Dynamics and management of Weeds in Rice

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SUMMARY

Weeds are serious problems for farmers of all hues and rice growing is no exception. Problems associated with weed management in rice are mounting dramatically during last few decades due to rapid changes in cultural practices of rice farming and also because of reduced availability of affordable labour and shortage of water. Changes in cultural practices viz., mechanized tillage, crop establishment by direct seeding, increased herbicide use, variable water availability, mechanized harvesting, rice-rice cropping sequence etc. led to shift from relatively easy-to-control sedges and broadleaved weeds to more difficult-to-control grassy weeds including weedy rice. New management strategies are required as no single method can solve all the problems of weeds in rice cultivation. Manual weeding 2-3 times in a season by engaging more than 100 person days ha^{-1} involves huge cost in weed control. Selection of suitable rice varieties with proper management practices should be integrated with direct control measures viz., mechanical weed control by using motorized weeder or by application of safest herbicide with broad spectrum to reduce the cost on weed management practices. The overall objective of modern weed management approaches is to reduce the degree of direct control inputs. Therefore, further research is needed for breeding weed competitive rice cultivars, herbicide tolerant rice. Also development of power weeder with high operation efficiency is highly important. Along with these technologies, emphasis on development and standardization of new and safe herbicides should be given to make rice cultivation more profitable.

1. INTRODUCTION

Weeds are undoubtedly a major biotic constraint to rice production, causing 33% of total yield losses in comparison to insects (26%) and diseases (20%). Extent of dominance of weed is dependent on prevailing agro-climatic conditions, soil types, water management, crop establishment practices, weed seed bank in soil and cropping system adopted in different rice ecologies. Depending upon various factors, the yield loss varies from 30% in irrigated to 70% in rainfed uplands (Saha and Rao 2011). Beside this, weeds interfere with rice growth by competing for light, nutrients, water and space and by creating a favourable habitat for the growth of various harmful organisms such as insects and pathogens. Problems associated with rice weeds are mounting dramatically due to changes in rice production systems in response to changing climate and declining accessibility of labour and water. Weeds are dynamic and new weeds keep emerging over a period of time owing to change in cropping pattern and, practices of crop cultivation. Changing climate may also lead to weed shifts, faster spread of invasive species and more competition to crops from weeds.

Change in traits and growth behavior in response to climate change is expected to make weed scenario more complex.

Access to supplementary irrigation has enabled crop establishment by direct seeding in non-puddled, non flooded fields under dry condition and lowland rice environment with limited water (Singh et al. 2006). Water and labour scarcity is also pushing the farmers to opt for direct seeded systems. These non-puddled, non flooded systems are threatened by heavy weed infestation. The absence of a seedling-size advantage between rice and weed seedlings, as both emerge simultaneously, can cause grain yield losses of 50–91%. Thus, weeds are the most severe constraints to direct sown aerobic rice systems (Rao et al. 2007). The key to success of these systems is efficient weed control techniques. Recently, weedy rice is emerging as another serious threat to direct seeded systems. The spread of weedy rice became significant all over the world mainly after the shift of rice cultivation from transplanting to direct seeding. For farmers, weedy rice is a difficult-to-control weed/ plant as strategy for its management is non-existent, and still remains elusive in non flooded aerobic situations (Saha et. al. 2014). The conception of herbicide tolerant (HT) rice may offer rice farmers a vital tool for controlling difficult to control grasses and mixed population of weeds. It can also help to control wild and other weedy rice species and provide an alternative tool for the management of those weeds that have already evolved resistance to particular herbicides. It also makes way for the replacement of some of the commonly used selective herbicides by new non-selective, environmentally safe herbicides.

Traditionally, manual weeding is done 2-3 times in a season (more than 190 person days/ha used) which involves huge cost in weed control. Additionally, seedlings of grassy weeds (e.g., *Echinochloa spp.*) look similar to rice seedlings and it makes hand/ manual weeding more tedious and difficult. Therefore, use of herbicides (and/ or bio-inoculants), or using machines (mechanical weed control) are considered as alternative/supplement to manual-weeding and most economical way to manage weeds. New safer herbicides need to be formulated and standardized for broad spectrum weed control in rice under different situations. However, use of herbicides is deemed with its own challenges like environmental pollution and herbicide resistance. In absence of strict guidelines and its implementation, herbicides are being used in excess, which cause water pollution through run-off, and negatively affect the soil by affecting the microbes. Weed resistance to the herbicides used in rice is a relatively new event. Since 1980s', with the introduction of sulfonylurea herbicides, several weed species have evolved resistance to herbicides due to continuous use of same herbicide in the same field. Even multiple resistances (the resistance to more than one type of herbicide action) have evolved in some cases. Low cost single row and modified two row self-propelled power weeder may serve as an alternative to herbicide with less drudgery. The machine has been designed and tested at ICAR-NRRI with 28-30% plant damage (CRRI Annual Report 2013-14). Further research is required to design efficient implements (weeder) to cut down the energy and cost incurred for manual weed control.

An important factor of modern weed management strategy – is not to rely too heavily on any one tactic. Current weed management technology consists of integration of appropriate crop husbandry (agronomic practices) along with direct cultural and chemical methods (Saha and Rao 2011). Thus, an integrated approach involving appropriate crop husbandry along with some direct weed management practices viz., cultivation of weed competitive varieties, selection of herbicides and farm mechanization. This chapter on weed management would give an insight on the possibilities to tackle the threat called 'weeds' with the existing knowledge and contemplate on what could be done further based on existing technologies. This chapter also explores the challenges and responsibilities that lie ahead in future rice production vis-a-vis weed management.

2. STATUS OF RESEARCH/KNOWLEDGE

2.1. Rice crop-weed interference

Among different categories of weed flora, grassy weeds are the most competitive and usually the first group that emerges and grows simultaneously with the rice crop for a considerable time period (7-70 days). Weeds that emerge before or simultaneously with rice crop are far more competitive than those that emerge 2 to 3 weeks later. Sedges and broadleaf weeds emerge subsequently at the later stages of crop growth. While, under aerobic conditions, several flushes of weeds come up because the weed seeds with differential dormancies germinate as and when conditions are favorable. Initial slow-growth phase of the rice crop is critical when the weed growth is fast. The weeds should be prevented at this particular stage until the crop enters the fast-growth phase, the influence of weed competition can be greatly reduced. In case of direct-sown rice, the initial 7-35 days is considered to be the most critical for crop-weed competition. In uplands, since short duration varieties are grown, the proportion of their life cycle infested by weeds is higher and hence the crop suffers more (Saha and Rao 2011). Direct-sown rice in rainfed lowlands encounters similar situation as that of uplands during the initial stage and experiences competition from mainly grassy weeds and few sedges. However, with the accumulation of rainwater in crop field during peak monsoon in lowlands, the crop faces competition from some non-grassy broadleaf and aquatic weeds. In transplanted rice, weed problems are generally of lower magnitude provided the puddling and water management are done properly. Majority of weeds (about 60%) emerge within 7-30 days after transplanting (DAT) and compete with rice plants till maximum tillering stage. About 15-20% of the weed populations emerge in the period between 30-60 DAT and 20-25% of weeds emerges later and are not important in yield reduction. While sedges and broad leaf weeds are mostly predominant in irrigated ecology under both wet seeded and transplanted cultures. In wet seeded system, the crop-weed competition is more intense (because of similarities in age of rice and weed seedlings) than that of transplanted system (where aged seedling with better competitive ability are raised). The ultimate loss in grain yield due to competition with weeds is more in direct than transplanted rice irrespective of growing season.

2.2. Weed management under changing climatic scenario

It is expected that growth of C_3 plants would be enhanced more by CO_2 enrichment as compared to C_4 plants. Due to greater adaptability, weeds will achieve a greater competitive fitness against the crop plants with a changed climate (Table 1). Probable changes in the weed biogeography of agricultural systems pose challenges to management. Environments with high degree of disturbance are more susceptible to annexation by newly introduced plant species and are likely to reach a relatively quick stability with emergent climatic factors. It is predicted that climate change can reduce the effectiveness of current weed management practices. Agronomic practices for particular crops are likely to change with time and space. New classes of herbicides, cultivars, tillage system, irrigation techniques and seed sowing practices will influence the geographic distribution of weeds and their invasiveness.

Under changed climatic scenario, temperature, precipitation, wind and relative humidity may influence the efficacy of herbicides. Thicker cuticle development or increased leaf pubescence, with subsequent reductions in herbicide entry into the leaf is expected in drought situation. These physiological changes can interfere with crop growth (reduced transpiration) and recovery after herbicide application. Overall, herbicides are most effective when applied to weeds those are free from environmental stress. For example, rising atmospheric CO_2 concentrations can reduce the glyphosate efficacy. High concentrations of starch in leaves in C_3 plants grown under high CO_2 environment might interfere with herbicide efficacy. Elevated temperature and higher metabolic activity in C_3 weeds tend to increase uptake, translocation and efficacy of many herbicides, while moisture deficit, especially when severely depressing growth, tends to decrease efficacy of post-emergence herbicides, which generally perform best when plants are actively growing.

Table1. Crop/weed competition outcome at elevated CO_2 conditions.

Weed species	Crop	Favored underelevated CO_2
Amaranthus retroflexus (C_4)	Soybean (C_3)	Crop
Amaranthus retroflexus (C_4)	Sorghum (C_4)	Weed
Chenopodium album (C_3)	Soybean(C_3)	Weed
Taraxacum officinale (C_3)	Lucern (C_3)	Weed
Albutilon theophrasti (C_3)	Sorghum (C_4)	Weed
Taraxacum and Plantago (C_3)	Grasses (C_3)	Weed
Red rice (C_3)	Rice (C_3)	Weed
Echinochloa glabrescens (C_4)	Rice (C_3)	Weed

Source: Modified from Bunce and Ziska 2000

Mechanical and manual removal of weeds are the most widely used weed management practices in developing countries. Mechanical control of perennial weeds is likely to be adversely affected by elevated CO_2. Elevated CO_2 could lead to increase in below ground carbon storage with subsequent increases in the growth of roots or rhizomes. This may consequently help additional plant propagation with mechanical tillage (e.g. Canada thistle) (Ziska et al. 2004). Perennial grasses and sedges like *Cynodon dactylon*, *Cyperus sp*. and *Schoenoplectus articulatus* propagate asexually, hence, disking/harrowing would result in greater number of propagules. Increased photosynthesis may stimulate more production of rhizomes and other storage organs which will make control of perennial weeds more difficult. Biological control of weeds is likely to be affected. Elevated CO_2 could alter the efficacy of weed bio-control agents by possibly changing the development, morphology and reproduction of the target pest. Direct negative effects of high CO_2 in environment would be related to variations in C: N ratio and changes in the feeding habits and growth of natural enemies.

2.3. Challenges of weed management in direct seeded/ aerobic systems

Dry direct seeding of rice (DSR) with subsequent aerobic soil conditions eliminates the need for standing water, thus reducing the overall water demand and providing opportunities for water and labour savings. Dry seeding of rice is now considered to be an emerging production system in India and Asia because of a reasonable shortage of water availability in agriculture. Despite the numerous benefits, DSR systems adoption by farmers has been seriously inhibited by weed management tradeoffs. The practice of DSR has resulted in a change in the relative density of weed species in rice crops. In particular, *Echinochloa* spp*., Ischaemum rugosum, Cyperus difformis, and Fimbristylis miliacea* are widely adapted to conditions of DSR (Rao et al. 2007). Presence of *Leptochloa chinensis* and *Dactyloctenium aegyptium* is widely reported from many areas, particularly in DSR.

Weed management in DSR is considered a serious threat and the risks of yield losses is very high due to weed competition than in transplanted rice because (1) early flooding suppresses initial flushes of weeds early in transplanted rice but not so in DSR (2) rice seedlings in DSR are less competitive with concurrent emerging weeds because of the absence of a size difference between the rice and weeds in DSR (Rao et al. 2007). Although herbicides are important in reducing weed competition and helpful in ensuring adequate yields under DSR, overreliance on herbicides poses both economic and environmental risks. It can result in shifts in weed communities and evolution of herbicide-resistant weed populations (Rao et al. 2007) that reduce herbicide efficacy and increase costs, as newer and more expensive herbicides may be required as the relatively fast emergence of “weedy” rice. This weed is phenotypically similar to rice cultivars but exhibit undesirable agronomic traits, viz. shattering. It is usually observed in areas where DSR is being practised, and this is a serious concern to the rice production system sustainability.

In view of these weed management challenges in DSR, as well as the potential problems associated with the overuse of herbicides, several recent works have highlighted integrated weed management approach such as integration of use of competitive cultivars, changes in seed rate, timing and geometry, use of residue mulching, crop rotation, water and nutrient management, and mechanical methods (Matloob et al. 2015; Rao et al. 2007). These works have also outlined the importance of preventive measures which include seed predation, seed decay, and fatal germination as important components of integrated weed management in DSR. However, detailed reviews on the potential of preventive approaches based on knowledge of the ecology of weed species is limited in DSR system.

In our previous study at ICAR-National Rice Research Institute, it was observed that grassy weeds viz. *Echinochloa colona, E. crus-galli, Leptochloa chinensis, Dactyloctenium aegyptium, Digitaria sanguinalis, Panicum repens* etc. are the most competitive weed-flora that emerge early and grow simultaneously with the rice crop for a considerable time period in direct-sown rice. Sedges viz. *Cyperus iria, C. difformis, Fimbristylis mileacea* etc. and broad leaved weeds *Alternanthera sessilis, Ageratum conyzoides, Ludwigia octovalvis, Sphenoclea zeylanica, Cleome viscosa etc.*) emerge subsequently at later stages of crop growth (Munda et al. 2017). Sometimes several flushes of weeds come up as seeds present in soil germinate as and when conditions are favourable in aerobic soil.

2.4. Hazard of herbicide resistance

Herbicide resistance is the inherent ability of a biotype of a weed to survive herbicide application to which the original population was susceptible. Herbicide resistance causes changes in the weed population because of resistant biotypes. Resistant biotypes are build up when the herbicide to which those individuals are resistant is used repeatedly. Herbicide-resistant weeds have been an issue since the early 1970s, although it was described as a potential problem as early as 1957 by CM Switzer. Like other organisms, random genetic mutations occur within plant populations. These mutations are often at very low frequencies. For herbicide resistance, a single plant in several million may have a mutation to survive herbicide treatment. Generally, herbicide applications do not cause any genetic mutations. Applications create selection pressure that favors the spread of resistant biotypes. Cross resistance can occur within weed populations.

The development of herbicide resistance poses three serious problems:

i. Very expensive and time consuming to test for and develop alternative management plans.

ii. Develop management techniques to continue utilizing current herbicides and protect them against resistance development.

iii. Development of herbicide resistance in a biotype limits weed management options.

Factors that control development of resistant weeds are selection pressure, weed biology and genetic factors. If herbicides with long soil residual activity are applied repetitively, high selection pressure is placed for resistant biotypes of a weed. Some weeds have high genetic variability i.e. many different varieties or biotypes exist under the one species. They generally develop resistance quicker, as there already exist resistant biotypes within a population. Seed longevity is another factor that controls the development of herbicide resistance. Plant species that produce long-lived seed tend to develop resistance early. This is because susceptible seeds from the seed bank germinate over many years adding variation to the population. The site of action of the herbicide on the plant is governed by genetic factors. There are differences pertaining to the frequency of mutations occurance at different biological target sites within plants. Sites that have high frequency of mutation, tend to develop quickly, for example resistance may develop with three or more years of continuous use at the site of action of ALS and ACCase inhibitors. In contrast, the target site of glyphosate do not mutate as frequently. Glyphosate resistance did not exist earlier, but it took many years to develop (Neve et al. 2011).

In general, herbicide-resistant weeds are likely to develop in fields under conservation tillage (minimum and no-till systems) as congenial environment is created with repeated application of high dose herbicides. Because of the reduced tillage, farmers rely primarily and, sometimes, solely, on herbicides for weed control, thereby imposing constant selection pressures on weeds. However, the intensity of selection pressure depends on herbicide family and type of tillage operation. Reports suggested that an escalation in the use of ACCase-inhibitors in conservation-tillage did not escalate the development of wild oat populations resistant to ACCase-inhibitors. Also, the onset of glyphosate resistance in rigid rye-grass was delayed in a minimum-tillage system.

2.5. Newly emerging weeds/weedy rice

During the last one decade, it was observed that *Leptochloa chinensis* emerged as one of the dominant grassy weed species in rice-rice cropping sequence where the rice field became wet during the major part of crop growing season. The dominance of grassy weeds (>60% of total weed population) was recorded in DSR plots during both wet and dry season. *Leptochloa chinensis* and *Cyperus difformis* were dominant species occupying 56% of total weed population in this system (CRRI Annual Report 2014-15). *Alternanthera philoxeroides*, which generally occurs in irrigation channels, water courses, wetlands during dry season (Feb-March) at high temperature, now become an emerging weed in rice field, may be due to changes in atmospheric temperature. *Ludwigia adscendens*, another weed generally occurs in wet lands or irrigation channel, has now became another emerging weed in rice-rice system in many States of eastern India, particularly lowlands due to continuous wet condition of rice fields (CRRI Annual Report 2013-14).

Weedy rice is a troublesome weed in many rice growing regions. The extent and type of competition imposed on cultivated rice by weedy rice depends on the structural, biological and physiological features of weedy rice which shows a wide variability among different populations (Londo et al. 2006). By definition, weedy rice is an introgressed form of wild and cultivated rice (*Oryza sativa* L.). Weedy rice belongs to the *Oryza* genus and *sativa* species as cultivated rice but with different form. It appears as hybrid swarms due to introgression of genes between wild and cultivated species in nature. In Asian rice, it is known as *Oryza spontanea* whereas in the African context it is known as *Oryza stapfii*. The most common feature among extremely variable weedy rice is their ability to disseminate seeds by early shattering. It is more problematic in the direct-seeded rice than transplanted rice. The potential ecological risks associated with transgene escape through gene flow (or crosspollination) are the foremost concerns. The spread of weedy rice infestations have been reported to 40-75% of the total rice area in Europe, 40% in Brazil, 55% in Senegal, 60% in Costa Rica and 80% in Cuba. In Asia, infestation of weedy rice became an emerging problem since 1980s. Its infestation was first reported in Malaysia in 1988, in the Philippines in 1990, and in Vietnam in 1994. Weedy rice infestation in Asia caused yield losses ranging from 16 to 74%. Yield loss of about 1 t ha^{-1} was caused by infestation of 35 weedy rice panicles m^{-2} as reported in Malaysia. It was reported from USA that the yield of cultivar New-bonnet was reduced by 219 kg ha^{-1} with one weedy red rice plant in square meter. The competitive ability of one weedy rice plant was equivalent to three rice plants (cultivar Mars).

Under a competitive environment, weedy rice competes well and utilizes resources more efficiently than the cultivated rice varieties. Therefore, study of nutrient (NPK) removal by weedy rice is essential to estimate the actual loss of nutrients from soil. In Asia, some weedy rice accessions have been found to have greater nitrogen-use efficiency for shoot biomass than cultivated rice (Dar et al. 2013). Researchers have given due attention to the mechanism of nutrient losses in soil, particularly N, but only few studies have been made on the impact of weedy rice competition on nutrient use efficiency and other major nutrients P and K. Limited studies have been made on the extent to which weedy rice populations, particularly of Indian subcontinent, can compete with cultivated rice for the three major nutrients (NPK).

At ICAR- NRRI, five thousand thirteen germplasm including 41 wild rice accessions collected from Assam and 139 wild and weedy rice accessions collected from Odisha during 2012 were sown and transplanted along with check Swarna for characterization and seed multiplication. One hundred and eighty wild and weedy rice were characterized based on agro-morphological traits as per the descriptors. Study on their genetic variation suggested that the genotypes selected for this study harbored enough genetic divergence. However, an UPGMA dendrogram based on the genetic relationships suggested a closer relationship of weedy and wild rice occurring within the same regions (CRRI Annual Report 2013-14).

3. KNOWLEDGE GAPS

- Robust herbicide management technologies are not available to address the issues of herbicide persistence in soil (causing environmental pollution) and herbicide resistance in weeds. Greater strides need to be made to make herbicide use safer for environment.
- Very little progress is made in the area of weed competitive rice varieties. Weed competitive rice varieties could be a cost effective measure for suppressing the weeds.
- Further research is needed regarding the development herbicide tolerant rice. There is need to clearly understand the tradeoffs of herbicide tolerant rice.

4. RESEARCH AND DEVELOPMENT NEEDS

Research and development needs have been broadly discussed under the following heads:

4.1. Rational use of herbicides

In an agricultural system, the aim is to produce the highest yield achievable whilst minimizing costs. Herbicides are one of the first labour and costs saving technologies. Improved weed control with herbicides has the potential to improve crop yields. Chemical weed control can provide a pro-poor technology for rice cultivation in Asia. The herbicide use in the tropical countries is directly related to the cost and availability of labour. The use of herbicides has gained importance due to rise in farm wages in the recent years as a consequence of overall economic growth and growth in non-farm employment opportunities, predominantly in Asia. Recent government mandates such as the National Rural Employment Guarantee Act has created agricultural labor shortages in India because guaranteed employment and wages mandated by the Act, making hand weeding an unsuitable practice (Toth 2011).

While the role of herbicides in improving crop productivity has long been recognized, the abuse of these chemicals has been among the major causes of environmental pollution. Increasing concern has triggered research on the fate and effect of continuous and massive use of pesticides to the environment. Smallholder farmers face a number of problems associated with herbicide use, due to either an inadequate knowledge about rate of application, or the optimum time for herbicides application to control the weeds. A major cause of this is possibly serious lack of information available to the farmers and the poor level of understanding. Often only nominal precautions are taken for safe use of herbicides. Frequent herbicide application has led to herbicide resistance within some weed populations. In the USA, Propanil application for 30 years continuously, resulted in resistant *Echinochloa sp*. Continuous use of Bensulfuron for four years resulted in resistance in four aquatic weed species. The evolution of herbicide resistant weeds is a real threat to effective weed control where herbicides are frequently used. Smallholder systems may be particularly vulnerable as herbicides are often not used at appropriate times or dosages, which may hasten the development of resistance. To prevent and manage existing herbicide resistant biotypes requires an integrative approach. This may include research on crop and herbicide rotation, standardization of herbicide mixtures (including tank mix) and development of herbicide with short residual activity and intensive use of farm machinery to reduce herbicide load.

Persistence of any pesticide is critical for weed control. Shorter than expected activity (less persistent herbicide) can lead to poor weed control and require additional action and expense by the farmer to supplement weed management. Residual activity longer than expected (more persistent herbicide) can lead to problems with injury to a subsequently crop and may cause non point pollution (Fig. 1). The persistence depends on the characteristics of the pesticide itself or its metabolites. Volatility, solubility, formulating agents, the method and site of application of pesticides

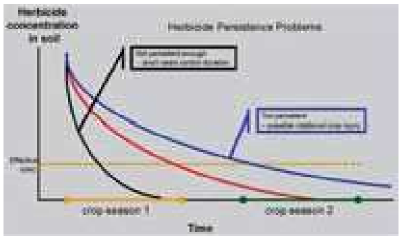

Fig.1. Herbicide persistence in soil.

Source: *http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=5929*

determine the persistence. Among the environmental factors, particularly temperature, moisture and wind determine the dissipation of pesticide. Soil characteristics like organic matter content, soil pH, soil structure and texture, nutrient content and its microbial population control the persistence of any pesticide. So, further research in required in this regard to developed herbicide which are safer to use and which allow much greater plasticity in application.

In rice, a number of herbicides like butachlor, pretilachlor, pendimethalin, oxadiazon, anilofos, oxadiargyl etc. have been recommended as pre-emergence control of early flashes of weeds. Pre-emergent herbicides are usually useful in direct-sown rice fields to suppress the early flashes of weeds. These herbicides generally have narrow spectrum of controlling annual grasses and some sedges. Their efficacy depends on soil moisture and is ineffective in dry soil conditions. However, on light soils, heavy rains may move the herbicide down in the soil to the germinating crop seeds and cause severe injury. These herbicides also show severe phyto-toxic effects to rice crop emergence under flooded condition immediately after herbicide application. Mild phyto-toxicity may cause extension of flowering time and total duration of rice crop. The high application rates of pre-emergent herbicides also show detrimental effect to the beneficial microorganisms extant in soil.

In recent times, some new post-emergent herbicides with low dosages viz., bispyribac sodium, cyhalofop butyl, fenoxaprop-p ethyl, ethoxysulfuron, penoxulam, azimsulfuron, flucetosulfuron etc. and herbicide mixtures like azimsulfuron + bispyribac sodium, fenoxaprop-p ethyl + ethoxysulfuron, bensulfuron methyl + pretilachlor, cyhalofop butyl + penoxulam, metsulfuron methyl + chlormuron ethyl etc. are showing promise for controlling weeds in rice fields. The rate and time of application of these new generation herbicides/ herbicide mixtures were standardized to keep the weeds under control during first 5-6 weeks of rice crop establishment. Thus, low-dosage high-efficacy post-emergent herbicides/ herbicide mixtures having broad spectrum of weed control are expected to be an intervention to suppress the weeds during critical period of crop-weed competition up-to 35-40 days of weed emergence (Munda et al. 2017; Saha et al. 2016). Among herbicide tested at ICAR-NRRI, the lowest weed biomass (9.0 g m^{-2}) was recorded in the Azimsulfuron + Bispyribac sodium treated plots with the weed control efficiency of 89% (ICAR-NRRI Annual Report 2014-15).

However, for successful control of weeds by herbicides, it is very much essential for the users to know different types of herbicides, specific herbicides to control different types of weed species, their doses and time of application, and safe handling and accurate application technologies for effective and environmentally safe weed control. Correct use of herbicides is essential to ensure that chemical residues on crops do not exceed the limits. Recommended herbicides generally do not pose any threat to people, livestock, or rice crops if used correctly and if suggested precautions are followed. However, the herbicides are potentially hazardous if not handled properly.

4.2. Weed competitiveness

Although, herbicides provide opportunity for relatively cheap control of weeds, relieving farmers of a heavy financial burden, the over-reliance on chemicals has also led to a number of environmental and agronomic concerns. The application of herbicides is leading to the reduction of non-weedy species and having impacts on biodiversity and ecosystem function. More notably, from a production viewpoint, herbicide resistance is now a common phenomenon and widespread amongst many problematic weed species in many countries, encouraged by the increasing dependence only on a few selected herbicides. In response to these challenges, there is new interest in the prospective for integrating non-chemical (or 'cultural') control options into weed control strategies. Competitive rice cultivars would offer a relatively cheap option in integrated weed management strategies. Many cultural methods can be integrated but, competitive cultivars are a potentially attractive option in comparison, because they do not incur any added costs. Breeding weed-competitive cultivars requires easily used selection protocol, based on traits that can be measured under weed-free conditions. Such cultivars may be more capable of reducing the competitiveness of a weed species, produce chemical exudates (allelochemicals) thereby reducing the economic burden by resisting weed growth and yield loss. Competitive cultivars could reduce the seed return of a weed species and contribute to medium to long-term weed management strategies, reducing the pressure on herbicides and improving the sustainability of cropping systems.

Variability in cereal cultivars in their ability to restrict yield losses from weed competition has been demonstrated in different crops. However, such comparative studies are of limited value outside of the experimental pool of cultivars. It is important that more practical approaches are developed that can be used to assess new cultivars for various situations and guide crop breeding efforts in future. Two aspects of cultivar competitiveness can be defined. The first is the ability of the crop to reduce the fitness of a competitor, and the second is the ability of the crop to withstand the competitive impact of neighbors (suppressive ability) and resist yield loss (tolerance ability). A strong suppressive cultivar can reduce seed production capacity of weeds, which could a viable long-term strategy in weed control. By contrast, tolerance means yield will be maintained under weed pressure. Although cultivars with high competitive ability have been recognized in many cereal crops (including wheat and barley), competitiveness has not traditionally been considered a priority by rice breeders.

At NRRI, above hundred early maturing rice germplasms (95-115 days duration) with five checks viz., Vandana, Anjali, Heera, Annada and Kalinga III were screened for weed competitiveness during kharif 2014. The germplasms viz., IC 426096, RH 145-55, Jhum Fulbadam, Deng-deng, IC 337590, IC 298485, IC 447256, CR 453 and DBT 2722 were found to be weed competitive (ICAR-NRRI Annual Report 2014-15). The germplasms viz., IR 83929-B-B-291-2-1-1-2, IR 83750-B-B-145-4-174-3, IR-84899-B-184-

18-1-1-1, IR-84887-B-153-33-1-1-3, IR-84887-B-157-38-1-1-3, IR 83750-B-B-145-4-174-2 and IR 82589-B-B-63-2-148-1 were found to be weed competitive at a different location, Santhapur (CRRI Annual Report 2013-14).

A number of relationships between competitive ability of crop and plant traits have been reported in the literature, viz. plant height, early vigour, tillering, canopy architecture, belowground traits, and nutrient partitioning. These traits are not independent of one another and have implications for other plant functions in addition to weed competition, including yield potential and tolerance of stress. To realize the potential of competitive crop cultivars, a faster, cheaper and simple-to-use protocol for measuring the competitive potential of new cultivars is essential; it is likely that this will not be based on a single trait, but will need to capture the combined effect of multiple traits. Further work would be required to measure the trade-offs and recognize win-win traits that improve competitive ability without negotiating other plant functions.

4.3. Herbicide tolerant (HT) rice

Herbicide tolerant (HT) rice may offer rice farmers a vital tool to control broad-spectrum of weeds. Rice varieties with an herbicide resistant gene would allow farmers to use an herbicide that is more environmentally-friendly than those in current use while simultaneously allowing better management of weeds. With HT-rice, farmers get the flexibility to apply herbicides only when needed. Farmers can make decision on input of herbicides with preferred environmental characteristics. HT-rice can control the weed flora associated with rice, especially of wild and other weedy rice species and also provide an alternative tool for the management of weeds that have already evolved resistance herbicides, especially grassy weeds like *Echinochloa spp*. It furthermore allows for the substitution of some of the currently used herbicides by other non-selective herbicides having less detrimental effect to the environment like glyphosate, glufosinate etc. Compared to other conventional herbicides used in rice, imidazolinone, glyphosate and glufosinate are considered environmentally benign.

There is a negligible threat of residual effects of glyphosate in soil as it is strongly adsorbed to the soil and crops. These herbicides can be used as post-emergent and therefore their rates can be adjusted to the actual weed pressure. Compared to conventional herbicides, HR-rice also provides a broader window herbicide application in terms of time frame and therefore alleviates some of the usual concerns (time pressure) for rice farmers. However, for season-long and broad-spectrum weed control, appropriate herbicide programs need to be developed for HR-rice in relation to the time of application, dose, herbicide mixture, and integration of non-chemical methods to ensure the long-term benefits of HR-rice technology.

4.4. Exploring herbicides – microbe compatibility

In modern agricultural production, herbicide application is one of the inevitable practices is being followed to minimize weeds problems in crop production. The indiscriminate usage of herbicides is reported to affect a group of organisms such as bacteria, fungi, nematodes, earthworms, termites and protozoa. The interaction between herbicides and soil biota is gaining practical significance since some of the herbicide molecules have adverse effects to microbial activities in soil. Many scientific evidences have revealed that the herbicides can cause both qualitative and quantitative change in soil enzyme activity. However, positive relationship may still exist with some herbicides molecules as noted in some studies. Herbicides application has both positive as well as negative effect to microbial activities in soil in response to different herbicides application.

Earlier, butachlor application was found to increase the reproductive ability of bacteria, but it is affecting the multiplication of free living nitrogen fixing bacteria particularly of Azotobacter sp. Some research findings indicated that application of organophosphates herbicides gradually increased azotobacter, arthrobacter, heterotrophic aerobic bacteria, actinomycetes and fungal counts. It is reported that herbicide viz., MCPB, bentazon, MCPB + fluozifop-p-butyl., bentazon+fluozifop-p-butyl, metribuzin, flouzifop-pbutyl+metribuzin, cycloxydin, and sethoxydin significantly increased the population of soil fungi (4 to 10 times higher) as compared uninoculated control, but these herbicides did not have any significant effect on nitrogen fixing bacteria. Different herbicides viz., pendimethalin, oxyflourfen, pursuit and pertialachlor application found gradually increased bacteria, fungi, actinomycetes and rhizobia. Arbuscular mycorrhizal fungi (AMF) is beneficial symbiotic endophytic fungi form a bridge between plants and soil and play a major role in the flow of energy and mobilization of nutrients (particularly P) from soil to plants. Other beneficial effects viz. plant growth promotion, inducing stress tolerance and enhancement of crop yield have been established. The field application of diuron and trifiuralin herbicides at recommended rates recorded minimal effects on AM fungi association. In another study, trifiuralin and diuron had little adverse effect on AMF formation. As the soil has mixed population of AM fungi, understating the side effects of herbicides on these non-target microorganisms are very complex. Because species of AM fungi differ in their response to a particular chemical, so no generalization can be made on the toxicity of a chemical to AM fungi.

In rice cultivation, herbicide application is essential but there effects on non-targeted organisms need to be studied in-depth. Moreover, information on proper herbicide use is very important for preserving beneficial microbes in soil. Hence, it is essential to study the effect of new herbicides on microbial properties in rice soils. More research is needed to better understand the different aspects of microbe-herbicide interactions. If we carry out some systematic studies on herbicides usage and their influence on soil microbial properties in rice based cropping systems, it will help to identify safe herbicides for rice cultivation, which in turn will preserve the soil beneficial microbes.

One of the most popular rice herbicide, Bispyribac sodium was evaluated in rice cv. Naveen at NRRI during 2015 under glass house condition to study its effect on AM fungal association. The results indicated that application of Bispyribac sodium even at double dose (600 ml ha^{-1}) did not show any inhibitory effect to AM fungal root colonization and sporulation in rice, the same treatment which recorded 33.3 and

9.09 % higher AM fungal colonization and sporulation respectively as compared to recommended dose (300 ml ha^{-1}). Similarly the AM fungi treated rice plants recorded significantly higher soil microbial biomass carbon (261.2 - 266.6 µg g^{-1} soil) after 30 days application of bispyribac sodium as compared uninoculated control (results unpublished).

5. WAY FORWARD

Wide variation in geographic, socio-economic, and agro-climatic conditions in rice-growing areas have resulted in equally diverse and contrasting extremes of weed control methods ranging from purely manual in developing countries to high-energy input technology in developed countries with large commercial farms. However, no single weed management strategy will solve all weed problems in rice. New management strategies will be needed as the established methods may no longer work in the changing environment. Current weed management technology consists of integration of appropriate crop husbandry (agronomic practices) along with direct cultural and chemical methods. It is also essential to develop weed database including noxious weeds in different ecosystems to track the weed dynamics. Such information will help to prepare list of weeds which are potential invaders and different models can be made use for prediction of invasiveness. The overall objective of proper crop management is to reduce the degree of direct control inputs. Thus, an integrated approach involving appropriate crop husbandry (indirect weed management strategy) including cultivation of weed competitive varieties and/or herbicide tolerant rice, good land preparation, proper water and fertilizer management, appropriate seeding rate/plant spacing, crop rotation is likely to improve rice grain yields. Future research on direct weed management practices viz. selection of herbicides with robust herbicide management strategy along with mechanical methods would bring about substantial dividends.

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