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Weed Management in Rice

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1. Introduction

Rice *(Oryza sativa)* is being used as a staple food by more than 50% of worlds' population which makes it highly significant in terms of plant production or food security [1]. The major producer and consumer of rice in Asia, contributing more than 90% to the global rice production and consumption. On global scale, the requirement of rice is projected to rise up by 25% to fulfil the demand of growing population up to 2025 [2]. In Pakistan, rice is considered as second most vital crop for earning foreign exchange after cotton [3]. Rice provides 27% of dietary energy and 20% of the protein diet in developing countries [4].

However, weeds are known as one of the significant issues in rice, which results in yield losses of 50-60% in direct-seeded while 70-80% in transplanted lowland rice. Therefore, weed management in rice fields is highly complicated and challenging. This chapter highlights the significance and implementation of different weed management approaches including mulching, tillage, manual weeding, herbicides, allelopathy, crop rotation, intercropping and other preventive measures, and also describes that how the judicious use of these weed control methods at optimum level could benefit the farmers along with environmental sustainability.

Weeds, a Dilemma in Rice

Several essential factors limiting rice production include weeds, insect pests, and diseases. A serious reduction in paddy yield is usually accredited to severe weed infestation in the fields [5]. Weeds are included among the big hurdles for restricting yield and productivity of rice [6-8]. "One year's seeding means seven years' weeding" is a well-known quote to describe the danger of letting weeds to produce seeds [9]. It was revealed that the weeds which are not controlled reduce about 80% production in direct seeded rice, which is much higher than transplanted rice seeded system [10,11]. Recently, the yield losses of 14-100% and 7-80% have been reported in the case of direct-seeded and transplanted rice, respectively [12]. Meanwhile, the reduction in crop yield due to weeds infestation may depend on location, the predominance of weed flora, or duration of weed attack [13]. The deleterious effects of such harmful plants on crop productivity may also be accompanied by their negative impacts on native beneficial microbial species [14].

Rice Cultivation Systems and Weed Infestation

It is essential to mention the adopted rice production systems in different countries for describing the occurrence and infestation level of weeds [15]. Several rice cultivation systems have been described, including transplanted and direct seeded rice being the main rice plant management methods [10]. Transplanting rice cultivation is the most conventional in Asian countries [16]. In the case of transplanted rice, the nursery is grown in seedbeds and then transplanted in the puddled or flooded fields manually or mechanically. The puddling is performed to suppress weeds and to support beneficial living organisms in the water. However, this approach is expensive and laborious as a huge amount of water is required. The direct seeded rice is further subdivided into wet-seeded rice, flooded rice, and dry direct-seeded rice. These different approaches are being used in different countries [15]. The fields facing the problems of weedy rice can be benefited by line sowing method as it is challenging to assess weedy rice and cultivated rice during early stages if the broadcast method is adopted [16]. The line sowing facilitates the identification and eradication of weedy rice plants between lines or rows during initial growth stages. Additionally, the mechanical and manual weeding is also easy to perform in case of row or line seeded rice as compared to broadcasting [17].

Weed Flora in Rice Crop

In paddy fields, above1800 plant species have been found during the last century [18]. However, fifty species have been known to be the most dominant in diverse environments. The rice weed flora varies with the method of rice cultivation, cultural practices, location of the field, and associated environment [15]. A classical weed atlas, "*C. rotundus*" is known as "The world's worst weeds" [19]. The ranking of weeds is done on the basis of frequency where *Echinochloa* species and weedy rice species dominate worldwide. After that, *Cyperus* species and other representatives of the Cyperaceae family are most frequent. During the end of the 20th century, *Leptochloa* species became major issue in rice fields. In some Asian countries including Vietnam or Malaysia, *L. chinensis* is known to be among the most common grass species found in rice [20] which was first discovered in Italy during the 21st century [21]. In South Asia, major rice weeds include: *Cyperus iria, Cyperus rotundus, Cyperus difformis, Cynodon dactylon, Dactyloctenium aegytium, Echinochloa crus-galli, Echinochloa colona, Eleusine indica, Fimbristylis miliacea, Ischaemum rugosum, Leptochloa chinensis* and red rice *(Oryza sativa)* [12].

Rice-Weed Competition

The losses in crop production due to weeds mostly vary depending on the intensity and types of weed species. A linear correlation has been observed between the level of weed attack and yield reduction. However, above a specific weed population yield losses become stable due to the competition of weed plants with each other. The most severe rice competitors include grassy weeds, followed by broad-leaved weeds and sedges [22,23]. The maximum yield loss by weeds occurs due to their competition with rice crop for nutrients, space, soil moisture, and light [24,25]. The cultivation of direct seeded rice along with jungle rice or *Ludwigia* species resulted in the significant reduction of growth, development, and productivity of rice plant due to shoot competition as compared to the root competition [26]. The productivity of wet seeded rice was highly affected because of severe weed competition with rice plant until 45 days after sowing [27,28]. It was therefore found essential to maintain weed-free period till 45 days after sowing for improving the production of rice crop. The critical time duration for the rice-weed competition was usually observed till 40 days after transplanting[29] however; the rainfed lowland rice showed critical period between 30-60 days after sowing to limit the reduction in yield [30].

Weed Control Strategies

Weed Prevention

Weed prevention is the most common method of weed control, which inhibits the initiation and extent of weeds in the crop area [31]. It generally involves all the practices to assess the access of weed seeds and their development in a specific field. One of the most critical tactic to prevent annual production of already present weed seeds, rhizomes, or tubers is farm hygiene, which includes all measures preventing the weeds infestation. For example, all the physical, chemical, or mechanical practices restricting weeds development are a part of farm hygiene. It also involves quarantine laws preventing weeds from getting access to a new habitat. Meanwhile, the non-cropped areas associated with fields such as irrigation/ drainage channels, fence lines, ditches, and bunds should not be neglected [32]. On the other hand, contamination of crop seeds with weed seeds must be prevented either by growing a weed-free rice crop or by cleaning the rice seeds before storage or at least at sowing time. If a clean field free of weed infestation is being planted with rice seeds which are contaminated with weedy rice at 2 seeds kg^{-1}, could cause an infestation of weed rice seeds at 10 kg ha^{-1} after three years of the plantation [33]. The weeds mimicking rice plants need special care for their eradication. Therefore, the rice nursery must be free from weed seedlings. It is suggested to use clean and certified seeds from a reliable source to minimize the spread of weeds to new fields [16]. In addition, maintenance of clean fields, irrigation channels, border, and farm equipment are included in weed prevention [34].

a) Physical/Mechanical Methods

Mechanical or physical control includes any practice that suppresses or kills weeds through physical disturbances. These methods include digging, pulling, plowing, mowing, and disking. Various hand tools were used to destroy and kill weeds. Jethro Tull created the first animal-drawn weeding tool, the horse hoe, in the 18th century. The rotary rice weeder and conoweeder can be used to control weeds in rice. Bushening and halod are used to control weeds in some regions of India [35]. A rotary weeder can be employed four times after 15 days of transplantation at an interval of 10 days to manage weeds in the field. In this way, labor can be saved by minimizing hand weeding. It also aerates the root zones and soil and improves root activity, which ultimately results in high yields [36]. In dry-seeded rice, inter-cultivation repeated twice or thrice by-passing small blade or hoe harrow between 20 and 45 days after sowing can efficiently control weeds. Two weedings are recommended in rain-fed rice where first weeding is carried out between 15-21 days after germination and second weeding may be done after first weeding between 30-45 days. It was reported that the conoweeder alone contributes to 17.4% increase in grain yield [37].

Manual Weed Eradication

Hand weeding is a conventional method for controlling weeds which is preferably used by smallholders [38,39]. In past, the agriculture as a major occupation and high availability along with cheap cost of labors had made the hand weeding as comparable to the management of weeds. Hand weeding is tricky and time consuming as one weeding takes almost 25-35 days ha^{-1} depending on the method of plant cultivation and type of land. Weed plants which can easily be pulled by hands are pushed out of the soil and wasted [40] however, smaller weeds can also be removed by hands with difficulty. Harrowing is effective in direct-seeded rice if plants are longer than weeds [41]. Any delay in weeding will enable the weeds to absorb nutrients thus early hand weeding is suggested. Hand hoeing is practiced as a faster and reliable method particularly where line/row seeded rice is grown. For resolving long-lasting issues associated with weeds, amalgamation of weed control approaches is very essential therefore, hoeing and hand weeding are also being used in modern agriculture. After the application of herbicides, the leftover weed plants should be uprooted before seed setting. Such weed plants could survive due to resistance or improper spraying technology. The escaped weeds must not be allowed to produce seeds. In order to limit their competition, the germinated weeds should be pulled two or three times during the crop growth period [42]. It was revealed that the hand weeding, if repeated twice results in reduced weed population as compared to chemical application like herbicides or untreated plants [43]. Continuous hand weeding for two times also showed reduction in weed dry biomass and improvement in mean straw or grain yield of crop [42]. In direct-seeded rice, manual weeding should be repeated three to five times for the complete eradication of weeds in a field [17].

Tillage Practices

The phenomenon of least soil disturbance is called tillage. The soil disturbance process significantly influences the profile, size and number of weed seed bank species [44]. Precision land levelling or using a laser leveller to create regular, sloping fields enables appropriate water management which has a profound impact on weed proliferation and the bio-efficacy of herbicides. A well-levelled field is important for best weed control: fields with low and high areas contain changing water depths, which are too deep for the rice in the low spots and too shallow for weed control in the high spots. The development of levelled fields by using precision land levelling or a laser leveller enables proper water management, along with a profound influence on the growth of weeds and herbicides efficiency. A well-levelled field is imperative for substantial weed control. The unlevelled fields contain variations in distances of water, too deep for the rice in low spots while too shallow for weed control at high spots [16].

Changing tillage practices alters the depth of weed seed in soil [45] which could influence the excess of weedy species [46] and efficiency of control methods in the field [47]. The exploitation of tillage system has a major influence on perennial weeds as compared to annual weeds. The conservation agriculture may be responsible to increase the growth and development of seeds of newly-shed weed which can be seen on or near the surface of soil. The utilization of zero tillage is arising as a significant method in the procedure of integrated weed control. The phenomenon of zero tillage helps to reduce weed density by eliminating the tillage [48]. It also offers efficient weed management in combination with the application of herbicides at reduced levels [49]. Under zero tillage, it is hard to manage perennial weeds due to the production of vegetative or reproductive parts such as tubers, stolons and rhizomes. If it is essential to employ minimum or zero-tillage practices, the other appropriate weed control methods should be used for successful eradication of weeds.

b) Cultural Practices

Cultural practices have a significant effect in analysing the competition of plant and weeds for above and below ground resources and thus effects weed control [50].

Rice Production Methods

The rice production methods affect the composition of species and the severity of weed infestation in the crop. Different rice production methods have been described, including transplanted or direct seeded rice being the main rice cultivation methods [10]. The uncontrolled weeds result in the reduction of grain production by 63, 71, and 76% under transplanted, wet-seeded, and dry-seeded rice, respectively [51]. The mean reduction in production due to weed-rice competition varies from 40 to 60%, which could rise up to 94-96% if uncontrolled [28]. For good weed control, transplanting method is primarily employed as puddling results in anaerobic conditions for destroying weed plants. In recent years, many South-East Asian countries have shown a shift from transplanted to direct-seeded rice, which is being preferred due to a shortage of water and deteriorated soil structure caused by puddling. Since the 1950s, the direct-seeding was practiced as the principal method of rice production. Farmers follow different direct-seeding methods depending on the resource levels such as land development, weather conditions, and infrastructure [52]. Direct-seeded rice gain several benefits over transplanting system such as minimized labor requirements, early crop maturity, efficient water usage, less drudgery, increased tolerance of water deficit, and lesser release of methane. However, weed proliferation is the main issue faced by direct-seeded rice. Therefore, the integration of several rice management practices has more significance in the case of direct-seeding as compared to transplanting. This is due to diverse weed flora which could not be controlled by a single control method. In direct seeding system, the problem of weedy rice can be greatly avoided by shifting to the manual transplantation of seedlings or by the broadcast method in flooded fields. The drudgery involved in manual transplanting can be reduced by the use of mechanical transplanters, which are equally effective for transplanting in zero-tilled or puddled fields [53].

Puddling or Submerged Conditions

Puddling or submerged conditions are helpful in reducing weed germination. In lowland rice, puddling or flooding is considered as an excellent weed management method. The transplanting system showed minimum weed density (63.5 m^{-2}) and dry weight (24.1 gm^{-2}) which happened by the sowing of sprouted seeds under puddled conditions [54]. The ploughing in summer season and cultivation of rice crops during post rainy days are helpful for reducing weed infestation. In direct-seeded lowland rice, soil compaction is a very effective tool for minimizing weed pressure by decreasing bulk density up to 1.8 g cm^{-3}. For wet-seeded rice production, well-drained fields along with appropriate water management systems are essential requirements for reduction of herbicide phytotoxicity on non-target flora. The variations in tillage practices for the cultivation of rice have caused major shifts in weed-flora during summers. Several new weeds such as *Cyperusdifformis, Fimbristylistenera,* and *Ischaemumrugosum* have also become inhabitants of rice fields. Furthermore, long-term cultivation of rice under flooded conditions have transformed the soil environment in favor of aquatic and semi-aquatic weeds like *Caesuliaaxillaris, Sagittariaguyanensis, Ammanniabaccifera, Ipomoea aquatic, Leptochloachinensis, Sphenocleazeylanica,* and *Oxalis* species. The variation from paddies (anaerobic) to aerobic conditions have changed the rice ecology, causing an abrupt shift in weed flora [10,55].

Weeds cause 12-46% reduction in water use efficiency of rice [56]. Although, productivity of water as evapotranspiration is low, huge amount of water is used for the preparation of land (paddies) in transplanted/puddled rice systems. Most of the weeds flora is unable to germinate under flooded/puddled conditions thus making flooding an efficient tool for weeds control. In addition to preparing slurry for sowing of seedling and forming a hard pan, puddling destroys weeds in lower layers of puddled soils where they are decomposed by the anaerobic process by forming ammonium compounds, which are further utilized by the crop. However, the deep ponding of water should not be done during early growth stages as it could destroy developing seedlings of rice crop. After the establishment of transplanted seedlings (about a week after transplanting), the field is completely flooded to a depth of 7.5-10 cm to avoid the growth of weeds. The depth of water can be slowly increased up to 15 cm as the rice plants develop.

The increase in ponding period from 3-9 days after transplanting improves the efficiency of rice herbicides. The exploitation of clean and good quality seeds and water seeding can reduce the problem of red/weedy rice. The practice of flooding rice fields is commonly used as a basic cultural control method to destroy weeds in transplanted rice under puddled conditions. However, its impact is often species-specific [57]. Thus, the flooding can be efficiently used to suppress the emergence of weedy rice, however, some weed species like *Eleusine indica* and *Leptochloa chinensis* may be flourished due to alternate drying and wetting in puddled and direct-seeded rice. The emergence of weed seeds is usually dependent on moisture content in the plough layer (0-15 cm).

Differential competition has been observed under water stress. For example, grass weeds under stressed conditions show serious competition with rice crops. Because of canal irrigation systems, weeds like *Ageratum conyzoides* have become residents of rice fields, water channels, and bunds of the fields. The semi-aquatic conditions developed due to flooded conditions have encouraged the weeds belonging to marshy places, e.g., *Eleocharis acicularis, Hydrilla verticillata, Scirpus roylei,* and *Najas argute*. In direct-seeding systems, there is a direct need to grow rice cultivars which are capable of germinating in flooded or anaerobic conditions to avoid the attack of weedy/red rice. In regions where water is plentiful, the introduction of such varieties with suitable flooding time and depth can significantly help to diminish weedy rice. This weed control method was highly useful in decreasing chemical load [56].

Intercropping

Simultaneous cultivation of two or more crops on the same field is known as intercropping, which results in the production of high yield as compared to a monoculture of any participating crop [58]. The establishment of intercrops as compared to simple cropping is determined by a succession of agronomic practices including final plant density, date of the plantation, provision of resources and intercropping models as interaction among species could be influenced by them [59]. The suppression of weeds by competition varies significantly in case of intercropping as compared to monoculture. The pattern of availability of resources exceptionally light to weeds can be changed by enhancing the complexation of cropping system by interplanting plant species of varied growth forms, physiologies, and phenologies [60].

Cover Crops/Mulching

Cover crops or mulches can diminish weed problems by adopting preventing measures for the germination of weed seed or by suppressing the development of growing weed seedlings. If tillage practices are followed, the perennial weeds can be suppressed by growing cover crops. At harvesting, an efficient smother crop can leave the field free of weed plants. Mulches, either organic or inorganic in nature, are composed of living ground cover, loose soil particles laid on the ground or layers of natural/artificial materials. The selection of cover crop depends on the crop growth duration, nitrogen fixation, and its rooting behavior. Azolla, being a green manure crop like sannhemp and sesbania is being used in rice fields for this purpose. One of the most important considerations involved in the selection of cover crop is that the selected crop should not be a competitor with the rice crop for main resources [16]. It was observed that the use of sesbania as a cover crop with azimsulfuron (30 g ha^{-1}) and fb bispyribac Na (25 g ha^{-1}) should be grown for reducing weed growth and improve the yield of rice [61].

Crop Rotation

In traditional farming system, a significant part of weed control was the rotation of diverse crops having variable life cycles. The crop rotation is defined as a practice of growing different types of crops in succession on the same land. As specific weeds are linked to a specific crop, the weedy plants increase rapidly due to continuous cultivation of a favorable crop in the same field. These weed plants, if allowed to survive for a long duration, are tough to control [62]. In conservation agriculture, crop rotation is a successful method to overcome the weed growth. The rotation of crops is considered to be effective for controlling crop-specific weeds. The dynamics of long-lasting weed populations can be disturbed by the sequencing and selection of suitable crops. Different management practices are related to different crops, and rotation of such crops is found to disrupt the life cycle of several weeds, including weedy rice [17,57]. The cultivation of non-rice crop causes the exploitation of different cultural practices along with the use of variable and effective herbicides. In rice monoculture systems, one rice crop (dry season crop) is rotated with an upland crop. However, weed infestation can be overcome by “mixed cropping” of rice and Azolla or rice and some green manure. The growth and germination of weedy rice can also be controlled by the addition of some short duration crop such as green/black gram between two crops of rice. The inclusion of sesbania as a green manure or summer cowpea as a fodder crop after harvesting the wheat crop during rice-wheat rotation can provide proper weed management, and also reduces the use of herbicides [63]. In Italy, about 90% reduction in weedy rice was achieved by the rotation of soybean for one year. Few crops, including maize, pearl millet, and sorghum, also suppress the intensity of weeds through allelopathic interruptions. The residual effect of pearl millet is useful for the suppression of weeds in the following crop. Therefore, it can be used in rotation as a fodder crop. However, the adoption of this system depends on the yield stability and market prices of rotation crops. Thus, weeds demography and population density are severely affected by crop rotation [64].

Planting Density

Good quality seeds and seedlings along with plant protection measures should be adopted to maintain maximum population of the crop. A crop ensures more repressing influence on weeds by maintaining high seed rates and narrow row spacing in an agriculture ecosystem as lesser space is vacant for weeds to grow [65,66]. Weeds population can be reduced by keeping up the predominant position of the crop over weeds and changing the canopy structure with the help of increasing crop density for every unit region [67]. However, row management and plant population also affect weed population by cutting light availability at the ground level. Crops become more competitive against weeds as they put pressure on space availability for weeds growth by growing higher plant population [68.69]. Thus, the development of rapid canopy cover with narrow row spacing improves the competitiveness of crops with weeds. With cultural management strategies like decreased plant row space, the ability of rice crop to struggle against weeds for light could be increased [26,70]. Depending upon weeds biology and rice cultivars existing in the field, high seed rates could partly control weed. Thus competition can be diverted to promote plant growth [71]. It is noted that increasing the plant density from 33-44 plants m^{-2} can reduce dry matter accumulation by weeds in a transplanted rice crop. The growth of weed is higher in a thinly populated crop compared to a thickly populated crop. By smothering the weeds and compensating the damage caused by rats and birds or for poor crop establishment, high seed rates are used to manage weeds in direct seeded rice. In organic production and low-input systems or where herbicides resistant weeds have been developed, higher plant population is of great importance. High seed rate help to minimize the weed problem in affected areas of rice [17]. The density of sedges is also affected by seed rate; however, the density of *E. canola* is not influenced by the rate of seeds in direct seeded rice. Sedge density was decreased by 35% when the application of seed was improved from 15-240 kg ha^{-1} [72]. Although, weed density decreases linearly with increasing seed rates; however, beyond the optimum level, the high seed rate has no effect on weed biomass. An increase in seed rate from 15-125 kg ha^{-1} led to rapid canopy closure, thus reducing weed competition and significantly decreasing weed biomass [73]. Narrower row spacing allows less light penetration through the rice crop leaves, and thus smothering weeds and preventing them from competing effectively with the crop in early crop canopy cover [74]. Higher grain yield and productive tillers are attained by narrowing row spacing [75]. In transplanted rice, seedlings are transplanted randomly by the farmers/laborers. However, changing the plant geometry could help farmers to control weeds more efficiently. Thereby, enabling the rice plant to comparison with weeds more efficiently and to produce substantial yields by achieving a favorable condition for plant growth by narrow row spacing and increased plant density [68].

Fertilization

Weeds are affected by both soil fertility and fertilizer use. Fertilizers use has a significant effect on weed population, its growth, proliferation, dormancy, hardiness and persistence, weed dynamics, weed diversity, and crop-weed competition in rice crops. Some weeds favor low-fertile soils, whereas others predominate in well-fed soils. Balanced use of fertilizers, especially nitrogen is favourable agriculture management for minimizing weed severity [76]. However, under high weed pressure, crop fertilization with different nutrients helps weeds more than the crop because the absorption of nutrients is higher and faster in weeds than in crops. The yield of rice in weeds-controlled areas was significantly improved through increased rate of nitrogen application up to 150 kg ha^{-1} in direct seeded rice, however, in reduced weed control environment it resulted in a severe yield reduction [77]. Thus, crop fertilization alone is not helpful in achieving higher net returns. There should also be more emphasis on the application of fertilizers using band placement methods along crop rows, at the most effective times and in optimum quantities. To date, limited research has been done in this directio, particularly for the rice crops.

Selection of Cultivars

For reducing hand weeding and herbicide inputs, selection of weed-competitive rice cultivars (producing high yields) could be a significant method [78]. Weed-competitive ability cannot be related to a single feature but, is an outcome of the relationship amongst various suitable varieties [79-81], thereby making it tough for plant breeders to work for weed-competitive varieties of crops. More work is needed for weeding upland direct-seeded rice field than lowland transplanted rice field [82]. Thus, the farmers of South Asia are favoring practices other than hand weeding or limiting the use of hand weeding by the exploitation of other weed control methods to minimize the cultivation cost [83].

Allelopathic Control and Development of C4 Rice

Allelopathic rice cultivars can play a role in weed suppression. According to Duke et al.[84], the weed suppression by allelopathy utilization can be increased either by increasing the existing crops' allelopathic potential or by introducing the allelopathic capability via incorporation of foreign genes that encode for allelochemicals. International Rice Research Institute (IRRI) established an approach for screening allelopathic rice or complete plant-bioassay [85] to reduce the results of competitive interference for common resources among test plant and rice. The barnyard grass can be controlled by 111 cultivars of rice in the Philippines [86] which showed that allelopathy might give 34% reduction in dry weight of weed after 8 weeks of seeding. The momilactone B was released by rice seedlings and found to be the primary source to the allelopathic potential of rice, especially for barnyard grass [87]. Commonly presumed allelochemicals discovered in rice are phenolic acid composites which include p-hydrobenzoic acid, p-coumaric acid, vanillic acid and ferulic acid [88-90].

In addition to allelopathic control, rice scientists are struggling for developing C4 rice crops either through conventional breeding or using transgenic methods [91]. Since rice is a C3 plant and shows less resistant to competition against C4 weed plants like *C. rotundus* and *E. crusgalli.* The development of C4 rice is appreciated because C4 plants are more competitive and efficient than weeds, even under water-stressed conditions [92].

b) Biological Control

The use of an agent, combination of agents or biological ways to suppress weeds is known as biological control of weeds. In biological control agents, all types of a microbial organism can be considered. Use of living organisms, including insects, herbivorous fish, animals, disease-causing organisms, and competitive plants to limit weed infestation is defined as biological control. This method can reduce the weed population to a significant degree but cannot eradicate weeds. For example, a rice root nematode (*Hirschmanniella spinicaudata)* that controls most upland rice weeds in case of rice; a moth *(Bactra verutana*) that destroys *Cyperus rotundus* ; the steel blue beetle (*Altica cyanea*) which completely destroys *Ludwigia parviflora* and the rust fungus (*Puccinia canaliculata*) which controls *Cyperus esculentus*. Various fungi are being used as myco-herbicides for example, *Cocholiobolus lunatas* and *Exserohilum monocerus* are used to overcome the infestation of barnyard grass [93]. Integrated rice-duck farming (Aigamo Method), a 500 years old Japanese tradition, to increase rice productivity, decrease weeds and pests in rice fields and increase fertilizer availability to rice crop by making use of the mutually beneficial relationship between rice and duck crops [94].

In weed management systems, seed predation through granivore fauna, like ants and other insects, could be used as an important tool mostly under zero-till systems where newly produced seeds of weed plants stay at the surface of the soil [95]. By mixing seed predation with other weed control measures, herbicide use, and the risks associated with it can be reduced. Thus, seed predation can significantly decrease the intensity of weed seed bank as they serve as forage for the predators of weed seeds, which could be stimulated by leaving plant wastes in fields. Since, no reserve price is involved in applying such management techniques, these environment-friendly, safe, and economic approaches for weed control can be mixed with existing practices as a part of an integrated weed management package. Biocontrol agents' potential should be exploited. However, it must be considered that there may be less population of natural enemies of weeds at the required time to control weeds in specific agricultural situations.

c) Chemical Control

Significance of Herbicides

The exploitation of herbicides is significantly proportional to the availability and cost of the worker. One of the first labor-saving techniques to be adopted is herbicides, which have been proved to offer the best weed management. Herbicides are energy and labor efficient than other weed control methods like mechanical or manual methods of weed management. These chemical measures are also highly efficient in controlling weed plants that mimic crops or which propagate asexually [62,96]. The success of direct seeding of rice is dependent on the use of herbicides because manual means of weed control are often not feasible. The application of anilophos at 0.6 kg ha^{-1} after one day of sowing along with a hand weeding after 45 days of sowing has proven significantly better in destroying weeds and securing high grain yield [97]. Also, weeds grow extremely rapidly without the use of herbicides in the early stages before the fields can be flooded. In addition, the application of herbicides is common in transplanted rice systems. Angiras and Kumar [98] reported that pyrazosulfuron ethyl applied at 25 g ha^{-1} between 3-10 days after transplanting was found effective in reducing weed density or dry matter yield. Sulfonylurea is a well-known group of herbicides worldwide which shows high activity, tremendous selectivity, application feasibility and minimum toxicity to mammals with a diverse range of weed control even at extremely low application rate [99-101].

The major constraint to the widespread adoption of herbicides is the involvement of economics. However, increased labor wages have led to the adoption of chemical weed control alone or as a component of an integrated weed control system by many farmers in Asia during recent times. Therefore, the use of herbicides varies considerably between countries [16].

Types of Herbicides

Different types of herbicides include non-selective or selective, and pre-, early post- or post-emergence. In rice production systems, the majority of herbicides being used are selective, having broad or narrow spectrum, and having a limited effect on the crop. The selection of herbicides is dependent on the chemical used for its formation, its rate, duration, and ways of application. Thus, it is critical to comply with recommendations for effective and selective weed control. The application of nonselective herbicides like glyphosate is suggested before rice establishment or on weed invasions like weedy rice which are not easy to control with selective herbicides. Pre-emergence herbicides are applied on the soil to manage weed before emergence, while the herbicides that are applied to weeds after they emerge are known as post-emergence herbicides. The amide group includes herbicides such as propanil, pretilachlor, and butachlor. Butachlor may be implemented both as a pre-emergence or early post-emergence herbicide to control a wide range of narrow as well as broad-leaved weeds. Different pre-emergence herbicides like thiobencarb, butachlor, oxadiargyl, pendimethalin, anilofos, pretilachlor, oxadiazon, pyrazosulfuron ethyl, nitrofen and oxyfluorfen offer a fair range of weed control [62,80,102,103]. For the efficient use of pre-emergence herbicides, they must be applied with some limitations, for example, under appropriate soil moisture and short time duration, preferably in standing water conditions. Also, the use of chemicals during early growth stages of the crop is impossible due to several limitations at field level while the continuous application of a single herbicide develops resistance in undesirable plants. Therefore, the use of post-emergence herbicides becomes essential [104]. In conventional rice cultivars, the use of selective herbicides is not common to manage weedy rice. Some studies have reported that effective control of weedy rice may be provided by pre-plant herbicides (e.g., oxidation and metolachlor). However, such herbicides should be applied before rice plantation for preventing damage to the rice crop. It is also essential to use mixtures of several suitable herbicides in direct seeded rice system where diverse weeds exist, especially in dry direct-seeded systems [57]. Therefore, sprays of pre-emergence herbicides followed by post-emergence herbicides are recommended to ensure good weed control [55]. It was reported that the pretilachlor applied as pre-emergence herbicide at 0.75 kg ha^{-1} followed by 2,4-Dicholorphenoxyacetic acid as post-emergence herbicide at 0.5 kg ha^{-1} was considered most efficient in diminishing the weed quantity and dry biomass thus improving the uptake of nutrients, grain yield and net return [105].

Herbicide-Resistant Weed Flora, a Constraint

Several species of weeds are not controlled effectively even after utilizing the mixture of herbicides. Moreover, a few weed species continue emerging throughout the plant life cycle due to the high level of seed dormancy. Injudicious and non-stop use of similar herbicide or herbicides with same mechanism of action over a prolonged time period may additionally results in resistant biotypes' development, alterations in weed flora and adverse impacts on the following crop [96], which put loads of chemicals in the environment [106-108]. Weed population has shifted from *Echinochloa* sp. to *Ischaemum rugosum, Cyperusiria* and *Caesulia axillaris* by continuous use of butachlor herbicide for years, and continuous use of pretilachlor have also resulted in weed population shift from *Echinochloa* sp*., Cyperusiria* and *Caesulia axillaris* to *Ischaemum rugosum* [109]. Thus, to increase the efficacy of applied herbicides and to cut back the cost of weed control, extremely efficient and low-cost herbicide application techniques such as spray instrumentation and nozzles, herbicides adjuvants and carriers should be adopted along with ensuring the appropriate timing of herbicides use. Furthermore, advanced research on the use of herbicides mixture is required to postpone the development of resistance and to provide more efficient and cost effective ways of weed management.

Herbicide-Resistant Rice, a Boon in Disguise

Herbicide-resistant rice technology has the potential to overcome infestation of a wide variety of weeds such as grasses, broad-leaved weeds, and sedges, which result in serious yield reduction in lowland rice, including weedy rice and *Echinochloa* spp. [110] and can be considered a boon in disguise.

Also, the aptitude to effectively manage weeds makes the development of herbicide-resistant rice a smart technology which can easily be adopted by the farmers in several circumstances. In rice, three systems of herbicide-resistance have already been develope, including imidazolinone, glyphosate, and glufosinate-resistant cultivars [111]. Glufosinate and glyphosate are post-emergence herbicides and known as comparatively environmentally benign. The application rates of these fertilizers can be managed according to the severity of weeds. Additionally, the technology has a broad time frame for the application of herbicides as compared to traditional technologies.

In spite of the expected benefits of herbicide-resistant technology, there are limitations related to the possibility of gene flow from herbicide-resistant rice to weedy and wild rice species. For example, in different regions, weedy and wild relatives are present; therefore, gene flow could take place from herbicide-resistant rice to such species [97]. The dependence on this technology for efficient weed management in a rice crop will rely on carefully introducing genes and further management of cultivars.

d) Integrated Weed Management

A single approach for weed management may not be capable of controlling weeds below the threshold level and may also cause a rift in weed communities, development of resistance, and environmental harms. Therefore, the implementation of a diverse system is important for weed control as weed flora is very responsive to weed control methods [47]. An effective weed control method must intend to reduce weed population at a certain level where weeds infestation would not have any adverse effect on ecological interests and economics of farmers. The combination of various suitable weed control practices is helpful for farmers to use additional opportunities for weed management thereby minimizing the occurrence of escaped weeds. Thus, integrated weed management is a scientifically decision-making practice that synchronizes the use of weed ecology and biology, environmental evidences and all currently implemented technologies to manage weeds by using most feasible and economical means, and posing the least threat to human and environment [112].

Integration of different weed management methods is a traditional approach. For instance, the conventional method of "puddled soils" to destroy pre-existing weeds and assist in water retention, use of transplanting method to obtain optimum plant density, and leaving standing water in rice field to kill unwanted plants followed by one or more hand weeding is a well-known example of this system [113]. Since, provision of resources is important for weed occurrence [114], improving the utilization of resources by intercropping also becomes a part of an integrated system. However, the most significant feature of all weed management practices is "weed prevention" which includes all measures to foresee the onset of weeds infestation and avoid their spread in the field [115]. Thus, effective integrated weed management is an amalgamation of preventive, physical, cultural, mechanical, biological and chemical control techniques for destroying weeds in an efficient and economical manner, and further considering the environmental sustainability.

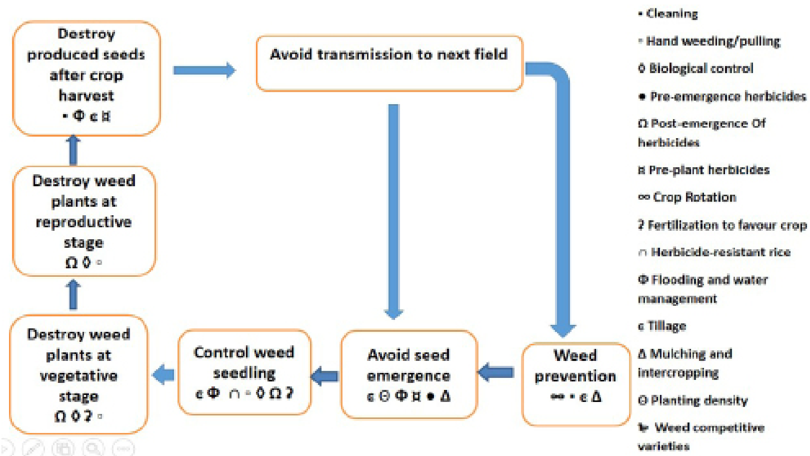

Figure 1: Weed Management Strategies During Different Growth Stages of Weeds

Conclusion

Rice is a vital food commodity being produced worldwide, especially in developing countries where it accounts for 33% of the total input of calories by these populations and has become an important employment source, especially in rural areas. Meanwhile, weeds play a significant role as a primary biological constraint in rice cultivation throughout the crop production systems. Under weedy conditions, yield losses in direct seeded and transplanted lowland rice were recorded around 50-60% and 70-80%, respectively. Thus, weed control in rice fields is quite complex and challenging. Among weed management strategies, the use of herbicides is a highly adapted practice nowadays. However, the large scale and consistent application of such chemical treatmentsare restricted due to the involvement of risks to the environment. The flooding of rice fields is another effective strategy which adversely effects the germination of weed seeds and results in the death of weed seedlings. Weed infestation could also be reduced by crop competitiveness during growth and reproductive stages. Hand weeding is widely practiced depending on the availability of labour however, mechanical weeding could reduce labour cost up to 72-74%. The judicious use of all weed control methods including mulching, tillage, hand weeding, herbicides, allelopathy, crop rotation, intercropping and other preventive measures as an integrated approach is preferred which could defeat the weed menace to an acceptable level.

Future Paths

Adequate knowledge of the agronomic, soil, genetic, biological, ecological, physiological, biochemical, environmental, toxicological and economic aspects of plant growth, behavior and production are required for the formulation of packages of complex strategies for different rice ecosystems. Moreover, complete coordination of different techniques and improved instrumentation is essential to ensure system productivity, prolonged weed management, food security, and environmental sustainability. The best management practice can be adopted by applying numerous herbicides, rotating crops, embracing best cultural weed management practices, use of weed-free seeds, scouting fields routinely, and cleaning the equipment, non-cropped areas and water channels to minimize weed transfer to other fields. A strategy that integrates different weed control systems allows us to manage weeds effectively and may help to delay the evolution of herbicide resistance. For different agro-ecological regions, it is important to develop and popularize integrated weed management techniques, which considers the geographic, ecological, agronomic, and climatic features of farming methods. To further attain sustainable, long-term, and effective weed management, an integrated approach that concentrates on prevention of weed attack, reproduction and recruitment must be developed. These complexes weed control packages could be environmentally sustainable and effective for continuing preservation of natural resources and improving agricultural productivity along with adequate economic returns and less adverse ecological influence on farmers.

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