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Role of herbicide-tolerant (HT) rice in the weed management of direct seeded crop: Challenges and opportunities

Jenifer Sylvia Johnson Sunder Singh[1], Thangaraj Kandasamy[2], Manonmani Swaminathan[3], Raveendran Muthurajan[4], Murali Arthanari Palanisamy[5], Vijayalakshmi Dhashnamurthi[6], Sudha Manickam[7]*

[1]*Department of Plant Breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India*
[2]*Department of Plant Breeding and Genetics, Agricultural University & Research Institute, Tamil Nadu Agricultural University, Madurai, Tamil Nadu, India*
[3]*Department of Rice, Centre for Plant Breeding and Genetics, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India*
[4]*Directorate of Research, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India*
[5]*Sugarcane Research Station, Tamil Nadu Agricultural University, Sirugamani, Tamil Nadu, India*
[6]*Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India*
[7]*Department of Plant Biotechnology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India*

**Corresponding author: thangaraj.k@tnau.ac.in*

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Abstract: Food insecurity which has been a global threat, forces researchers to develop crops with increased productivity even under varying climatic conditions. Rice, being a significant staple and strategic crop, helps ensure economic stability, food, and nutritional security globally. It meets 20% of the calorie requirement of people residing all over the world. Lately, rice cultivation and research have been facing hitherto unprecedented difficulties in the context of climate-induced water scarcity and dwindling resources of manpower, arable land, etc. In this regard, direct seeded rice (DSR) as a resource conservation technique is gaining popularity as a potential alternative to conventional transplanting with reduced input requirement, reduced methane and CO_2 emission, increased adaptability to climate change, and increased economic returns. The weed menace in DSR prevents it from reaching its fruitful attainment to a significant level. DSR highly depends on herbicide for weed control as manual weeding and other cultural practices are labour intensive which again meets a setback of crop injury (non-selective herbicide) and resistant weeds (selective herbicides). Herbicide-tolerant (HT) rice could be an effective and long-term solution for weed management in DSR. Three HT rice systems, viz., imidazolinones, glyphosate, and glufosinate, have already been developed in this context. This review gives an insight into the need for HT rice in DSR, its production system, limitations, and stewardship guidelines for proper weed management in rice.

Keywords: direct seeded rice; geneflow; herbicide; herbicide tolerance; weed menace

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Rice is an integral part of the staple diet of more than 60% of the global population is cultivated throughout the world with approximately 90% of the global production from Asian countries (Fukagawa & Ziska 2019). Rice, popularly known for its paramount role in sustaining food and nutritional security, acts as a source of dietary intake for 20% of the world's population (Bin Rahman & Zhang 2023) and meets 43% of the calorie requirement of nearly two-thirds of the Indian population (Shankari et al. 2023). India being the second largest producer and consumer of rice next to China, produces 129.47 million tonnes of rice from 46.27 million hectares of area with a productivity of 2 798 kg/ha (INDIASTAT 2020–21; www.indiastat.com). By 2035, a whopping 114 million tonnes of milled rice should be produced additionally, which equates to a 26% boost in the upcoming 25 years (Dorairaj & Govender 2023). There isn't much scope for increasing the arable land under rice. In a bid to ensure long-term sustainability, this rising demand will need to be satiated by less water, less land, labour, and chemicals.

Among the facets of global warming, climate-induced water scarcity is one of the pressing issues affecting agriculture productivity (Sandhu et al. 2013), especially rice, which exploits nearly 50% of freshwater resources for field preparation and irrigation (Mythili et al. 2020). Rice, being a semi-aquatic crop, is cultivated in a broad spectrum of agro-ecosystems ranging from flooded wetland to rainfed dryland, namely flood-prone deep water, irrigated, rainfed lowland and rainfed upland. 75% of the rice production is predominately from irrigated rice system, which occupies 55% of the global rice area (Sandhu et al. 2021). As a crop with a high affinity for water, rice requires 3 000 L of water for the production of 1 kg of rice under puddled conditions (Anandan et al. 2022). In recent years, rice cultivation and research have been facing hitherto unprecedented difficulties owing to their water-sensitive nature, fluctuations in climatic conditions, diminishing arable lands, escalating labour, and water shortage, which necessities the search for alternative crop establishment methods with increased water productivity without impairing crop productivity in the slightest. In this regard, water and labour shortages in both rainfed and irrigated areas could be efficiently addressed by direct seeded rice (DSR) technology (Sagare et al. 2020).

DIRECT SEEDING RICE – A POTENTIAL ALTERNATIVE TO PUDDLED TRANSPLANTING RICE

Amidst the other crop establishment methods, puddled transplanting is predominantly employed for rice cultivation in the tropical regions of Asia as it provides competitive advantage to rice seedlings to suppress weed growth, increased nutrient availability, better establishment of seedlings, reduced seepage loss and elevated production. Contrary to the aforementioned benefits, transplanting is both water and labour intensive which are the most limiting factors in the present scenario as Asia is anticipated to experience a "physical water scarcity" by 2025 which affects around two million hectares of dry-season lowland rice and thirteen million hectares of wet-season lowland rice (Tuong & Bouman 2003) and agricultural labour forces are shrinking at a rate of 0.1–0.4% with 0.2% annually on average (Dawe 2005). Puddling alone accounts for 30% (1 300 to 1 500 mm) of the overall water requirement. Apart from that, the seasonal water utilization in the puddled transplanted rice (PTR) system varies from 660 to 5 280 mm regarding the growing season and transpirational loss (Sandhu et al. 2013). In terms of using groundwater for irrigation, India is at the top of the list, which resulted in a decline of available groundwater by 0.5 to 1.0 megalitres per year (Mythili et al. 2020). A 10% decrease in the amount of water used in irrigated rice will free up to 150 000 million m^3, or around 25% of the total freshwater used for non-agricultural purposes globally (Meena et al. 2019). The other major cascade of setbacks limiting traditional PTR system are increased labour wages, depletion of soil fertility, a decline in resource use efficiency, negative impact on subsequent crop, greenhouse gas emission and environmental problems. The potential benefits of both PTR and DSR are compared in Figure 1.

Direct seeded rice, a resource conservation technique is gaining popularity as a potential alternative to conventional transplanting concerning reduced input requirement, methane and CO_2 emission, and increased economic returns (Nie & Peng 2017). DSR is an impending version of upland rice cultivation where rice is sown directly in the un-puddled soil and unsaturated soil. It is regarded as the best alternative crop establishment method with water productivity of 64 to 88%, less labour requirement (50% less), reduced methane and nitrous oxide emission, and

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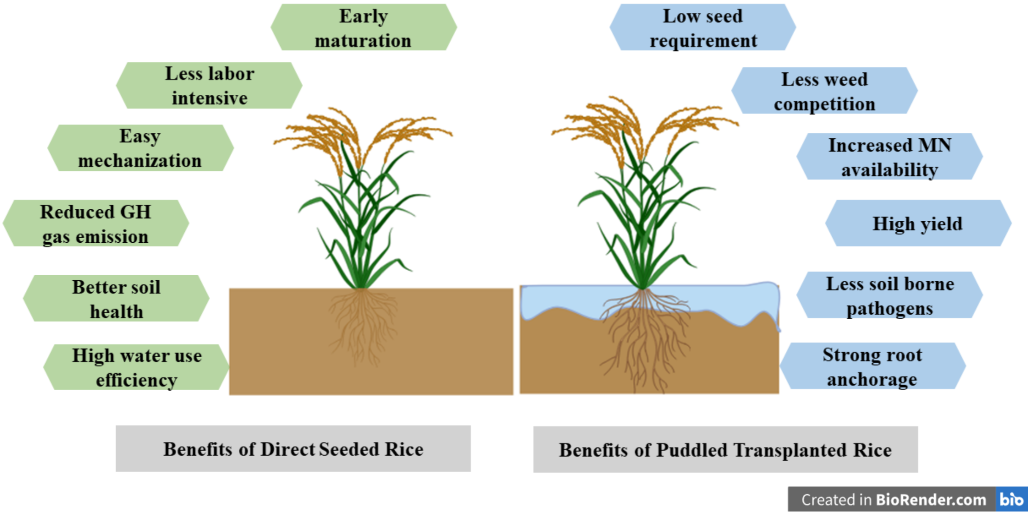

Figure 1. Comparison of potential benefits of puddled transplanted rice and direct seeded rice
GH – greenhouse; MN – micronutrient

adaptability to climate change. The predictions of depleting water resources under a varying climate and escalating labour scarcity have brought a paradigm swing from conventional transplanted rice to DSR in many countries namely, India, Malaysia, Sri Lanka, Vietnam (Rao et al. 2007) and United States, Latin America, Australia, West Africa and Europe (De Datta & Baltazar 1996). Coastal districts of Tamil Nadu *viz.*, Cuddalore, Thiruvarur, Nagapattinam, and Pudukkotai are witnessing an increased area under DSR due to the prevailing water scarcity (Robin et al. 2022).

IMPLICATIONS OF WEEDS ON DSR

Weed infestation is the major setback in DSR which holds accountable for the yield loss ranging from 15–20%, but in severe case, it may exceed 50% or even can cause complete failure (Sen et al. 2021) and the extent of loss yield caused by weeds in different establishment methods is depicted in Table 1. In India, weed-triggered yield loss under DSR is in the range of 20–85% (Rao et al. 2007). Direct seeded rice is comparatively subjected to much higher weed pressure as it germinates together with weeds, eliminating the "head start" of transplanted seedlings. Weeds being a major threat in direct seeded rice, not only competes with rice for resources but also harbours pests and diseases, which ultimately hamper the productivity of rice. The weed-free environment should be maintained till 70 days after sowing (DAS) to achieve desirable productivity, although the crucial period of weed rice competition is till 41 DAS (Chauhan & Johnson 2011). Grover et al. (2020) advocate that with effective weed management, DSR yields are almost identical to those of transplanted rice. Weed control by manual weeding and cultural practices is restricted as they are labour-intensive and cumbersome in the context of labour scarcity. Thus, the application of broad-spectrum herbicides is an effective and economical way to control weeds under DSR and the development of herbicide-tolerant

Table 1. Extent of yield loss in various rice establishment methods

Rice establishment methods	Yield reduction due to weeds (%)	References
Upland rice	97	Singh et al. (2011)
Dry-seeded rice	90	Chauhan and Opeña (2012)
Upland direct seeded rice	80	Sharma et al. (2007)
Transplanted puddled rice	57	Mahajan et al. (2009)
Wet direct seeded rice	85	Singh et al. (2011)
Dry seeded rice zero tillage	98	Singh et al. (2011)

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rice varieties is one of the feasible and practical long-term solutions.

WEED FLORA AND THEIR DYNAMICS

Although the initial composition of weeds in DSR may not differ significantly from that of PTR, over time, a notable shift of weed flora towards more species-rich plants, particularly grassy weeds and sedges, was reported (Bhullar et al. 2018). In PTR, the predominant weed species reported by Ramachandra (2010) were *Echinochloa crus-galli*, *E. colona*, *Cyperus iria*, *C. rotundus*, *C. difformis*, *Ammania baccifera* and *Eclipta alba* while Reddy (2010) observed *Echinochloa crus-galli*, *C. difformis*, *Fimbristylis miliacea*, *Eclipta alba* and *Ammania baccifera* as the dominant weed species in DSR. Mythili et al. (2020) discerned the predominance of grassy weeds in DSR namely, *Echinochloa crus-galli*, *Cynodon dactylon*, *Chloris barbata*, and *Brachiaria reptans* followed by *Cyperus rotundus* (sedge) and broad-leaved weeds *viz.*, *Basilicum polystachyon*, *Bergia ammannioides*, *Eclipta prostrata* and *Alternanthera paronychioides*. This was found to be following the previous report of weed spectrum found in DSR by Rao et al. (2007). Weed flora in rice is found to be regional-specific. In the USA, the weeds that are commonly found in rice field include red rice (*Oryza sativa*), *Echinochloa crus-galli*, *Sagittaria montevidensis*, *Echinochloa oryzicola*, *Cyperus iria* and *Ammania auriculata* (Heap 2014) while in Brazil, *Echinochloa crus-galli*, red rice (*Oryza sativa*) and *Leersia hexandra* under grasses, *Cyperus difformis*, *C. laetus*, *C. esculentus* and *C. ferax* under sedges, *Ipomoea* sp., *Hymenachne amplexicaulis*, *Alternanthera philoxeroides* and *Aeschynomene* sp. under broad-leaved weeds were found to be the major weed flora in rice. Red rice and barnyard grass were found to be the omnipresent weeds causing major yield loss in most of the rice-growing countries *viz.*, USA, Australia, Spain, etc. Some of the major weeds and their impact on rice yield are depicted in Table 2.

CHEMICAL CONTROL OF WEEDS IN RICE

Herbicide-based weed control is the most feasible option considering the non-availability of water and manpower. Herbicides suppress weed infestation by inhibiting/ interfering with the enzymatic pathway of branched-chain amino acids (acetolactate synthase (ALS) inhibitors), aromatic amino acids (glyphosate), photosynthetic activity (photosynthesis inhibitors), disrupting cell membrane, lipids (acetyl-CoA carboxylase (ACCase) inhibitors), *etc*., which ultimately results in the death of plants. The mode of action of these herbicides is pictorially represented in Figure 2. Rational and need-based application of herbicide plays a pivotal role in weed management in DSR. The list of pre- and post-emergence herbicides recommended for rice under DSR is listed in Table 3.

NEED FOR HERBICIDE RESISTANCE IN RICE

Weed Science and Society of America in 1998 defined herbicide tolerance as “the inherent ability of the crop species to survive and procreate after herbicide application without the influence of selection and genetic manipulation” while herbicide resistance is defined as “the inherited ability of a plant to survive and reproduce even after being exposed to a dosage

Table 2. Major weeds of rice and their impact on yield loss

Weeds	Scientific name	Yield loss in rice (%)	Reference
Red rice/weedy rice	*Oryza sativa*	80 90	Shivrain et al. (2010) Ferrero (2003)
Barnyard grass	*Echinochloa crus-galli*	7–50 13–55	Shekhawat et al. (2020) Zhang et al. (2017)
Nut grass	*Cyperus rotundus*	20–90	Peerzada (2017)
Flat sedge	*Cyperus iria*	64	Dhammu and Sandhu (2002)
Jungle rice	*Echinochloa colona*	27–62	Rao and Matsumoto (2017)
Small-flower umbrella plant	*Cyperus difformis*	12–50	Moody et al. (1984)
Hoorah grass	*Fimbristylis milliacea*	42	Hakim et al. (2011)
False daisy	*Eclipta prostrata*	10	Lee and Moody (1989)

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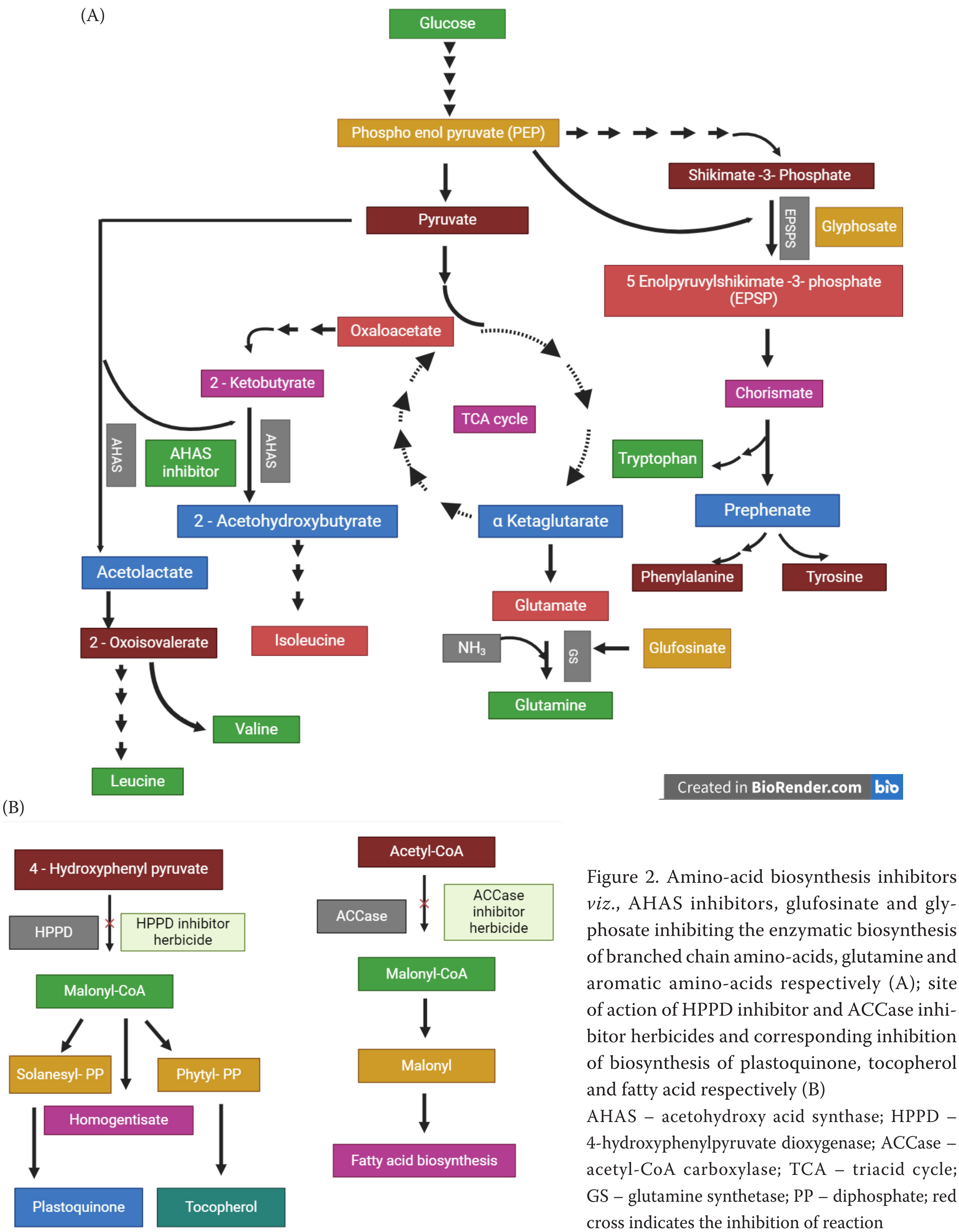

Figure 2. Amino-acid biosynthesis inhibitors *viz.*, AHAS inhibitors, glufosinate and glyphosate inhibiting the enzymatic biosynthesis of branched chain amino-acids, glutamine and aromatic amino-acids respectively (A); site of action of HPPD inhibitor and ACCase inhibitor herbicides and corresponding inhibition of biosynthesis of plastoquinone, tocopherol and fatty acid respectively (B)

AHAS – acetohydroxy acid synthase; HPPD – 4-hydroxyphenylpyruvate dioxygenase; ACCase – acetyl-CoA carboxylase; TCA – triacid cycle; GS – glutamine synthetase; PP – diphosphate; red cross indicates the inhibition of reaction

of herbicide that would typically be fatal to the wild type which can be acquired either *via* natural or induced through genetic manipulation or selection from mutagenesis". Thus, herbicide tolerance is a natural ability while herbicide resistance is an acquired ability of plants to withstand the harmful effects of her-

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Table 3. Recommended herbicides for rice cultivation

Herbicide	Application time (DAS)	Dose (g a.i./ha)	Mode of action	Effective	Ineffective
Pendimethalin	1–3	1 000	microtubule assembly inhibitor	effective against grasses, some sedges and BLW	–
Oxadiargyl	1–3	90	protoporphyrinogen oxidase inhibitor	effective against broad spectrum of weeds	–
Pyrazosulfuron	1–3 or 15–20	20	ALS inhibitor	effective control of *Cyperus rotundus*, other sedges, grasses and BLW	ineffective against *L. chinensis* and *Dactyloctenium aegyptium*
Bispyribac-sodium	15–25	25	ALS inhibitor	efficient control of wide spectrum of weeds particularly *Echinochloa* sp.	poor on grasses namely, *L. chinensis*, *Dactyloctenium aegyptium*, *Eleusine indica*, and *Ergrostis* sp.
Penoxsulam	15–20	22.5	ALS inhibitor	wide-spectrum control of grasses, broad leaves weeds and sedges	poor on grasses namely, *L. chinensis*, *Dactyloctenium aegyptium*, *Eleusine indica*, and *Ergrostis* sp.
Fenoxaprop-ethyl	25	60	ACCase inhibitor	effective against grassy annual weeds	ineffective against BLW and sedges
Fenoxaprop-ethyl + safener	15–20	60–90	ACCase inhibitor	effective against grassy annual weeds	ineffective against BLW and sedges
Cyhalofop-butyl	15–20	120	ACCase inhibitor	effective against grassy annual weeds	ineffective against BLW and sedges
Propanil	15–25	4 000	photosynthesis at photosystem-II inhibitor	effective against wide range of weeds	–
Azimsulfuron	15–20	17.5–35	ALS inhibitor	effective against wide range of weeds especially *Cyperus rotundus*	ineffective control of *Echinochloa* sp.
Ethoxysulfuron	15–20	18	ALS inhibitor	effective on BLW and annual sedges	poor control on grasses and ineffective against perennial sedges like *Cyperus rotundus*
Triclopyr	15–20	500	synthetic auxins	effective on BLW	no effect on grassy weeds
2,4-D ethyl ester	15–25	500	synthetic auxins	effective against BLW and annual sedges	–
Carfentrazone	15–20	20	protoporphyrinogen oxidase inhibitor	effective on BLW	no effect on grassy weeds
Chlorimuron + metsulfuron	15–25	4 (2 + 2)	ALS inhibitor	effective against BLW and annual sedges	no effect on grassy weeds and ineffective against *C. rotundus*
Bispyribac + azimsulfuron	15–25	25 + 17.5	ALS inhibitor	effective against wide range of weeds including *C. rotundus*	poor control on grasses besides *Echinochloa* sp.
Fenoxaprop + ethoxysulfuron	15–25	56 + 18	ACCase and ALS	effective against grassy weeds *viz.*, *L. chinensis* and *D. aegyptium* and other BLW and sedges	poor on perennial sedges such as *C. rotundus*

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Table 3 to be continued

Herbicide	Application time (DAS)	Dose (g a.i./ha)	Mode of action	Effective	Ineffective
Propanil + pendimethalin	10–12	4 000 + 1 000	photosynthesis and microtubule assembly inhibitor	controls wide spectrum of weeds	ineffective control on perennial sedges like *C. rotundus*
Propanil + triclopyr	15–25	3 000 + 500	photosynthesis and synthetic auxins	controls wide spectrum of weeds	ineffective control on perennial sedges like *C. rotundus*

DAS – days after sowing; a.i. – active ingredient; ALS – acetolactate synthase; ACCase – acetyl-CoA carboxylase; BLW – broad-leaved weeds; adopted and modified from Kumar and Ladha (2011)

bicide. Repeated use of selective herbicides leads to the evolution of weeds with herbicide resistance, while the application of broad-spectrum herbicides is hampered by crop sensitivity, which limits their effective utilization in weed management. Red/weedy rice (*Oryza sativa* f. *spontanea*) has become a notorious weed, causing a potential yield loss of 15 to 100% in the areas, which evidenced swift change from TPR to DSR (Kumar & Ladha 2011). Red rice management in DSR is extremely difficult due to their morphological and genetic synteny with rice which hinders their targeted control using selective herbicides without injuring the rice crop. It is the need of the hour to develop herbicide-tolerant rice varieties suitable for direct-seeded rice cultivation systems, which are reinforced by the factors. Namely, the availability of efficient novel herbicide molecule, increased cost of manual weeding, reduced herbicide cost, scarcity of labour and needs for mechanization. There are three herbicide-tolerant rice (HTR) systems *viz.*, Liberty Link® (glufosinate tolerant), Roundup Ready® (glyphosate tolerant), and Clearfield® (imidazolinone tolerant) developed and commercialized by Bayer Crop Science, Monsanto and BASF (Duke 2005) respectively. Among these systems, Clearfield® rice is alone a non-transgenic developed through chemical mutagenesis while others were produced through transgenics. These three HT rice systems have been compared in Table 4. The herbicide-tolerant rice systems put forward numerous benefits *viz.*, (*i*) effective management of a wide range of weed species using non-selective herbicides with little to no phytotoxic effect on rice; (*ii*) provides flexibility in selecting suitable crops for rotation as they do not have any residual effect; (*iii*) reduced crop injury; (*iv*) flexibility in the management practices as the herbicide can be sprayed at any stage of crop growth and (*v*) effective utilization of resources which results in enhanced productivity of rice. The imidazolinone group of herbicides are highly preferred over other herbicides for breeding herbicide-tolerant crops owing to their characteristics like controlling a wide range of weeds, effective at a low application rate, low mammalian toxicity and having a good environmental profile. Farmers were able to selectively control 95 to 100% of the weedy rice population by spraying imazethapyr (Avila et al. 2005) with the advent of imidazolinone resistant Clearfield® rice (Tan et al. 2005).

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Table 4. Comparison of three herbicide-tolerant rice systems with different mode of action

Inhibitor	Imidazolinones	Glyphosate	Glufosinate
Herbicide			
Target enzyme	AHAS	EPSPS	GS
Target amino acid	valine, leucine and isoleucine	tryptophan, phenylalanine, and tyrosine	glutamine
Pathway involved	branched chain amino acid biosynthesis pathway	aromatic amino acid biosynthesis pathway	glutamine biosynthesis pathway
Nature of enzyme – substrate	uncompetitive	uncompetitive, competitive	competitive
Dosage (g a.i./ha)	20–1 700	160–4 200	320–1 560
Application method	foliar, soil	foliar	foliar
Time of application	pre-emergence, post-emergence	post-emergence	post-emergence
Residual effect	yes	no	no
Acute rat oral toxicity (LD_{50} g/kg)	> 5.0	5.6	1.91
Herbicide-tolerant rice			
Commercialized crop name	Clear Field®	Roundup Ready®	Liberty Link®
Developed by	BASF	Monsanto	Bayer Crop Science
Mechanism of tolerance	tolerant AHAS	tolerant EPSPS, detoxification of glyphosate	detoxification of glufosinate
Method of development	mutagenesis	genetically engineered	genetically engineered
Foreign gene inserted	none	*gox* gene obtained from *Agrobacterium* sp. strain CP4, *Ochrobactrum anthropic* strain LBAA	*bar* or *pat* gene obtained from *Streptomyces hygroscopicus*, *S. viridochromogenes*
Modified or inserted target-site gene	variant AHAS gene	CP4-EPSPS or modified maize EPSPS gene	none

AHAS – acetohydroxy acid synthase; EPSPS – 5-enolpyruvylshikimate-3-phosphate synthase; GS – glutamine synthetase; a.i. – active ingredient

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MECHANISM OF HERBICIDE TOLERANCE

Deciphering the molecular, physiological, and biochemical mechanisms behind the herbicide tolerance of genotypes is imperative to develop HT varieties suitable for DSR cultivation system. The mechanisms which are considered to confer resistance to herbicides in crops are the exclusionary resistance mechanism, metabolic detoxification, differential resistance at the site of action, and overexpression of the target enzyme (Figure 3). The order of degree of herbicide resistance is primarily due to metabolic detoxification (Duke & Cerdeira 2010) followed by differential resistance at the site of action and

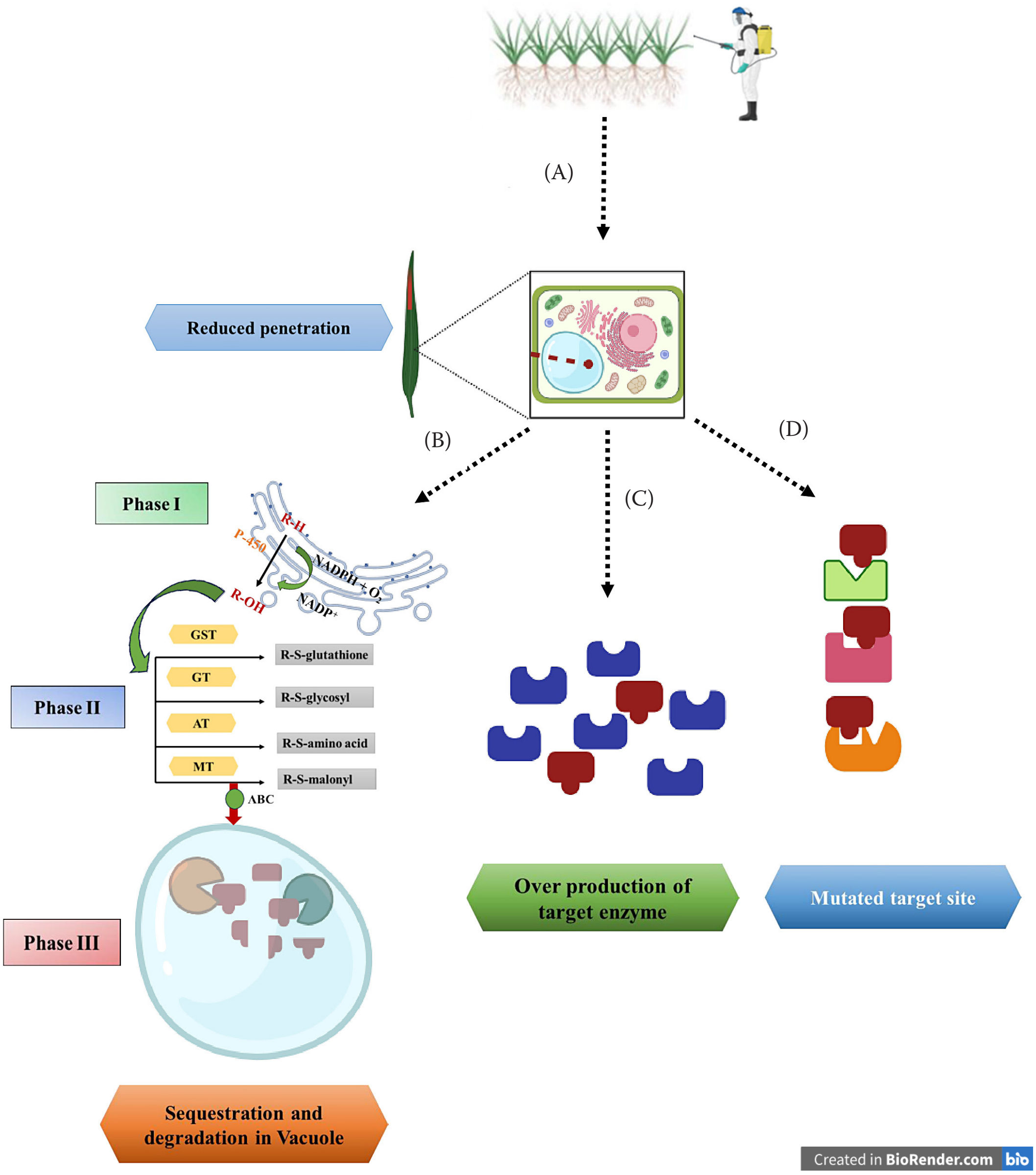

Figure 3. Mechanisms involved in the herbicide resistance in plants: reduced penetration of herbicide into plants (A); Phase I – functionalization of herbicide molecule, Phase II – hydroxylation and conjugation of herbicide, Phase III – sequestration/compartmentalization into vacuole and subsequent degradation of herbicide (B); overproduction of target site of action renders herbicide to be ineffective (C); mutation at the specific target site of action results in reduced affinity for herbicide binding (D)

R-H – alkane; R-OH – alcohol; P450 – cytochrome P450 monooxygenase; GST – glutathione-S-transferase; GT – glycosyl transferase; AT – amino acid transferase; MT – malonyl transferase; ABC – ATP-binding cassette

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exclusionary resistance mechanism and with the advent of site-directed mutagenesis, overexpression of target enzyme is found to confer herbicide resistance in crops.

Exclusionary resistance mechanism. It is the physiological and morphological adaptations of the plants that prohibit the entry of the herbicide molecule into the target sites. Plants are bestowed with adaptive structures like cuticles, waxes, etc., which act as a first-level defence mechanism prohibiting the entry of herbicide molecules. Herbicide molecules are inactivated either through sequestration (binding) or translocated to metabolically inactive regions like cell walls and vacuoles (compartmentalization) by encasing them in vacuoles, dispersing them with exudates, and restricting their movement within plants thereby averting their detrimental effects. This mechanism is found in glyphosate-resistant plants which accumulate glyphosate molecules in the leaves, preventing their further movement within the plants. Ge et al. (2010) observed *Conyza canadensis* and *Lolium rigidum* compartmentalizing 85% of the glyphosate into the vacuoles.

Metabolic detoxification. One of the extensively employed mechanisms by plants against herbicides is the degradation or solubilization of toxins into non-toxic form by enhanced metabolism well before reaching the target site. Herbicides are detoxified through biochemical processes like oxidation, hydrolysis, reduction, and conjugation. The hydroxylation mechanism is commonly witnessed in plant resistant to cyanazine, bromoxinyl, 2,4-D, and propanil. *HIS1* (4-hydroxyphenylpyruvate dioxygenase (HPPD) inhibitor sensitive 1) gene identified by Maeda et al. (2019) in rice encodes $Fe^{2+/2-}$ oxoglutarate-dependent oxygenase that confers resistance to β-triketone and benzobicyclon herbicides by detoxification through hydroxylation mechanism. Cytochrome P450 plays a significant role in the detoxification of numerous herbicides through hydroxylation or dealkylation of ALS-, PS II – and ACCase inhibitors in addition to their pivotal role in various metabolic processes of lipids, secondary metabolites and hormones making them indispensable in the plant (Yu & Powles 2014). As of now, in rice only one cytochrome P450 gene conferring tolerance to photosynthesis inhibiting herbicide, bentazone has been identified.

Differential resistance at the site of action. All herbicides have a specific site of action, which is either controlled by a single or few genes, any change or mutation in that site will prevent herbicide from binding to them which confers resistance to the corresponding herbicides. This mechanism of altering the target site of action is the prime focus on developing resistance crops through site-directed mutagenesis. Most of the herbicide-resistant plants are found to have various target site specific mutations which make them resistant to various herbicides *viz.*, ALS, ACCase, 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) inhibiting herbicides. JD164, a rice variety with an altered site at S627N of the *AHAS* gene, conferred resistance to imazethapyr. Altered enzyme spatial conformation and reduced protein affinity for herbicides were the reasons behind the resistance towards ALS inhibitor herbicides caused by the mutation of amino acids in the ALS domain (Jin et al. 2022). Zhang et al. (2022) highlighted the cause of glufosinate resistance in *Eleusine indica* to be a naturally evolved point mutation involving Ser_{59}Gly substitution in $EiGS_{1\text{-}1}$ and transformed rice calli with this mutant *EiGS*$_{1\text{-}1}$ gene which showed resistance to glufosinate. OsGS1:1, a rice glutamine synthetase mutant harbouring Gly and Arg at positions 59 and 296 respectively showed elevated tolerance towards glufosinate (Deng et al. 2019).

Overexpression of the target enzyme. Herbicide resistance can also be achieved by over-production of the target molecular site of action *via* amplification of genes encoding target enzymes and their enhanced expression. As each herbicides target specific protein, their overproduction in plants makes the effect of herbicide to be negligible (Mulwa & Mwanza 2006). This mechanism is widely exploited in the commercialization of glyphosate-resistant transgenic crops. Hu (2014) observed that the over-expression of glutathione-S- transferase gene (*OsGSTL2*) in rice conferred enhance tolerance towards chlorsulfuran and glyphosate. Likewise, over-expression of cytochrome P450 genes in rice exhibited higher resistance against various herbicides with different mode of action through rapid degradation of herbicide molecules (Chen et al. 2009).

CONVENTIONAL BREEDING APPROACHES FOR HERBICIDE TOLERANCE

Screening of germplasm. Rice is considered the most highly diverse crop among the cereals. Rice germplasm exhibits variability for the traits *viz.*, plant height, grain quality, days from emergence to flowering, herbicide tolerance, yield, and other stress-related traits. The working collection of USDA-

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ARS rice germplasm containing 17 279 accessions was evaluated for 30 descriptors with herbicide tolerance as one among them and identified accessions conferring tolerance to non-selective herbicides *viz.*, glyphosate and sulfosate (Dilday et al. 1999). Kuk et al. (2008) unveiled the presence of the vast amount of genetic variability within the rice germplasm for various herbicides. The germplasm should be evaluated by screening under herbicide-sprayed conditions where germplasm lines are sprayed with varying doses of respective herbicides. The lines should be evaluated for the parameters namely, average plant stand, leaf damage score, days to flowering, days to maturity, floral development, photosynthetic ability, normalized difference vegetation index (NDVI) score, difference in yield between control and herbicide sprayed (treatment), harvest index, *etc.*, (Prakash et al. 2017). Further screening of the selected best lines should be carried out at multi locations for stability analysis of the herbicide tolerance. Superior lines identified can be either released as a variety or utilized as a donor in further breeding programme for the development of herbicide-tolerant variety.

Screening of wild relatives. Wild relatives of crops harbour desirable alleles for stress-resilient traits which were lost in the context of domestication. The phenomenon of superweeds led to the thought of utilizing wild relatives and volunteer weeds in developing herbicide tolerance in plants (Bain et al. 2017). Wild relatives of rice such as red rice (weedy rice) co-exist with rice as weeds in fields. Application of herbicide followed by selection pressure results in the development of herbicide in weeds (Prakash et al. 2020). Gene flow occurs frequently between wild relatives and crops and similarly among wild relatives themselves (Song et al. 2003). Shrestha et al. (2022) identified B2 weedy accession to be distinct from other 54 weedy accessions with elevated herbicide tolerance and allelopathic properties. Low breeding barrier between weedy rice and rice can be exploited for rice improvement programme as they are closely associated. Transfer of desirable herbicide tolerance/resistance alleles from weeds to cultivated rice can be achieved through hybridization and selection.

Induced mutagenesis. Genetic diversity in crops can be enhanced through induced mutagenesis using physical and chemical mutagens. Mutation serves to be an excellent source of herbicide tolerance even when there is no sufficient variability available in the germplasm (Bernasconi et al. 1995). Induced mutagenesis proves to be a reliable alternative for developing rice varieties with resilience to various stresses as it has the potential to speed up the spontaneous mutation and expand the genetic pool of allelic variants useful for genetic improvement (Viana et al. 2019). Clearfield rice varieties *viz.*, CL121 and CL141 conferring tolerance against imazethapyr have been developed from 93AS3510 mutant (Ethyl Methane Sulfonate) by BASF (Sudianto et al. 2013). Argentine scholars carried out ethyl methane sulfonate (EMS) mutagenesis on the local variety IRGA417 and developed Puita' Intacl, a popular mutant variety harbouring mutation at the Ala122Thr region of *ALS* gene (Goulart et al. 2012). Likewise, IMINTA1 and IMINTA4 mutants were developed from IRGA417 using sodium azide. JD 164 is an imazethapyr tolerant japonica variety obtained by crossing Hudao55 (HD55) with a chemically mutated (EMS) indica variety 9311 containing single mutation (S627N) in AHAS conferring tolerance towards imidazolinone herbicides, including imazethapyr and imazamox (Piao et al. 2018). Correspondingly, using EMS, rice varieties showing resistance to ACCase-inhibitor and quizalofop-p-ethyl were developed (Camacho et al. 2019). Herbicide-tolerant mutant (HTM) Robin, an imazethapyr tolerant rice mutant was identified from an EMS mutagenized population an upland variety, Nagina 22 (N22) containing approximately 100 000 plants in M_2 generation (Shoba et al. 2017). Suitable donor parents for the future backcross breeding with adapted lines are listed in the Table 5.

Marker-assisted backcross breeding. Marker-assisted backcross breeding (MABB) provides an effective and precise means of trait introgression controlled by a single gene while retaining the core characteristics of the recurrent plant (Collard & Mackill 2008). It is found to be effective for genes or QTLs with major effects. This method utilizes molecular markers for identifying target loci, minimizing the linkage drag, and accelerating the recurrent parent genome recovery during back-crossing (Hospital 2001). Two imidazolinone-tolerant irrigated rice lines, CNA10756 (BRS Sinuelo CL) and CNA10757 were developed using BRS 7 Taim and BRS Pelota as recurrent parents and mutant line, 93AS3510 as a donor of the herbicide tolerance allele (Rangel et al. 2010). Grover et al. (2020) used MABB for transferring the mutant allele of acetohydroxy acid synthase (AHAS) gene, from the donor parent (DP) Robin into the genetic background of an elite popular Basmati rice variety, Pusa Basmati 1121 (PB 1121), for tolerance towards imidazolinone group of herbicides. The gene-linked

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Table 5. Non- transgenic rice varieties developed through mutagenesis and hybridization

Mutant	Wild type/donor parent	Amino acid substitution	Method	Herbicide	Gene	Reference
93-AS3510	AS3510	G654E	EMS	imidazolinone	ALS	Sudianto et al. (2013)
CL 121 & CL 141	93-AS3510	–	hybridization with Cocodrie and Maybelle	imidazolinone	ALS	Wenefrida et al. (2007)
Puita-Inta-CL	IRGA 417	A122T	EMS	imidazolinone	ALS	Livore et al. (2003)
PWC-16	Cypress rice	S653A	EMS	imidazolinone	ALS	Wenefrida et al. (2004)
CL161 and Clearfield XL8	PWC-16	S653A	EMS	imidazolinone	ALS	Wenefrida et al. (2004)
SH Hyb	CL161	S186P, K416E, L662P	spontaneous mutation	imazethapyr	ALS	Rajguru et al. (2005)
IMINTA1, IMINTA4	IRGA417	A122T	sodium azide	imidazolinone	ALS	Tan et al. (2006)
IRGA 422 CL	93-AS3510	G654E	EMS	imidazolinone	ALS	Roso et al. (2010)
MR220CL1 and MR220CL2	CL1770	–	hybridization with MR220	imidazolinone	ALS	Sudianto et al. (2013)
HTM-N22	N22	S627D, G152E	EMS	imazethapyr	AHAS	Shoba et al. (2017)
JD164	9311	S627N	EMS	imazethapyr	AHAS	Piao et al. (2018)
Sabbore (APPs resistant)	Sabbore	W2027C	gamma rays	aryloxyphenoxy propionate	ACC	de Andrade et al. (2018)
BRS A701 CL	Cypress CL	–	hybridization with BRS 7 Taim	imidazolinone	ALS	Rangel et al. (2018)

EMS – ethyl methane sulfonate; ALS – acetolactate synthase; ACC – acetyl-CoA carboxylase; AHAS – acetohydroxy acid synthase

marker RM 6844 and 112 SSR markers were utilized for foreground and background selection, respectively. A set of 12 BC4F4 near-isogenic lines (NILs) with recurrent parent genome (RPG) recovery ranging from 98.66 to 99.55% were developed.

Mapping of herbicide tolerance trait. Following the identification of sources for herbicide tolerance, the next important step is deciphering the mechanism behind it and mapping the genomic location of the genes imparting herbicide tolerance in a precise manner. Identification of genes conferring resistance is empirical to develop functional markers which in turn helps in locating the precise genomic region containing genes associated with resistance. Shoba et al. (2017) carried out the genetic characterization of HTM Robin and analysed the inheritance herbicide tolerance in a cross between Pusa 1656- 10-61/HTM which showed that this trait is governed by a single dominant gene. Bulked segregant analysis (BSA) using microsatellite markers flanking the three putative candidate genes viz., an *acetolactate synthase* (*ALS*) on chromosome 6 and two *acetohydroxy acid synthase (AHAS*) genes, one on chromosomes 2 and another on chromosome 4 respectively were carried out to identify the causal gene. The marker, RM 6844 on chromosome 2, which is located 0.16 Mbp upstream of AHAS (LOC_Os02g30630), was found to be linked with herbicide tolerance.

BIOTECHNOLOGICAL APPROACHES FOR HERBICIDE TOLERANCE

Tissue culture and selection. Plant tissue culture is the simplest biotechnological approach which is purely based on the principle of "totipotency". The discovery of heritable changes in the genome of plant cells known as soma-clonal variations, which can be triggered by applying selective pressure in vitro conditions (Hernández-Soto et al. 2021), paved the way for the selection of desirable traits like herbicide resistance from *in vitro* culture. Bae et al. (2002) isolated 3 HT rice lines *viz*., CHB1, CHB2 and CHB3 against cyhalofop butyl (CHB) from gamma-irradiated anther cell cultures. Ekanayaka et al. (2016) proved tissue culture could be a potential tool for developing HT rice calli by inducing glyphosate tolerance in a susceptible variety Bg250 variety *via* 0.2% EMS treatment on seed-derived calli. They also identified an amplified fragment length polymorphism (AFLP) marker, E11M32 specific to the HT trait in rice through which can further utilized to identify HT rice mutant.

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Genome editing. Genome editing harbours programmable nucleases for genetic manipulation of organisms by creating double-stranded breaks at desired locations in the genome. It utilizes the innate DNA repair mechanisms *viz.*, non-homologous end joining (NHEJ) and HR (homologous recombination), which allows highly specific and efficient manipulation of the genome through insertion, deletion, and substitution of target DNA (Romero & Gatica-Arias 2019). For developing herbicide-tolerant cultivars, genome editing *via* homologous recombination and substitution of herbicide-specific target domain of target enzyme with a mutated variant having reduced affinity for binding of herbicide molecule could be a reliable method. Li et al. (2016a) made use of CRISPR-Cas 9 mediated NHEJ mechanism to execute site-directed substitution of Thr_{102}Ile and Pro_{106}Ser (TIPS) bases of rice EPSPS gene with the corresponding TIPS mutations for glyphosate resistance. Lately, overexpression of this gene in rice led to enhanced yield and glyphosate tolerance at the field level (Achary et al. 2020). Cytosine base editor (CBE) was employed by Zhang et al. (2021) to generate a large number of missense mutations in the codons *viz.*, Pro_{171} and Gly_{628} of *ALS* gene in rice to exhibit tolerance against bispyribac sodium. Kuang et al. (2020) put forward a technique called the base-editing mediated gene evolution (BEMGE) method, which utilizes cytosine and adenine base editors in conjunction with an sgRNA library that encompasses the entire coding region of the target gene in order to efficiently induce a wide range of mutations within the target gene. The mutant with the highest bispyribac sodium resistance was Pro171Phe among the other mutants viz., Pro171Leu, Arg190His, Pro171Ser, Ala154Thr and Ala152Thr which were obtained by editing the rice ALS gene using the BEMGE method. Ren et al. (2023) employed BEMGE method to evolve *OsGS1* gene endogenously and identified two novel and one previously reported glufosinate resistant alleles *viz.*, *OsGS1-AVPS*, *OsGS1-+AF* and *OsGS1-SGTA* respectively. Zafar et al. (2023) evolved bispyribac-sodium tolerant Super Basmati by introducing point mutation (W548L) *via* HDR mediated CRISPR-Cas9 system. The mutated herbicide resistance genes obtained by genome editing techniques are listed in Table 6.

Transgenic approach. In the context of functional genomics and genetic improvement of crops, genetic transformation is still the most sought-after technology especially for introgressing certain new traits and modifying or recombining already existing traits (Anjanappa & Gruissem 2021). Herbicide resistance *via* transgenesis can be achieved by the following four mechanisms which can be either used alone or in combination with others.

– Introgression of genes encoding herbicide degrading or detoxifying enzymes.
– Introgression of genes encoding herbicide insensitive form of the corresponding normal functioning enzyme or overexpression of genes encoding herbicide specific target enzyme in such a way that normal metabolism of plants remains unaltered.
– Modification of herbicide-specific target site of action rendering herbicide from binding to it.
– Engineering plants for active herbicide efflux.

Transgenic versions of IR64 plants containing CP4 EPSPS gene were found to be tolerant to 10 times the dosage of commercial recommendation of glyphosate (Chhapekar et al. 2015). Cui et al. (2016) identified a novel gene encoding glyphosate resistance labelled as *I. variabilis* EPSPS from *Isoptericola variabilis* and transformed it into a *japonica* variety, Zhonghua 11. Subsequently, highly resistant transgenic events were produced. Nevertheless, Yi et al. (2016) transformed *aroAJ.sp* gene cloned from *Janibacter* sp. into Minghui 86 to generate high glyphosate-resistant transgenic plants. Fartyal et al. (2018) developed a transgenic rice event from Swarna (*indica* variety) having low herbicide residue in addition to high resistance towards glyphosate *via* transformation of two genes *viz.*, mutant *epsps* gene and *igrA* gene. (Cui et al. 2020) obtained three transgenic restorer line namely MY28, MY50 and MY51 by introgression of *I. variabilis* EPSPS gene into elite restorer line Minghui 86.

UNINTENDED CONSEQUENCES OF HTR TECHNOLOGY

The unintended consequences of herbicide tolerance in rice farming are multifaceted and require careful consideration. Some of the major consequences of herbicide-tolerant rice were discussed as follows.

Weed shifts. A swift change in the spectrum of weeds predominantly towards non-native, invasive weeds and the evolution of herbicide-resistant weeds were the repercussions of monoculture of herbicide-tolerant rice and exclusive reliance on the corresponding herbicide. This shift in weed species includes a paradigm change in the diversity or density of weed flora as a result of existing weed control practices. In glyphosate resistant crops (GRCs), this weed species shifts were mainly due to highly

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Table 6. Herbicide-resistant genes and corresponding mutations obtained by genome editing tools

Gene	Position	Protein	Obtained mutation	Method	Herbicide	References
Acetohydroxy acid synthase	Chr 2	Q6K2E8	W548 L or P171S	recombinant protein	imidazolinone	Kawai et al. (2008)
			W548, E549	CRISPR-prime editing		Xu et al. (2020)
			W548L, S627I	CRISPR		Sun et al. (2016)
			W548L, P171S	CRISPR-prime editing		Xu et al. (2020), Lin et al. (2020)
			G628 W	CRISPR/Cas9		Wang et al. (2021)
Os02g0510200			A96V (C287 T)	CRISPR/Cas9 base editor	imazamox	Shimatani et al. (2017)
HPPD inhibitor sensitive 1 (*HIS1*) *Os02g0280700*		Fe (II)/2-oxoglutarate – dependent oxygenase	28-bp deletion allele (his1)	wild Nipponbare lacked deletion	β-triketone herbicides	Maeda et al. (2019)
ACCase2	Chr 5	B9FK36	I1879V, W2125S	CRISPR/Cas9 base editor	ACC inhibitor herbicides	Liu et al. (2020)
Os05g0295300			D2176G, G2201A	CRISPR-prime editing		Xu et al. (2020)
			C2186R	CRISPR-base editor		Li et al. (2018)
			P1927 F, W2125C, S1866 F and A1884P	CRISPR-base editor		Li et al. (2020b)
OsEPSPS	Chr 6	A0A0N7KLH2	T169I, A170 V P173S	CRISPR-prime editing	glyphosate	Li et al. (2020a)
Os06g0133900			T102I + P106S	CRISPR		Li et al. (2016b)
OsTubA2 *Os11g0247300*	Chr 11	Q53M51	Q53M51	CRISPR/Cas9 base editor	pendimethalin	Liu et al. (2021)

HPPD – 4-hydroxyphenylpyruvate dioxygenase; ACC – acetyl-CoA carboxylase

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resistant biotypes or late blooming cohorts which avoids glyphosate effects. The emerging problematic weeds of GRCs are johnsongrass, Common lambsquarters, *Ambrosia* sp., Italian ryegrass, *Ipomoea* sp., *Amaranthus* sp., *Commelina*, *Cyperus* sp. and *Setaria* sp. Integrated weed management practices are of paramount importance in controlling/delaying weed shifts and sustaining HTR in the long run (Reddy et al. 2010).

HT rice as volunteer plants. It is becoming more common to find volunteer rice plants among the succeeding crop, especially in the tropics where there is no winterkill of seeds. The shattering ability of the cultivar, efficiency of previous crop harvest, and weed management between cropping seasons were some of the factors that highly influence the density of volunteer rice plants (Sudianto et al. 2013). Volunteer HT rice would be a major constraint when HT trait is the same in both volunteer and HT plants being cultivated in the same season. These volunteer plants act as an alternative host for pests and diseases preventing the crop from reaching its maximum productivity (Reddy & Nandula 2012). Hardke (2020) noticed that there was an abrupt increase in imidazolinone resistant *O. sativa* f. *spontanea* population due to the presence of HT hybrid volunteers and hybridization with weedy relatives. Volunteer plants from transgenic rice pose a serious threat because of potential gene flow from them to weedy rice which calls for effective and efficient weed management practices both in and out of season in the herbicide-tolerant rice system.

Potential gene flow. Futuyma (1979) defined gene flow as "the incorporation of genes into the gene pool of one population from the gene pool of other populations". It is inevitable even in self-pollinating crops provided when compatible species exhibit synchronized flowering and are sympatrically distributed (Kumar et al. 2008). Several cases of gene flow from HT rice to wild/weedy relatives of rice have been reported in USA, China and Europe (Shivrain et al. 2006). The rate of outcrossing in these cases was observed to be less than 1% and sometimes, it can vary from 1% to 52% based on cultivar type (Langevin et al. 1990) where *indica* cultivars are highly compatible with wild/weed species compared to *japonica* cultivars (Oka 2012). The cascade effects of gene flow include (a) evolution of weeds with increased invasiveness; (b) herbicide-tolerant crops with insignificant effect on weed management and (c) biodiversity loss (Kumar et al. 2008). The invasiveness of weeds can be enhanced either through the introgression of HT trait or selection pressure due to exclusive reliance on selective herbicide. Regulatory measures and careful management practices are essential to mitigate these risks.

Genetic erosion of wild species. Ellstrand (2003) indicated that there is a heightened probability of genetic erosion of wild species mainly attributed to the flow of transgene. Genetic assimilation in wild species wherein unique genes of wild plants were replaced by crop genes *via* demographic swamping or repeated hybridization which ultimately results in the shrinkage of biodiversity (Wolf et al. 2001). Inevitably, HT rice has a potential effect on the *in-situ* conservation of biodiversity of wild species, particularly when the transgenes pose any fitness penalty or advantage. However, the fitness effect of HT trait is comparatively negligible as the trait is considered to be neutral in the absence of herbicide application (Kumar et al. 2008).

Herbicide resistant weeds. The genetic evolution of weeds with herbicide resistance is primarily due to selection pressure exerted by extensive application of herbicide (Owen & Zelaya 2005) (Figure 4) and through gene flow from herbicide-resistant crops (Figure 5). As imidazolinone exerts a relatively high

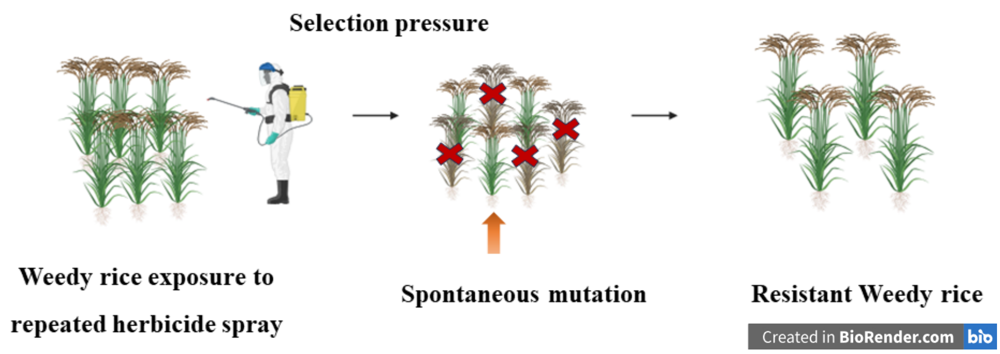

Figure 4. Evolution of herbicide-resistant weeds through spontaneous mutation

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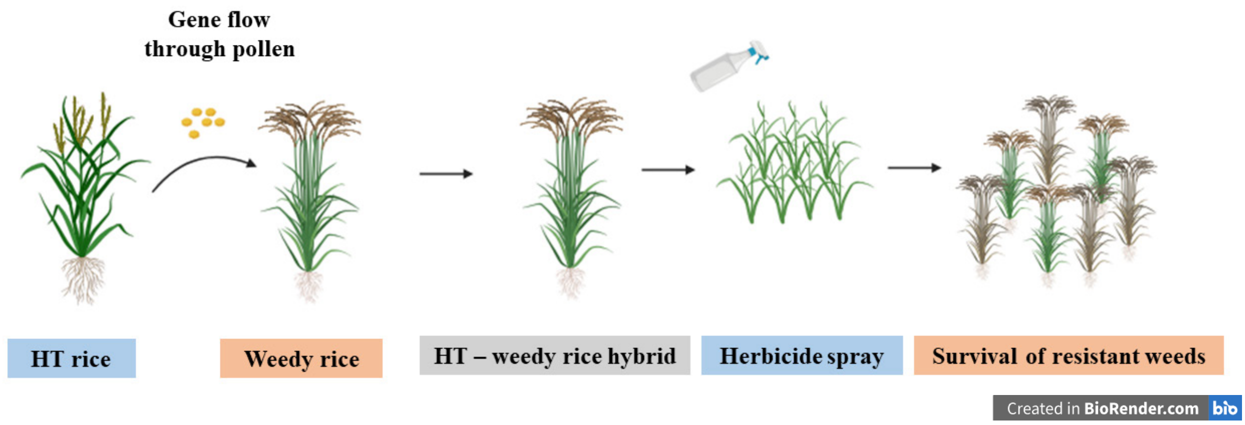

Figure 5. Evolution of herbicide-resistant weeds through gene flow from herbicide-tolerant (HT) rice

selection pressure, the evolution of imidazolinone-resistant weeds has been considerably higher than that of glyphosate and other herbicides (Tranel & Wright 2002). HR weeds of rice field reported across the world are listed in Table 7 (Heap 2024).

Public perception and acceptance. Transgenic herbicide-tolerant rice had faced public scrutiny and scepticism for commercialization regarding the harmful effects of transgene on the environment and the associated use of herbicides (Reddy & Nandula 2012). Building public trust and ensuring transparency in the development and regulation of herbicide-tolerant rice technology is crucial. Momentarily, Bt cotton is the sole GM crop authorized for commercial production by the Genetic Engineering Appraisal Committee (GEAC) of Ministry of Environment, Forest and Climate Change (MoEF&CC) under the Government of India following a thorough assessment and fulfilment of all legal criteria. Strong opposition from environmentalists, consumers and farmers in India who are against the idea of commercialization of genetically modified (GM) food crop have resulted in an indefinite moratorium on Bt brinjal during 2010 and the approval of Dhara Mustard Hybrid-11 (DMH-11), a GM mustard have been withheld by the Indian Government (Singh et al. 2020). India had been reluctant to adopt GM food crops, but the current government, which is in favour of GMOs, has taken necessary steps to facilitate adequate field trials and regulatory measures.

MANOEUVRES TO OVERCOME THE NEGATIVE EFFECTS OF HTR

Meticulous stewardship guidelines are required for the effective utilization of HR rice in a long run. Lax fidelity to these guidelines results in the development of herbicide resistance in weeds due to outcrossing between HTR and weedy rice (Sudianto et al. 2013). Necessary steps should be taken to prevent the escape of HT gene to weedy rice and to minimize the dispersal of weed seeds.

The following are the best weed control practices recommended for Clearfield® production system (Burgos et al. 2008):

– Utilization of authenticated seed.
– Implementation of herbicide program which includes herbicides with different modes of action available for rice cultivation in all possible combinations.
– Adoption of suitable management practices in which maximum efficacy of herbicide is ensured.
– Synchronization of flowering between weedy rice and HT rice should be minimized by adjusting the sowing dates.
– Prevention of remnant weeds from producing seeds.
– Adoption of crop rotation with imidazolinone tolerant crops (legumes, pastures, etc.,) to prevent seed production of weedy or volunteer rice.
– Zero or minimum tillage can be practiced.
– Stale seedbed – to reduce the density of the weedy rice population which was allowed to germinate before rice planting and killed either using herbicide or by tillage.
– Weed-free fields should be harvested first followed by weed-infested fields.
– Rotation of Clearfield® with other crops to break the cycle of weedy rice.

CONCLUSION

Though DSR is gaining popularity as a resource conservation technique, its effective adaptation

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Table 7. List of globally identified herbicide-resistant weeds of rice (Heap 2024)

Species	Common name	Country	First year	Site of action
Cyperus difformis	small flower umbrella sedge	Australia	1994	inhibition of acetolactate synthase
Echinochloa crus-galli var. *crus-galli*	barnyard grass	Brazil	1999	auxin mimics
Cyperus difformis	small flower umbrella sedge	Brazil	2000	inhibition of acetolactate synthase
Cyperus difformis	small flower umbrella sedge	Brazil	2000	inhibition of acetolactate synthase
Fimbristylis miliacea	globe fringer ush	Venezuela	2010	inhibition of acetolactate synthase
Echinochloa colona	jungle rice	Australia	2010	inhibition of enolpyruvyl shikimate phosphate synthase
Cyperus iria	rice flat sedge	Brazil	2014	inhibition of acetolactate synthase
Echinochloa crus-galli var. *crus-galli*	barnyard grass	Brazil	2015	multiple resistance: 3 sites of action inhibition of acetyl CoA carboxylase inhibition of acetolactate synthase inhibition of cellulose synthesis
Echinochloa oryzoides	early watergrass	Argentina	2016	inhibition of enolpyruvyl shikimate phosphate synthase
Cyperus difformis	small flower umbrella sedge	India	2017	inhibition of acetolactate synthase
Echinochloa crus-galli var. *crus-galli*	barnyard grass	India	2017	inhibition of acetolactate synthase
Echinochloa crus-galli var. *crus-galli*	barnyard grass	Brazil	2018	multiple resistance: 3 sites of action inhibition of acetolactate synthase inhibition of cellulose synthesis auxin mimics
Oryza sativa var. *sylvatica*	red rice	Colombia	2018	inhibition of acetolactate synthase
Chloris radiata	radiate fingergrass	Colombia	2019	multiple resistance: 2 sites of action inhibition of acetolactate synthase inhibition of enolpyruvyl shikimate phosphate synthase
Oryza sativa var. *sylvatica*	red rice	Turkey	2020	inhibition of acetolactate synthase
Echinochloa crus-galli var. *crus-galli*	barnyard grass	Australia	2021	inhibition of acetyl CoA carboxylase
Digitaria ciliaris	southern crabgrass	China	2021	inhibition of acetyl CoA carboxylase
Ammannia multiflora	many flowered ammannia	China	2022	inhibition of acetolactate synthase
Echinochloa phyllopogon	late watergrass	China	2023	inhibition of acetolactate synthase
Leptochloa chinensis	Chinese sprangle top	China	2023	inhibition of hydroxyphenyl pyruvate dioxygenase

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to meet the demand of the expanding population is restricted predominately due to weed menace. Chemical control of weeds utilizing broad-spectrum herbicides is found to be an effective and efficient option in the context of labour shortage, wage, and availability of low-cost herbicides. With the advent of HT rice varieties, chemical control can be exploited to the fullest as it allows for flexibility in the timely application of herbicide and controls a wide spectrum of weeds without injuring the rice and the subsequent crops in case of crop rotation. Introgression of herbicide tolerance trait into adapted drought or upland rice varieties could be a potential breakthrough in achieving higher yield under DSR conditions. While the debate on whether to approve GM rice or not for cultivation is a never-ending saga, non-transgenic HT rice could be a futuristic option for DSR provided with the dwelling natural resources and ever-changing climatic conditions. Framing effective stewardship guidelines for HTR utilization, creating awareness among farmers, crop rotation and integrating it with other weed management practices can help in realizing the fullest potential of HT rice varieties without any harmful effects on the environment and biodiversity.

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