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水稻田除草剂的应用及杂草抗药性现状

刘兴林,孙 涛,付声姣,钟国华
(华南农业大学 昆虫毒理研究室,广东 广州 510642)

[摘 要] 稻田杂草是造成水稻减产的最大影响因素,化学除草技术已经成为杂草防除的重要手段。针对水稻田杂草开发了多种除草剂,形成了独特的稻田杂草化学防除体系。近年来,由于除草剂大量、高频率的不合理使用,稻田杂草抗药性呈明显上升趋势,稗草、雨久花、慈姑、耳叶水苋等稻田杂草的抗药性问题已较为严重。文章综述了我国水稻田主要除草剂的应用及稻田抗药性杂草的发生现状,并对几类代表性除草剂品种的抗药性机理进行了简要分析,提出了稻田抗性杂草的治理策略。

[关键词] 水稻;除草剂;抗药性杂草;抗性机制;综合防治
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Herbicide application and weeds resistance in rice field in China

LIU Xing-lin, SUN Tao, FU Sheng-jiao, ZHONG Guo-hua
(*Lab of Insect Toxicology, South China Agricultural University, Guangzhou, Guangdong* 510642, *China*)

Abstract: Weeds in rice field are the biggest influential factor that decreases production, and chemical weeds control technology had become an important means of weeds control. A variety of herbicides are registered in China for efficient management of weeds in rice fields. Meanwhile, the frequent, large and continuous use of herbicides gradually increases weeds resistance. Resistant weeds such as *Echinochloa crusgalli* (L.) Beauv., *Monochoria korsakowii* Regel et Maack, *Sagittaria montevidensis* and *Ammannia arenaria* H. B. K in paddy fields have been reported in recent years. In this paper, the application status of herbicides and herbicide-resistant weeds in rice fields in China were reviewed, and resistance mechanisms of weeds were summarized, especially for butachlor, quinclorac and bensulfuron-methyl. In addition, integrated management strategies for resistant weeds were proposed.

Key words: rice; herbicides; herbicide resistance; resistance mechanisms; integrated management

水稻是世界上重要的粮食作物,高效、绿色防控水稻生产过程中的有害生物,减少粮食损失,是植物保护领域的最重要工作之一。在现代农业生产系统中,杂草已成为稻田中最主要的有害生物,它与作物争肥、争光、争空间,传播病虫,严重影响作物的产量和品质。2002 年统计表明水稻草害发生面积 140.8 万 hm^2,减产稻米 100 亿 kg,占总减产量的近 60%[1]。除草剂的应用在保证粮食增产和稳产中起到了重要的作用,是目前世界范围内采取最为普遍的除草方式。1956 年,我国在稻田应用 2,4-D 除草,标志着除草剂在我国的大面积使用和应用研究推广的开始。1993 年,我国首次明确报道了稻田稗草对禾草丹和丁草胺的抗药性[2-3],标志着我国稻田杂草抗药性研究工作的开始和兴起。近年来,抗药

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[作者简介] 刘兴林(1990-),男,四川德阳人,在读硕士,主要从事杂草抗药性机理及治理研究。E-mail:xllsana@163.com
[通信作者] 钟国华(1973-),男,广东梅州人,教授,博士,主要从事昆虫生理毒理及杂草治理研究。
E-mail:guohuazhong@scau.edu.cn

性的快速发展给我国稻田化学除草带来了考验,吉林、湖北、湖南、浙江、广东等主要水稻产区均先后报道了多种稻田抗性杂草的发生发展。本研究归纳了我国水稻田主要除草剂的应用及稻田抗药性杂草的发生现状,并对几类代表性除草剂品种的抗药性机理进行了简要分析,提出了稻田杂草的综合治理策略。

1 稻田除草剂的应用

根据形态学差异,稻田杂草可分为单子叶杂草和双子叶杂草,禾本科杂草和莎草科杂草属于单子叶杂草,而阔叶杂草一般指双子叶杂草,这为根据杂草的种类选择不同除草剂提供了依据[4]。经过几十年的发展,稻田除草剂品种数量与日剧增,形成了包括酰胺类(丁草胺、丙草胺、苯噻酰草胺)、磺酰胺类(五氟磺草胺)、二苯醚类(乙羧氟草醚)、四唑啉酮类(四唑酰草胺)、硫代氨基甲酸酯类(禾草丹)、二硝基苯胺类(二甲戊灵、氟乐灵)、联吡啶类(百草枯)、喹啉羧酸类(二氯喹啉酸)、羧酸酯类(氰氟草酯、噁唑酰草胺)、有机磷类(莎稗磷)、磺酰脲类(苄嘧磺隆、醚磺隆等)和杂环类(噁草酮、异恶草松)等类别的化学防除体系。按照其防除的杂草靶标,可将目前我国稻田中应用的除草剂单剂分为禾本科杂草除草剂、阔叶杂草和莎草科杂草除草剂及水稻田广谱性除草剂3类。

1.1 禾本科杂草除草剂

丁草胺(butachlor),由美国孟山都公司开发,1982年在我国正式推广应用,直至现在仍在华南地区广泛使用,主要用于防除稗草等禾本科杂草。噁唑酰草胺(metamifop)是由韩国东部韩农化学公司开发的苗后应用除草剂,2010年在我国登记,对水稻具有高度的安全性,主要用于防除禾本科杂草,对阔叶杂草及莎草科杂草无效[5-6]。二氯喹啉酸(quinclorac)属激素型喹啉羧酸类除草剂,杂草中毒症状与生长素类作用相似,主要用于防治稗草且适用期很长,1～7叶期均有效,对水稻安全性好,在我国稻区广泛使用,许多地区的杂草对其产生了严重的抗药性。氰氟草酯(cyhalofop-butyl),美国陶氏益农公司开发,2006年在我国正式登记,对防除千金子有特效,尤其适用于直播稻田。此外,禾草丹、敌稗、异恶草松等也是稻田广泛应用的禾本科杂草除草剂(表1)。

表1 水稻田常用禾本科杂草除草剂单剂品种

Table 1 Herbicides commonly used in rice field against gramineous weeds

通用名称 Common name	作用方式 Mode of action	类别 Family	作用特点 Function characteristics	施药时期 Applying time	主要敏感杂草 Main susceptible weeds
丙草胺 Pretilachlor	内吸(抑制细胞分裂) Systematic (Inhibition of cell division)	氯代乙酰胺类 Chloroacetamides	通过植物下胚轴、中胚轴和胚芽鞘吸收,根部略有吸收,直接干扰杂草体内蛋白质的合成,并对光合及呼吸作用有间接影响 Absorbed through the plant hypocotyl, mesocotyl and coleoptile, root absorbed slightly and the weed body protein synthesis was directly interfered, and photosynthesis and respiration could have been indirectly affected	杂草出芽前或苗后早期 At pre-emergence or early post-emergence of weeds	稗草、异型莎草、牛毛毡、鸭舌草、窄叶泽泻等 *Echinochloa crusgalli*, *Cyperus difformis*, *Eleocharis yokoscensis*, *Monochoria vaginalis*, *Alisma canaliculatum*, etc.
丁草胺 Butachlor	内吸(抑制细胞分裂) Systematic (Inhibition of cell division)	氯代乙酰胺类 Chloroacetamides	主要通过杂草幼芽和幼小的次生根吸收,抑制体内蛋白质的合成 Mainly absorbed through the weed shoots and young secondary root, protein synthesis in the plant body can be inhibited	稗草在萌芽或1.5叶期以前 At emergence or 1.5 leaf stage before of barnyard grass	稗草、千金子、异型莎草、碎米莎草、牛毛毡、鸭舌草、节节草、尖瓣花、萤蔺等 *Echinochloa crusgalli*, *Leptochloa chinensis*, *Cyperus difformis*, *Cyperus iria*, *Eleocharis yokoscensis*, *Monochoria vaginalis*, *Equisetum ramosissimum*, *Sphenoclea zeylanica*, *Scirpus juncoides*, etc.
苯噻酰草胺 Mefenacet	内吸(抑制细胞生长和分裂) Systematic (Inhibition of cell division)	氧乙酰胺类 Chloroacetamides	主要通过芽鞘和根吸收,经木质部和韧皮部传导至杂草的幼芽和嫩叶,阻止杂草生长点细胞分裂伸长 Mainly absorbed through bud sheath and root, it can be conducted to weed shoots and leaves through the xylem and phloem, preventing cell division and elongation of weeds growing point	稗草在萌芽至2叶期 At emergence up to 2 leaf stage of barnyard grass	稗草、千金子、牛毛毡、泽漆、鸭舌草、节节菜、异型莎草、球穗扁莎草、碎米莎草等 *Echinochloa crusgalli*, *Leptochloa chinensis*, *Eleocharis yokoscensis*, *Euphorbia helioscopia*, *Monochoria vaginalis*, *Rotala indica*, *Cyperus difformis*, *Pycreus globosus*, *Cyperus iria*, etc.

续表 1　Continued table 1

通用名称 Common name	作用方式 Mode of action	类别 Family	作用特点 Function characteristics	施药时期 Applying time	主要敏感杂草 Main susceptible weeds
四唑酰草胺 Fentrazamide	内吸（抑制超长链脂肪酸合成） Systematic (Inhibition of VLCFAs)	四唑啉酮类 Tetrazolinones	抑制叶鞘表皮细胞向纵方向伸长，使叶、节间、分叉、冠根生长受阻 Inhibition of leaf sheath epidermal cell elongation in longitudinal direction, so that the leaf, stem, fork and crown root stunted	稗草 2.5 叶期前 At 2.5 leaf stage before of barnyard grass	稗草、千金子、异型莎草、牛毛毡和鸭舌草等 *Echinochloa crusgalli*, *Leptochloa chinensis*, *Cyperus difformis*, *Eleocharis yokoscensis*, *Monochoria vaginalis*, etc
敌稗 Propanil	触杀（抑制光合作用 PSⅡ） Contact toxicity (Inhibition of photosynthesis at PSⅡ)	酰胺类 Amides	在稗草体内由于缺乏芳基羧基酰胺水解酶解毒，细胞膜最先遭到破坏 Tag type. Due to a lack of aryl carboxyl amide hydrolase detoxification in the body of barnyard grass, the cell membrane will be destroyed first	稗草 1 叶 1 心至 2 叶 1 心期 At 1 to 2 leaf stage of barnyard grass	稗草、鸭舌草、水芹、马唐、狗尾草等 *Echinochloa crusgalli*, *Monochoria vaginalis*, *Oenanthe javanica*, *Digitaria sanguinalis*, *Setaria viridis*, etc
禾草丹 Thiobencarb	内吸（抑制 α-淀粉酶活性，抑制蛋白质及脂类物质合成） Systematic (Reduce α-amylase activity, inhibition of protein and lipid synthesis)	硫代氨基甲酸酯类 Thiocarbamates	被杂草的根部和幼芽吸收，特别是幼芽吸收后转移到植物体内，对生长点有很强的抑制作用。阻碍 α-淀粉酶和蛋白质合成，对植物细胞有丝分裂也有强烈的抑制作用。 Absorbed by weed roots and shoots, especially after germ absorption and then transferred it to the plant body and had a strong inhibitory effect on weeds growing point. And hinder α-amylase and protein synthesis, the plant cell mitosis also could been strongly inhibited	稻苗 2～3 叶期施药，杂草均应在 2 叶期以前 At 2 to 3 leaf stage of rice, 2 leaf stage before of weeds	稗草、牛毛草、鸭舌草、矮慈姑、水马齿、香附子等 *Echinochloa crusgalli*, *Bulbostylis barbata*, *Monochoria vaginalis*, *Sagittaria pygmaea*, *Callitriche stagnalis*, *Cyperus rotundus*, etc
禾草敌 Molinate	内吸（抑制 α-淀粉酶活性，抑制蛋白质及脂类物质合成） Systematic (Reduce α-amylase activity, Inhibition of protein and lipid synthesis)	硫代氨基甲酸酯类 Thiocarbamates	被杂草初生根尤其是芽鞘吸收，并积累在生长点的分生组织，阻制蛋白质合成，使增殖的细胞缺乏蛋白质及原生质而形成空脆 Absorbed by weeds primary roots, especially coleoptile, and accumulated in the meristem of the growing point, hindered protein synthesis, so that the proliferated cells became embrittlement by the lack of protein and plasma	1～4 叶期的各种生态型稗草 At 1 to 4 leaf stage of all kinds of barnyard grass biotypes	稗草、牛毛毡、碎米莎草、异型莎草等 *Echinochloa crusgalli*, *Eleocharis yokoscensis*, *Cyperus iria*, *Cyperus difformis*, etc
莎稗磷 Anilofos	内吸（抑制细胞分裂） Systematic (Inhibition of cell division)	有机磷类 Organophosphates	主要通过植物的幼芽和地中茎吸收，抑制细胞分裂与伸长 Absorbed mainly through plant shoots and stem in the ground, inhibited cell division and elongation	杂草 3 叶期以前或 2 叶 1 心期以内 At 3 leaf stage before or within 2 leaf stage of weeds	稗草、光头稗、千金子、牛毛草、碎米莎草、异型莎草、鸭舌草、飘拂草、尖瓣花等 *Echinochloa crusgalli*, *Echinochloa colonum*, *Leptochloa chinensis*, *Bulbostylis barbata*, *Cyperus iria*, l*Cyperus difformis*, *Monochoria* l*vaginalis*, *Fimbristylis dichotoma*, *Sphenoclea zeylanica*, etc
二甲戊灵 Pendimethalin	内吸（抑制细胞分裂） Systematic (Inhibition of cell division)	二硝基苯胺类 Dinitroanilines	在杂草种子萌发过程中幼芽、茎和根吸收药剂，进入植物体内的药剂与微管蛋白结合，抑制分生组织细胞分裂，不影响杂草种子的萌发 Absorbed by shoot, stem and root in the process of weed seed germination, entered the body of a plant as an inhibitor of microtubule assembly and meristem cell division, and did not affect the germination of weed seeds	直播旱稻播后苗前 Pre-emergence and after seeding in direct seeding aerobic rice field	稗草、千金子、马唐、狗尾草、碎米莎草、异型莎草等 *Echinochloa crusgalli*, *Leptochloa chinensis*, *Digitaria sanguinalis*, *Setaria viridis*, *Cyperus iria*, *Cyperus difformis*, etc
二氯喹啉酸 Quinclorac	内吸（合成生长素抑制剂） Systematic (Synthetic auxin inhibitor)	喹啉羧酸类 Quinoline-carboxylic acids	具有激素型除草剂的特点，能被萌发的种子、根及叶部吸收，详细作用方式未知 With the characteristics of a synthetic auxin herbicide, it can be absorbed by germinating seeds, roots and leaves, but detailed action were still unknown	秧苗 2.5 叶期以后，稗草 1～7 叶期均有效 After 2.5 leaf stage of rice, 1 to 7 leaf stage of barnyard grass	稗草、鸭舌草、水芹等 *Echinochloa crusgalli*, *Monochoria vaginalis*, *Oenanthe javanica*, etc

续表 1 Continued table 1

通用名称 Common name	作用方式 Mode of action	类别 Family	作用特点 Function characteristics	施药时期 Applying time	主要敏感杂草 Main susceptible weeds
氰氟草酯 Cyhalofop-butyl	内吸,脂类物质合成抑制剂(抑制 ACCase) Systematic, lipid synthesis inhibition (Inhibition of ACCase)	芳氧苯氧羧酸酯类 Aryloxyphenoxypropionates (FOPs)	由植物的叶片和叶鞘吸收,韧皮部传导,积累于植物体的分生组织区,使脂肪酸合成停止,细胞的生长分裂不能正常进行,膜系统等含脂结构破坏 Absorbed by plant leaves and leaf sheaths, conducting through phloem, and it accumulated in the plant meristem area, so that fatty acid synthesis were stopped, and the growth and division of the cells were unable to proceed normally, also lipid-containing systems such as plasma membrane could get structural damage	杂草 5 叶期以前 At 5 leaf stage before of weeds	千金子、低龄稗草、双穗雀稗等 *Leptochloa chinensis*, *Echinochloa crusgalli*, *Paspalum paspaloides*, etc
噁唑酰草胺 Metamifop	内吸,脂类物质合成抑制剂(抑制 ACCase) Systematic, lipid synthesis inhibition (Inhibition of ACCase)	芳氧苯氧羧酸酯类 Aryloxyphenoxypropionates(FOPs)	苗后广谱除草剂,有效成分需到达植物体内靶标才能发挥作用 A broad-spectrum postemergence herbicide, active ingredients required to reach the target action of plants can only play a role	水稻 2 叶 1 心以后,杂草 3~5 叶期 After 2 leaf stage of rice, 3 to 5 leaf stage of weeds	稗草、千金子、马唐、牛筋草等 *Echinochloa crusgalli*, *Leptochloa chinensis*, *Digitaria sanguinalis*, *Gramineae*, etc
五氟磺草胺 Penoxsulam	内吸,乙酰乳酸合酶(ALS)抑制剂(抑制支链氨基酸合成) Systematic, inhibition of ALS(Branched chain amino acid synthesis)	三唑并嘧啶磺酰胺类 Triazolopyrimidines	苗后广谱除草剂,能被杂草叶片、鞘部或根部吸收,传导至分生组织,使杂草生长停止 A broad-spectrum post-emergence herbicide, which can be taken by leaf, sheath or roots, then conducted it to the meristematic tissue to stop the growth of weeds	水稻 2~3 叶期 At 2 to 3 leaf stage of rice	稗草、沼生异蕊花、鲤肠、田菁、竹节花、鸭舌草等 *Echinochloa crusgalli*, *Heteranthera limosa*, *Eclipta prostrate*, *Sesbania exaltata*, *Commelina diffusa*, *Monochoria vaginalis*, etc
噁草酮 Oxadiazon	内吸(抑制原卟啉原氧化酶) Systematic (Inhibition of protoporphyrinogen oxidase)	杂环类 Heterocycles	主要通过杂草幼芽或茎叶吸收,在光照条件下才能发挥杀草作用,但并不影响光合作用的希尔反应 Mainly absorbed through weed shoots, the stems or leaf, the part absorbed by the ground part can only kill weeds under light conditions, but did not affect the Hill reaction of photosynthesis	杂草萌芽至 2~3 叶期 At emergence to 2-3 leaf stage of weeds	稗草、千金子、鸭舌草、节节草、牛毛草、泽泻、矮慈姑、香附子、日照飘拂草等 *Echinochloa crusgalli*, *Leptochloa chinensis*, *Monochoria vaginalis*, *Equisetum ramosissimum*, *Bulbostylis barbata*, *Alisma plantagoaquatica*, *Sagittaria pygmaea*, *Cyperus rotundus*, *Fimbristylis miliacea*, etc
异恶草松 Clomazone	内吸(抑制 1-脱氧木酮糖-5-磷酸(DOXP)的合成) Systematic (Inhibition of DOXP synthase)	杂环类 Heterocycles	主要由杂草根部吸收,随蒸腾流水分通过木质部传导,抑制敏感植物异戊二烯化合物合成,阻碍胡萝卜素和叶绿素的生物合成 Mainly absorbed by the weeds roots, along with the transpiration stream conducted through the xylem, inhibiting the synthesis of isoprenoid compounds in susceptible plants, hindering carotene and chlorophyll biosynthesis	用药时间灵活,杂草芽前或芽后均可 Applying time is flexible, at preemergence or post emergence of weeds	稗草、千金子等 *Echinochloa crusgalli*, *Leptochloa chinensis*, etc

1.2 阔叶杂草及莎草科杂草除草剂

苄嘧磺隆(bensulfuron-methyl),商品名农得时,是由美国杜邦公司开发的选择性内吸传导型磺酰脲类除草剂,具有生物活性高、对水稻安全、适药适期长、用量低、易降解等多种特点[7-8],已成为水稻田防除阔叶杂草用量最大的除草剂品种。磺酰脲类除草剂是一类重要的阔叶杂草及莎草科杂草除草剂,其开发应用于稻田中的品种多样。另外,二甲四氯、灭草松也是水稻插秧后广泛采用的阔叶类杂草除草剂品种[9](表 2)。

表 2　水稻田阔叶杂草及莎草科杂草除草剂单剂品种

Table 2　Main herbicides used in rice field against broadleaf and cyperaceae weeds

通用名称 Common name	作用方式 Mode of action	类别 Family	作用特点 Function characteristics	施药时期 Applying time	主要敏感杂草 Main susceptible weeds
吡嘧磺隆 Pyrazosulfuronethyl	内吸，ALS 抑制剂（抑制支链氨基酸合成） Systematic, ALS inhibition (Branched chain amino acid synthesis)	磺酰脲类 Sulfonylureas	被杂草的根部吸收后传导到植株体内，阻碍氨基酸的合成，抑制杂草茎叶部的生长和根部的伸展 After that being absorbed by weed roots and conducted in the vivo plants, which hindered amino acids synthesis and inhibited the growth of weeds stem and leaf and stretching of roots	水稻 1～3 叶期 At 1 to 3 leaf stage of rice	异型莎草、水莎草、萤蔺、鸭舌草、水芹、节节菜、野慈姑、眼子菜、青萍、鳢肠等 *Cyperus difformis*, *Juncellus serotinus*, *Scirpus juncoides*, *Monochoria vaginalis*, *Oenanthe javanica*, *Rotala indica*, *Sagittaria trifolia*, *Potamogeton franchetii*, *Lemna minor*, *Eclipta prostrate*, etc
苄嘧磺隆 Bensulfuron-methyl	内吸，ALS 抑制剂 Systematic, ALS inhibitor	磺酰脲类 Sulfonylureas	杂草根部和叶片吸收后转移到其作用部位，阻碍氨基酸的生物合成，阻止细胞的分裂和生长 After that being absorbed by weed roots and leaves and transferred to its site of action, which hindered amino acids biosynthesis and prevented cell division and growth	作物芽后，杂草芽前或芽后 2 叶期以内 After the crop budding, preemergence or post-emergence within 2 leaf stage of weeds	鸭舌草、眼子菜、节节菜、牛毛草、异型莎草、水莎草等 *Monochoria vaginalis*, *Potamogeton franchetii*, *Rotala indica*, *Bulbostylis barbata*, *Cyperus difformis*, *Juncellus serotinus*, etc
环丙嘧磺隆 Cyclosulfamuron	内吸，ALS 抑制剂 Systematic, ALS inhibitor	磺酰脲类 Sulfonylureas	能被杂草根系和叶面吸收，在植株体内传导，阻碍亮氨酸、异亮氨酸、缬氨酸等支链氨基酸的合成，使细胞停止分裂 It can be absorbed by weeds root and leaf and conduct in plant body, and prevent branched chain amino acids synthesis such as leucine, isoleucine, valine, etc. Finally, make the cell stop dividing	水稻 1 叶 1 心至 2 叶期，稗草 1.5 叶期以前，扁秆藨草、日本藨草在株高 7 cm 以前 At 1 to 2 leaf stage of rice, 1.5 leaf stage before of barnyard grass. *Scirpus planiculmis* and *Scirpus nipponicus* (less than 10 cm tall)	稗草、扁杆藨草、日本藨草、泽泻、鸭舌草、雨久花、野慈姑、眼子菜等 *Echinochloa crusgalli*, *Scirpus planiculmis*, *Scirpus nipponicus*, *Alisma plantago-aquatica*, *Monochoria vaginalis*, *Monochoria korsakowii*, *Sagittaria trifolia*, *Potamogeton franchetii*, etc
醚磺隆 Cinosulfuron	内吸，ALS 抑制剂 Systematic, ALS inhibitor	磺酰脲类 Sulfonylureas	主要通过根部和茎部吸收后由输导组织传送到分生组织，抑制支链氨基酸生物合成 Mainly absorbed by the root and stem and transmitted to meristem tissue through conducting tissue, and inhibited branched-chain amino acid biosynthesis	水稻 2～4 叶期 At 2 to 4 leaf stage of rice	泽泻、香附子、苹、眼子菜、慈菇、鸭舌草等 *Alisma plantagoaquatica*, *Cyperus rotundus*, *Marsilea*, *Potamogeton fran-chetii*, *Sagittaria sagittifolia*, *Monochoria vaginalis*, etc
乙氧磺隆 Ethoxysulfuron	内吸，ALS 抑制剂 Systematic, ALS inhibitor	磺酰脲类 Sulfonylureas	高毒，由杂草根、叶吸收传导 High toxicity, it can be absorbed and conducted by the weed roots and leaves	水稻 1.5 叶期后，杂草 3 叶期前 After 1.5 leaf stage of rice, 3 leaf stage before of weeds	三棱草、慈姑、雨久花、泽泻、眼子菜、节节菜、香附子、鸭舌草等 *Scirpus planiculmis*, *Sagittaria sagittifolia*, *Monochoria korsakowii*, *Alisma plantago-aquatica*, *Potamogeton franchetii*, *Rotala indica*, *Cyperus rotundus*, *Monochoria vaginalis*, etc
二甲四氯 MCPA	内吸（合成生长素抑制剂） Systematic, synthetic auxins inhibitor	苯氧羧酸类 Phenoxycarboxylic acids	由根、叶吸收传导，破坏植物体内新陈代谢 It can be absorbed and conducted by the weed roots and leaves, and destroy metabolism in the plant body	水稻分蘖末期 At late tillering of rice	鸭舌草、泽泻、野慈姑等 *Monochoria vaginalis*, *Alisma plantagoaquatica*, *Sagittaria trifolia*, etc

续表 2 Continued table 2

通用名称 Common name	作用方式 Mode of action	类别 Family	作用特点 Function characteristics	施药时期 Applying time	主要敏感杂草 Main susceptible weeds
灭草松 Bentazone	触杀,抑制光合作用 Contact toxicity,inhibition of photosynthesis at PSⅡ	苯并噻唑类 Benzothiadiazinone	通过叶面渗透传导到叶绿体内抑制光合作用,也可通过根部吸收,传导到茎叶,强烈阻碍杂草光合作用和水分代谢 Conducted by foliar penetration into the chloroplast,the active ingredient inhibited photosynthesis, which also can be absorbed by the roots and conducted to stems and leaves to strongly inhibit weeds photosynthesis and water metabolism	杂草3~5叶期 At 3 to 5 leaf stage of weeds	鸭跖草、蚤缀、苍耳、地肤、苘麻、繁缕、香附子等 *Commelina communis*,*Arenaria serpyllifolia*,*Xanthium sibiricum*,*Kochia scoparia*,*Abutilon theophrasti*,*Stellaria media*,*Cyperus rotundus*,etc

1.3 水稻田广谱性除草剂

水稻田广谱性除草剂主要有五氟磺草胺、双草醚、嘧啶肟草醚等(表3)。五氟磺草胺(penoxsulam),2008年在我国正式登记,由美国陶氏益农公司开发,是优良的广谱性除草剂,对稗草有特效,为目前稻田用除草剂中对水稻安全、杀草谱最广的品种[10-11],适宜应用时期为稗草2~3叶期,在直播水稻田苗后早期应用效果更好[12],但因其为乙酰乳酸合成酶(ALS)抑制剂,产生抗药性的风险较高,国外研究发现抗五氟磺草胺稗草生物型对敌稗、二氯喹啉酸也产生了交互抗药性[13],应注意合理使用。嘧啶肟草醚(pyribenzoxim),商品名韩乐天,由韩国LG化学集团研发,具有原卟啉原氧化酶(PPO)除草剂所没有的高除草性和植物选择性,易被水解,环境污染极小[14],可有效防除1至6叶期的稗草[15]。双草醚(bispyribac-sodium),高效、持效期长、用量低,能够有效防除异形莎草、陌上菜、耳叶水苋、稗草、千金子、鳢肠等杂草,对高龄稗草也有较好的防治效果,但较易产生药害[16],应用时应谨慎。另外,乙氧氟草醚(oxyfluorfen)、双环磺草酮(benzobicyclon)也是活性高、杀草谱广的水稻田除草剂,且双环磺草酮对磺酰脲类抗性杂草生物型也有较好的防治效果[17],具有推广应用潜力;与双草醚相同,乙氧氟草醚未严格按照使用说明操作易产生药害,对环境和作物也有潜在的负面影响[18],限制了其广泛应用。

表 3 水稻田广谱性除草剂单剂品种

Table 3 Broad-spectrum herbicides used in rice field

通用名称 Common name	类别 Family	作用方式 Mode of action	施药时期 Applying time	防治对象 Target weeds
嘧啶肟草醚 Pyribenzoxim	嘧啶水杨酸类 Pyrimidinyl(thio) benzoates	触杀和内吸,ALS抑制剂 Contact and systematic toxicity, ALS inhibitor	稗草1.5~6.5叶期 At 1.5 to 6.5 leaf stage of barnyard grass	稗草、大穗看麦娘、辣蓼等各种杂草 *Echinochloa crusgalli*, *Alopecurus myosuroides*, *Polygonum flaccidum* and other weeds
双草醚 Bispyribac-sodium	苯甲酸类 Benzoic acids	抑制ALS Inhibition of ALS	杂草3叶1心至6叶1心期 At 3 to 6 leaf stage of weeds	稻田稗草及其他禾本科杂草,兼治大多数阔叶杂草和一些莎草科杂草,如稗草、双穗雀稗、稻李氏禾、异型莎草、日照瓢拂草、萤蔺、雨久花、野慈菇、水竹叶、空心莲子草、花蔺等 Barnyard grass and other gramineous weeds,and most of the broadleaf weeds and some cyperaceae weeds. For example, *Echinochloa crusgalli*, *Paspalum paspaloides*, *Leersiahexandra* Swartz, *Cyperus difformis*, *Fimbristylis miliacea*, *Scirpus juncoides*, *Monochoria korsakowii*, *Sagittaria trifolia*, *Murdannia triguetra*, *Alternanthera philoxeroides*, *Butomus umbellatus*, etc
五氟磺草胺 Penoxsulam	三唑并嘧啶磺酰胺类 Triazolopyrimidines	抑制ALS Inhibition of ALS	水稻2~3叶期 At 2 to 3 leaf stage of rice	禾本科杂草、一年生莎草科杂草,并对众多阔叶杂草有效,如稗草、沼生异蕊花、鳢肠、田菁、竹节花、鸭舌草等 Gramineous weeds, annual cyperaceae weeds and many broadleaf weeds. For example, *Echinochloa crusgalli*, *Heteranthera limosa*, *Eclipta prostrate*, *Sesbania exaltata*, *Commelina diffusa*, *Monochoria vaginalis*, etc

为扩大杀草谱、提高防效及阻止或延缓杂草抗药性产生,可以利用除草剂之间的协同增效作用,目前我国研发和生产了一大批具有优良除草活性的混配制剂,主要围绕丁草胺、丙草胺、苄嘧磺隆、二氯喹啉酸、氰氟草酯、灭草松、二甲戊灵、二甲四氯、苯噻酰草胺等重要的水稻田除草剂展开。目前水稻生产

上应用的主要除草剂混配配方有：丁草胺＋敌稗、丁草胺＋丙炔噁草酮、丁草胺＋乙氧氟草醚、丁草胺＋吡嘧磺隆、丁草胺＋苄嘧磺隆；丙草胺＋吡嘧磺隆、丙草胺＋苄嘧磺隆、丙草胺＋醚磺隆、丙草胺＋吡嘧磺隆＋苄嘧磺隆、丙草胺＋吡嘧磺隆＋异噁草松、丙草胺＋苄嘧磺隆＋稻喜（五氟磺草胺＋氰氟草酯）；二氯喹啉酸＋吡嘧磺隆、二氯喹啉酸＋苄嘧磺隆、二氯喹啉酸＋五氟磺草胺、二氯喹啉酸＋敌稗、二氯喹啉酸＋氰氟草酯；氰氟草酯＋双草醚、氰氟草酯＋精噁唑禾草灵、氰氟草酯＋氯氟吡氧乙酸、氰氟草酯＋嘧啶肟草醚、氰氟草酯＋醚磺隆、氰氟草酯＋五氟磺草胺；灭草松＋噁唑酰草胺、灭草松＋二甲四氯、灭草松＋唑草酮；二甲戊灵＋异恶草松、二甲戊灵＋苄嘧磺隆、二甲戊灵＋苄嘧磺隆＋异丙隆、二甲戊灵＋噁草酮；二甲四氯＋唑草酮＋苄嘧磺隆、二甲四氯＋唑草酮、二甲四氯＋氯氟吡氧乙酸；苯噻酰草胺＋吡嘧磺隆、苯噻酰草胺＋苄嘧磺隆、苯噻酰草胺＋恶草酮等。此外，还有苄嘧磺隆与莎稗磷、噁嗪草酮、乙羧氟草醚、丙炔噁草酮、环庚草醚或四唑草胺的混配。以上混配方案还有不同成分含量混配比及不同剂型的混配。据统计，2008－2012 年 5 年间复配制剂登记数量约占我国水稻田除草剂总数的 45％[19]。除草剂的混用在延长药剂持效期、降低对作物药害及延缓杂草抗性的发生等方面起到了重要作用，未来还会有更大的发展。

2　稻田主要杂草抗药性现状及抗性机理

2.1　我国稻田主要杂草抗药性现状

据国际抗性杂草调查网站（http://www.weedscience.org）统计，目前全球已有 50 余种杂草的 136 个生物型在各类水稻田系统中产生了抗药性[20]。我国稻田杂草中以稗草的发生和危害面积最大，其次为异型莎草、鸭舌草、扁秆藨草、千金子、眼子菜等，我国已明确报道有明显抗药性的主要稻田杂草见表 4。

表 4　我国水稻田的主要抗药性杂草

Table 4　Main resistant weeds reported in paddy field in China

杂草 Weed	抗性种群分布地点 Distribution	抗性除草剂 Resistant herbicide	所属类别 Family	使用年限 Years of use	抗性系数(*RI*) Resistance index
稗草 *Echinochloa crusgalli*	浙江绍兴 Shaoxing city in Zhejiang	二氯喹啉酸 Quinclorac	喹啉羧酸类 Quinolinecar-boxylic acids	10 年以上 More than 10 years	718.48 倍[23] 718.48 times
	吉林中西部 The midwest in Jilin	丁草胺 Butachlor	氯代乙酰胺类 Chloroacetamides	20 年以上 More than 20 years	28.5 倍[24] 28.5 times
	安徽庐江 Lujiang county in Anhui	双草醚 Bispyribac-sodium	苯甲酸类 Benzoic acids	二氯喹啉酸 6 年以上，连续 2 年复合施用双草醚 Quinclorac used more than 6 years, then Bispyribac-sodium for composite applications for 2 years in a row	11.87 倍[25] 11.87 times
	广东 Guangdong district	禾草丹 Thiobencarb	硫代氨基甲酸酯类 Thiocarbamates	10 年以上 More than 10 years	10.60 倍[26] 10.60 times
千金子 *Leptochloa chinensis*	湖北 Hubei district	氰氟草酯 Cyhalofop-butyl	芳氧苯氧羧酸酯类 Aryloxyphenoxy-propionates(FOPs)	—	未知[20] Unknown
雨久花 *Monochoria korsakowii*	吉林柳河 Liuhe county in Jilin	苄嘧磺隆 Bensulfuron-methyl	磺酰脲类 Sulfonylureas	20 年以上 More than 20 years	13.6 倍[27] 13.6 times
鸭舌草 *Monochoria vaginalis*	江西鄱阳湖区 Poyang lake district in Jiangxi	苄嘧磺隆、吡嘧磺隆 Bensulfuron-methyl, Pyrazosulfuron-ethyl	磺酰脲类 Sulfonylureas	—	未知[28] Unknown
大慈姑 *Sagittaria montevidensis*	吉林延边 Yanbian city in Jilin	苄嘧磺隆 Bensulfuron-methyl	磺酰脲类 Sulfonylureas	20 年以上 More than 20 years	16.04 倍[29] 16.04 times
耳叶水苋 *Ammannia arenaria*	浙江宁波 Ningbo city in Zhejiang	苄嘧磺隆 Bensulfuron-methyl	磺酰脲类 Sulfonylureas	20 年以上 More than 20 years	124.4 倍[30] 124.4 times

需要指出的是,杂草的抗药性水平因测定方法而异,有时可比性并不强,对抗性高低的评价也有差异。例如,Carey等[21]在测定敌稗的抗性水平时将敌稗有效成分用量3.4 kg/hm^2设为正常使用量,敌稗(20 kg/hm^2)对稗草的防效超过90%为轻度抗性,敌稗(34 kg/hm^2)对稗草的防效超过80%为中度抗性,敌稗(67 kg/hm^2)对稗草的防效超过81%为高度抗性,而敏感性生物型在以上所有任何之一剂量下的防效均超过90%。现在普遍被接受的观点是,某种群除草剂的ED_{50}值是敏感性种群ED_{50}值的10倍以上,就认为该种群产生了抗药性[22]。尽管杂草抗药性的测定方法和抗性水平评价有差异,但总体上还是可以表明:我国稻田杂草的抗药性问题已逐渐呈现出来,一些杂草对某些除草剂的抗性已达到了极高抗水平。加之相对滞后的杂草科学研究可能掩盖了我国杂草抗药性问题的真实情况,因此更应该引起高度重视,加强抗药性监测,积极探索抗性杂草的综合治理策略。

2.2　几种常用水稻田除草剂的抗性机理

杂草对除草剂的抗药性一般分为靶标抗性和非靶标抗性。靶标抗性主要涉及两方面:一是由氨基酸突变造成靶标蛋白的结构性改变,主要是由核基因控制的单基因突变或整个密码子的删除所导致的连续氨基酸的突变,大多数为显性或半显性等位基因所控制,也有部分为隐性基因所控制,由靶标蛋白的结构性改变所造成的抗性大多数为高、中抗水平,极少数情况下会增加杂草对除草剂的敏感性(如超敏反应);二是靶标蛋白的过量产生。非靶标抗性涉及杂草中复杂的非生物逆境响应途径,在这些途径中,多种蛋白质在杂草对除草剂的区室化(运输蛋白)、降解(细胞色素P450s、GSTs、糖基转移酶、酯酶、水解酶)及保护(过氧化物酶、氧化酶类)中扮演着重要的角色[31-32]。当然,非靶标抗性也涉及单基因或多基因突变,包括编码蛋白质基因的改变或修饰以及氨基酸改变增加了对除草剂的降解能力。尽管靶标抗性和非靶标抗性在基因控制方面有所不同,但在合适的选择压下,靶标抗性和非靶标抗性在同一物种、种群或个体中是可以共同进化的。以下就我国水稻田中几种常用除草剂单剂的抗性机理进行简要分析。

2.2.1　*丁草胺的抗性机制*　丁草胺属氯代乙酰胺类选择性内吸传导型除草剂,主要通过杂草幼芽和幼根所吸收,破坏了由赤霉酸(GA_3)诱导的α-淀粉酶的形成过程[33-35],但也有不少文献对其作用机制提出不同看法,如认为丁草胺可能通过诱导抗毒素的积累[36]来减少α-淀粉酶的合成,但并不起主要作用,氯代乙酰胺类除草剂(丁草胺)抑制了超长链脂肪酸的合成[37-39],β-酮脂酰-CoA合酶(VLCFA synthase,EC 2.3.1.199)是其唯一的关键作用靶标[40]。由于丁草胺的作用机理尚未完全清楚,其作用位点可能不止一个,对于抗性机理的研究角度也各不相同,涉及α-淀粉酶、水解酶和谷胱甘肽S-转移酶(GST)等多种酶类,如稗草对丁草胺的抗性机理与体内的α-淀粉酶活性密切相关,其对丁草胺的抗性水平与α-淀粉酶活性抑制率呈负相关,而与连续使用时间呈正相关[41]。另有文献报道显示,稗草对丁草胺的抗性是因其体内水解酶活性升高,使进入抗性稗草体内的丁草胺被迅速降解代谢,除草剂不能在稗草体内积累到足以起到杀死稗草的有效剂量[41],其抗性机理可能涉及氨同化作用过程中的谷氨酰胺脱氢酶活性的提高。

稗草对丁草胺的另一种可能的抗药性或耐药性机制是解毒酶GST活性提高,对丁草胺代谢能力增强,这甚至可能是我国稻田抗丁草胺稗草的主要抗性机制[42]。对于其他可能的抗性机制,如细胞色素P450单加氧酶(参与了超长链脂肪酸的羟基化)、谷胱甘肽还原酶等有待更深入的研究。

对于丁草胺诱导抗毒素累积作用机制的观点,也有文献报道认为丁草胺可能是促进苯丙氨酸解氨酶(PAL)活性的提高,进而诱导水稻叶片中植物抗毒素的积累[36],而且这种诱导能力特异于丁草胺和丙草胺,其积累的量与除草剂处理的浓度及时间有关。丁草胺是否能够诱导杂草体内植物抗毒素的积累,其杂草抗性的获得是否与植物抗毒素有关,仍需要进一步的研究。

2.2.2　*二氯喹啉酸的抗性机制*　二氯喹啉酸是具有生长素效应的除草剂。二氯喹啉酸在抗性稗草和敏感性稗草体内的吸收、传导和分解代谢没有明显差异,不是产生抗药性的原因[43-44],也不抑制稗草细胞壁的合成[45]。目前对其抗药性机制的研究至少涉及两方面:一是根据二氯喹啉酸诱导乙烯生物合成过程中所产生的副产物(氰化物)在植物细胞体内积累以杀死杂草的作用机理,如研究发现氰化物解毒酶、氰丙氨酸合成酶(β-CAS)等解毒酶活性提高[46-47];二是二氯喹啉酸通过调控有毒氰化物的产量而产生抗药性[44],不能诱导乙烯及其有毒副产物氰化物在稗草体内积累,促使乙烯生物合成途径中ACC合酶和ACC氧化酶发生变化[48]。植物生长

素早期响应基因 *EcGH3* 在抗二氯喹啉酸稗草中表达异常，可能引起抗性稗草的生长素代谢异常[49]。从稗草感知二氯喹啉酸到氰化物积累的信号传导过程也可能涉及分子伴侣 *EcDnaJ* 基因，二氯喹啉酸通过诱导稗草体内 *EcDnaJ* 基因的表达，来调控稗草对二氯喹啉酸的抗药性；无论是在苗期根和叶中还是成株期的根、茎、叶和种子中，*EcDnaJ*1 表达量均是抗性稗草高于敏感稗草[50]。

2.2.3　苄嘧磺隆的抗性机制　苄嘧磺隆是防治稻田杂草的最重要的磺酰脲类除草剂，支链氨基酸（缬氨酸、亮氨酸、异亮氨酸）生物合成第一步的催化酶乙酰乳酸合成酶（ALS 或 AHAS）是其唯一的靶标酶。杂草对苄嘧磺隆的抗性主要涉及 ALS 的变构和植物解毒代谢功能的提高两方面。据 Heap 研究统计，目前已报道与杂草抗药性相关的 ALS 氨基酸突变位点有 22 个，而且许多杂草的抗药性变异涉及的突变位点往往不只 1 个（图 1），结合部位的变构直接影响着 ALS 与除草剂化合物的结合能力[51]。

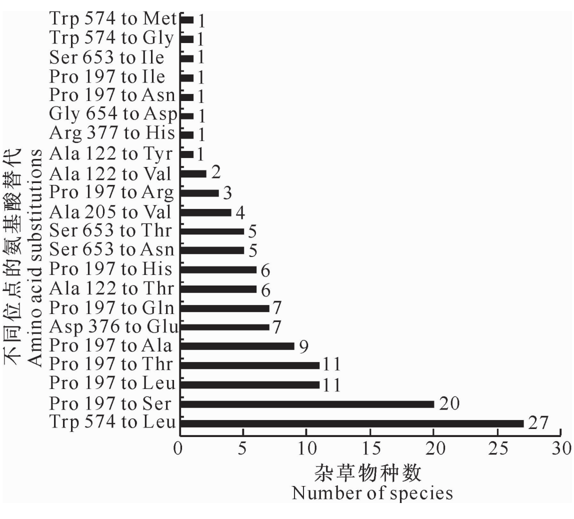

图 1　ALS 抑制剂抗性杂草的抗性机制[11]

Fig. 1　ALS inhibitor-resistant species by amino acid substitution[11]

稻田杂草对苄嘧磺隆的抗性主要是靶标抗性。研究发现，苄嘧磺隆在欧洲泽泻（*Alisma plantago-aquatica*）或北水毛花（*Scirpus mucronatus*）抗性生物型和敏感性生物型之间的吸收、传导和代谢没有差异，抗性生物型中 ALS 的活性高于敏感性生物型[52-53]，北水毛花抗性生物型对苄嘧磺隆及其他磺酰脲类除草剂表现出强烈的交互抗性，苄嘧磺隆的交互抗性水平也是最高的，抗性机制是 ALS 第 197 位的脯氨酸（Pro）被组氨酸所替代[53]。Figueroa 等[54]的研究结果也表明，泽泻对苄嘧磺隆的抗性机制虽然也涉及非靶标抗性，但主要还是苄嘧磺隆对作用靶标敏感性降低造成的。此外，萤蔺（*Schoenoplectus juncoides*）对苄嘧磺隆产生抗药性的原因也主要在于靶标酶 ALS 第 197 位的脯氨酸突变所致[55]。总的来看，ALS 基因编码区碱基密码的改变所造成的抗性，以第 197 位脯氨酸的突变或结构改变尤其重要，我国稻区杂草对苄嘧磺隆的抗性机制也主要是第 197 位脯氨酸的替代。例如，抗性雨久花（*Monochoria korsakowii*）生态型的 ALS 第 197 位的脯氨酸被组氨酸替代[56]，耳叶水苋（*Amnunnia arenaria*）抗性生物型的 ALS 第 197 位脯氨酸被丝氨酸（Ser）取代[57]，抗性慈姑（*Sagittaria sagittifolia*）生态型的出现也是 ALS 第 197 位发生了非脯氨酸的替代突变[58]。

3　稻田抗性杂草的治理策略

应用除草剂是控制杂草的主要手段，但杂草抗药性已成为稻田杂草防除不得不面临的严峻问题。杂草抗性的产生和发展，尤其是靶标抗性的快速发展，往往是除草剂的不科学使用与单一作物以及减少耕作实践相联系的结果[59-61]。稻田抗性杂草的治理，应坚持预防性治理的原则，农业防治与化学防治措施相结合，以最大限度地延缓或阻止杂草抗药性的发生，确保除草剂在保证我国粮食和食品安全中所发挥的重要作用。结合我国稻田杂草防除的实践，稻田杂草抗药性治理的关键是要降低选择压，具体措施包括如下几点。

（1）除草剂混用或者轮用。具有不同作用位点的除草剂混用或轮用，对于阻止或延缓不同作用靶标的抗性问题具有极其重要的意义。在实践中要注意提高除草剂混用或轮用的有效性，不同除草剂的轮用可以获得相似的杂草防除效果[62]，但两者相比混用对于阻止或延缓杂草抗性的发展更为有效[63]。如果是基于增强新陈代谢的抗性，这种方法可能更有实用性，因为这种代谢过程对于特定类型的分子可能是特殊的，但需要确定最佳除草剂组合。

（2）培育抗除草剂及抗杂草水稻品种。筛选对杂草有明显抑制效果、竞争能力强以及培养对土壤残留活性较低的除草剂具有抗性的水稻品种。现有的抗除草剂作物往往是以允许使用杀草谱广的除草剂（如草甘膦、草铵膦等）为主，这就减少了多种不同作用机理除草剂的使用，对杀草谱广的除草剂产生抗性的杂草种群的治理也会变得更加困难[64]，为此

应有前瞻性、战略性眼光以提供相关的技术储备,应用转基因技术来研究、筛选抗杂草的水稻品种。

(3)采用与耕作实践相结合的综合农艺措施。实施作物轮作,加强水稻田中土壤养分和水分的管理及中耕除草,增强作物竞争能力,使用不同作用机理的除草剂或栽培技术。清洁农田及农用设备,减少抗性杂草种子传播。适量、适时使用除草剂,科学评估杂草控制效果,及时改变防治策略。

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