the competitive ability of crop over weeds for the above and below ground resources can be enhanced. Regular monitoring and early detection of the evolution and mechanism of herbicide resistance is necessary. The adoption of suitable management strategies on herbicide is also important. Hence, in the future, researchers need to develop integrated weed management strategies along with effective herbicides which do not only favor crop yield and reduce weed infestation but also discourage the resistance of weed flora to herbicides.

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