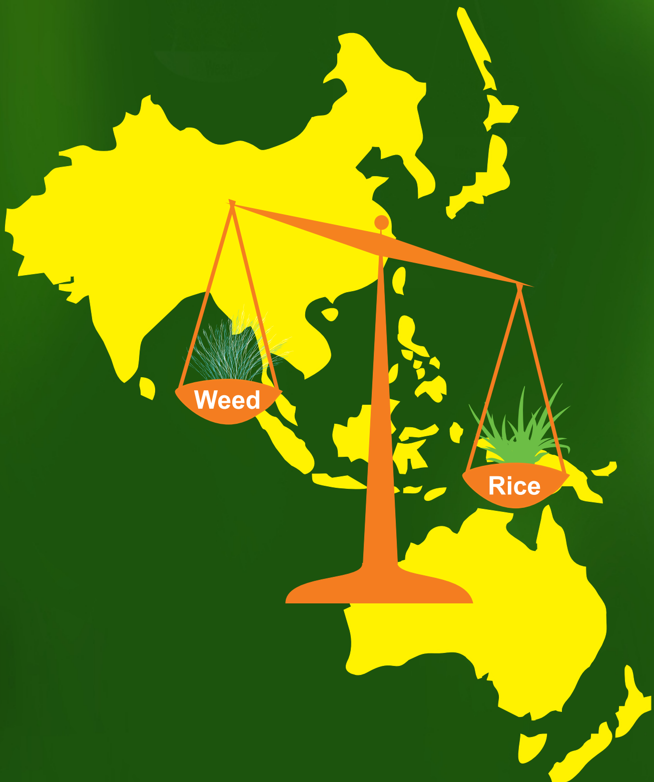
WEED MANAGEMENT IN RICE
IN THE ASIAN-PACIFIC REGION



Editors

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Asian-Pacific Weed Science Society
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An Overview of Weeds and Weed Management in Rice of South Asia

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Abstract

South Asia produces slightly above 225 million tons of rice (30.7% of global production) on 60 million hectares (37.6% of the global area). India and Bangladesh are the major rice-growing countries. India contributes around a quarter of global production from 43 million hectares (the largest rice cultivating area). In South Asia, manually transplanting rice seedlings into flooded soil (TPR) is the common method of rice establishment. But direct-seeded rice (DSR) is gaining importance due to shortage and increased cost of resources. In Sri Lanka 93% of rice is cultivated as wet-seeded rice. However, the weeds are major constraints in DSR causing higher (14 to 100%) than in TPR (7 to 80%). Major rice weeds in South Asia include: *Echinochloa crus-galli* (L.) P. Beauv., *Echinochloa colona* (L.) Link., *Cyperus rotundus* L., *Cyperus iria* Linn., *Cyperus difformis* L., red rice (*Oryza sativa* L.), *Leptochloa chinensis* (L.) Nees, *Ischaemum rugosum* Salisb., *Paspalum distichum* L., *Dactyloctenium aegyptium* (L.) Willd., *Cynodon dactylon* (L.) Pers., *Echinochloa crus-galli* (L.) P. Beauv., *Eleusine indica* (L.) Pers., *and Fimbristylis miliacea* (L.) Vahl. Weeds flora was reported to vary with location, method of rice establishment, cultural practices used and associated environment. The small-holders' traditional weed control method is hand weeding by hand-held hoe and hand pulling. Hand weeding is still a major method of weed control. However, the herbicide use is increasing due to non-availability and increased cost of labour in several of the South Asian countries. Mechanical weeders are being used by farmers as they reduce labor use and cost of weeding (72 to 74%). Tillage, mulching, crop rotation, allelopathic competitive crop cultivars, intercropping, balanced nutrient and water management and preventive measures have proven to be effective as a component of integrated weed management in rice of South Asian countries. Herbicide resistance among weeds in rice was not reported in India, Bangladesh, Nepal and Pakistan. Herbicide resistant biotypes of *E. crus-galli*, *I. rugosum* and *C. iria* were reported in Sri Lanka. In South Asia, herbicide tolerant rice is yet to be made available to farming community. Weed management research must be focused on identifying location specific effective, environment friendly, economically viable integrated weed management strategies.

Keywords: South Asia, rice, weed management, herbicides, herbicide resistant weeds, herbicide tolerant rice

1. Introduction

Rice is a source of staple food for the majority of the 1.7 billion population of South Asia and a source of livelihood for more than 50 million households. The region cultivates rice on 60 million ha and produces slightly above 225 million tons of paddy, derived from 37.6% of the global area under rice and 30.7% of global rice production (http://www.fao.org/faostat/en/#data/QC). Within South Asia (Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan and Sri Lanka), India and Bangladesh are the major rice growing countries. India has the largest area under rice in the world with 43 million ha (more than one quarter of the global rice area) and contributes to around one quarter of global production (Table 1). Bangladesh, the world's fourth largest rice producer, has more than 11 million ha under rice and produces 52 million tons of paddy. The per capita production and per capita consumption have followed an upward trend until the early 1990s. However, it later declined for a few years and then stabilized at 80–82 kg during the past 15 years, thus making South Asia a growing exporter of rice. Its rice exports increased from 2 million tons in the early 1990s to 14 million tons in 2013. Apart from India, the largest exporter of rice in the world, rice exports from Pakistan have been steadily rising for the past three decades, reaching 4 million tons in the recent past. However, Bangladesh and Nepal import 1–2 million tons annually (http://irri.org/rice-today/ rice-in-south-asia).

Table 1. Area, Production and Productivity of Rice in Major Rice Producing Countries of South Asia

Countries	Area ('000 ha)	% of SA total	Production ('000 tons)	% of SA total	Productivity (t/ha)
India	43855	71.66	157200	68.99	3.58
Bangladesh	11319	18.49	52325	22.96	4.62
Pakistan	2890	4.72	7002	3.07	2.89
Nepal	1486	2.43	5047	2.21	3.39
Sri Lanka	881	1.44	3381	1.48	3.84
South Asia (SA)	61202	37.61*	227870		3.72
World	162716		741477		4.56

* % of the word

Despite impressive production growth in the past five decades and the growing status as one of the largest rice exporting regions in the world, South Asia was still home to 295 million undernourished people in 2011-13, accounting for about 35% of the 842 million hungry people in the world. In 2011-13, 16.8% of the people in South Asia were hungry. This is the highest percentage among other Asian regions, only to be followed by Africa. The South Asian population is projected to be 2242 million by year 2050 in spite of reduced population growth of 0.89% (Alexandratos and Bruinsma, 2012). It is estimated that the increased population poses a major food security challenge (FAO, 2014). This necessitates immediate raise in agricultural production in order to tackle food insecurity in South Asia. Given that the area under rice may not further expand, a yield growth of 1 to 1.3% per annum (Fischer, 2014) is required to meet the demands of increasing population by 2050. This is achievable by alleviation of many associated constraints such as growing water and labour shortages; imbalanced use of inputs such as water, fertilizer and pesticides; the rising cost of inputs; competition for rice land from nonagricultural uses and biofuel crops; and increasing frequency of extreme weather conditions due to climate change besides biological constraints. Weeds constitute a major biological constraint in South Asia (Rao and Ladha, 2014; Rao and Yaduraju, 2015; Rao and Wani, 2015). Weeds cause the highest potential crop yield loss (34%), while the insect pests and pathogens cause 18 and 16% losses, respectively (Oerke, 2006).

1.1. Seasons of Rice Cultivation in Major Rice Producing Countries of South Asia

1.1.i. India: In India, there are four seasons: winter (Dec-Feb), summer (Mar-May), rainy southwestern monsoon (Jun-Sep) and postmonsoon, also known as northeastern monsoon, in the southern peninsula (Oct-Nov). Rice is grown in early-*Kharif* (Planting: Mar-May and harvest: Jun-Oct); mid-*Kharif* (Planting: Jun-Oct and harvest: Nov-Feb) and *Rabi* (Planting: Nov-Feb and harvest: Mar-Jun).

1.1.ii. Bangladesh: There are three rice growing seasons in Bangladesh and they are called: *boro* (Planting: Dec-Feb and harvest: Apr-May), *aman* (Planting: Jun-Jul and harvest: Nov-Dec) and *aus* (Planting: Apr-May and the harvest: Jul-Aug). The *boro* and *aman* are the major rice growing seasons, accounting for 93% of the planted area (*boro* 55% and *aman* 38%).

1.1.iii. Pakistan: Rice is planted once a year and the cropping season is *Kharif* (Planting: May-Jul and harvesting in Oct-Nov).

1.1.iv. Sri Lanka: In Sri Lanka, the *Maha* (Oct-Feb) is the major cultivating season during which rain is received from the Second inter-monsoon (Oct to Nov) and Northeast monsoon (Dec-Feb) (Marambe et al., 2015a). The *Yala* season is the minor growing season (Mar to Sep) which receives rain from the First Inter-monsoon (Mar-Apr) and South-West monsoon (May to Sep).

1.1.v. Nepal: In Nepal, rice is grown during the main season (Planting: Jun- Jul and harvest: Oct– Nov) and second (spring) season (planting: Feb-Mar and harvest: Jun-Jul).

1.1..vi. Bhutan: One rice crop per year is generally grown mostly under irrigated transplanted rice on bunded terraces, due to the steep terrain. Nurseries are raised in Mar-Apr, with transplanting and harvesting in October.

1.1.vii. Afghanistan: In Afghanistan, rice is grown mainly between Apr-May and Oct-Nov due to low temperatures.

Irrespective of the country and season in which rice is grown, weeds constitute a major production constraint in South Asia.

1.2. Methods of Rice Establishment

Transplanting rice seedlings in the flooded soil (TPR) is the common method of rice establishment in Afghanistan (CCO, 2012); Bangladesh (BBS, 2016), India (Rao and

Chauhan, 2015); Nepal (Bhattarai, 2016) and Pakistan (Khaliq et al., 2014). In TPR method, 10 to 30 d old seedlings are transplanted. The flooding condition gives rice seedlings a competitive advantage against the associated weeds (Rao et al., 2007; Kumar and Ladha, 2011).

In recent times, the direct-seeded rice (DSR) system is gaining popularity within the farming community of South Asia as it requires 35 to 57% less water and 67% less labour than TPR (Dhakal et al., 2015; Farooq et al., 2011; Kumar and Ladha, 2011; Mazid et al., 2006; Rao et al., 2007). However, weeds are more problematic in the DSR than TPR system (Dhakal et al., 2015; Kumar and Ladha, 2011; Rao et al., 2007). In recent surveys, farmers reported weeds as the main constraint in DSR in India (Rao et al., 2015), Sri Lanka (Abeysekera et al., 2010) and Nepal (Dhakal et al., 2015). Direct-seeding includes both wet-seeded rice (WSR) and dry-seeded rice (dry-DSR) methods which eliminate the need for nursery preparation, raising seedlings, uprooting of seedlings and transplanting.

In Sri Lanka, more than 90% of the rice area grown in low land, which is rainfed with supplementary irrigation, while about 5% of rice is rainfed upland. Direct-wet-seeded (WSR) rice system has largely replaced transplanting in Sri Lanka. In WSR, pre-germinated seeds are broadcast after puddling and levelling the field. The WSR in Sri Lanka covers about 93% of the total rice cultivated area and it is expected to increase further due to rising labour costs and decreasing profitability of rice production. Direct-seeded rice with alternate wetting and drying is also being practiced to a limited area. However, weeds have been identified as the major problem even compared to wet-seeded rice (Gunawardhana et al., 2013).

In India, dry-seeding is extensively practiced in rainfed lowlands, uplands and flood-prone areas, while wet-seeding remains a common practice in irrigated areas (Misra et al., 2005). Upland rice, mostly dry-seeded, is found in parts of Assam, Bihar, Chattisgard; Gujarat, Jharkhand, Kerala, Karnataka, Madhya Pradesh, Orissa, Uttar Pradesh and West Bengal states (Rao and Nagamani, 2007). The upland rice area is around 5.5 million ha which accounts for 12.33% of the total area under rice in India. The area under WSR system is increasing in parts of Andhra Pradesh, Punjab and Haryana in India (Rao, 2010).

In Bangladesh, during the *aus*, farmers mostly cultivate short duration rice varieties with minimum management practice, with these covering only 7% of the area (BBS, 2016). The major rice ecosystems in Bangladesh are upland (direct-seeded or transplanted premonsoon *aus*), irrigated (mainly dry-season *boro*), rainfed lowland (mostly monsoon-season transplanted *aman*, 0–50 cm), medium-deep stagnant water (50–100 cm), deep-water (>100 cm), tidal saline and tidal non-saline. DSR is practiced on a small scale in *aus* and *aman* seasons. Farmers usually practice random broadcast either dry seeds or sprouted seeds into the puddled soil or after dry tillage. In *boro*, DSR is not feasible because of shorter sowing time and low temperatures during the early growth, thereby creating a problem on seedling emergence and establishment (Ahmed et al., 2016). Due to recent climate change (untimely and shortage of rainfall) and increasing costs of production (labour, inputs, etc.), farmers of some areas (north-west, and south-west part of Bangladesh) are becoming more interested in DSR (Ahmed et al., 2015; Ahmed and Chauhan, 2014; Rashid et al., 2012). Farmers mostly practice dry-DSR, currently, because of availability of seeding devices and little irrigation water requirement at the time of seeding.

In Nepal, direct-seeding of rice is practiced traditionally by some ethnic groups in Parsa, Bara, and Rupandehi districts like Tharu (Dhakal et al., 2015). The DSR technology is now becoming popular in the districts of Rupandehi, Nawalparasiand, Banke and Bardiya (http://csisa.org/accelerating-adoption-of-direct-seeded-rice-in-bangladesh-and-nepal/).

In Afghanistan, the rice area, production and productivity were 210,000 ha, 449,400 tons and 2.14 tons ha^{-1}, respectively in 2011-2012 (CSO, 2012). The most of the rice is grown in the North Eastern provinces, including Baghlan, Kunduz, Takhar, Laghman, Nangarhar, Bahlk and Kunarha. In the East, rice is grown, immediately after wheat, as a transplanted crop. In Herat, it is either seedling-transplanted or seed-broadcast at very high seed rates.

1.3. Importance of Weeds in Rice of South Asia

Weeds are identified as a major biological constraint that hinders attainment of optimal rice productivity in major rice producing countries of South Asia like India (Rao et al., 2015a; Rao and Nagamani, 2010); Bangladesh (Kabir, et al., 2003; Rashid et al., 2012); Sri Lanka (Weerakoon et al., 2011) and Pakistan (Irshad and Cheema, 2006). This, in part, is due to favourable environmental conditions that prevail in these countries (Rao et al., 2007). The rice grain yield losses vary with the type of rice cultivation, country or region where rice is grown as also the environmental and cultural factors associated with rice agro-ecosystem (Yaduraju et al., 2015; Yaduraju and Rao, 2013). A survey of tropical Asian rice fields revealed that in farmers' fields uncontrolled weeds were the most significant pest factor in reducing yields, causing 23% and 21% lower yields due to weeds growing above and below the rice canopy, respectively (Savary et al., 2000). Although the actual yield losses caused by weeds are yet to be assessed in scientific manner, one study found them causing a grain yield loss of 6 to 9% depending on the rice farming system in South Asia (Hyman et al., 2008). In India, they account for 33% of the losses caused by various biological factors (Yaduraju et al., 2015).

In Bangladesh, the loss in rice grain yield due to weeds in farmers' fields was estimated as 43–51% (Rashid et al., 2012). Seasonal variation was also observed in the yield losses caused by weeds, with estimated rice yield losses due to weeds at 70-80%, 30-40% and 22-36% in *aus* rice (early summer), transplanted *aman* rice (late summer) and *boro* rice (winter rice), respectively (BRRI, 2006; Mamun, 1990). Weed infestation in *aus* and *aman* seasons are relatively higher than in *boro* and it is mainly due to high temperatures throughout the growing season, and this enhances weed seed germination and growth. During the initial stage of *boro* season, temperatures remain low, resulting in inability of weed seeds to germinate and grow until temperatures rise between early and mid-February (Ahmed and Chauhan, 2014). In addition, farmers grow their *boro* crop in well-irrigated areas than in *aus* and *aman* seasons because of potentially higher yield and lower weed problems.

In Sri Lanka, Amarasinghe and Marambe (1998) reported that yield loss caused by weeds in rice vary from 20% to 40% and in high in rainfed lowlands than in irrigated lowlands. Weerakoon et al. (2000) found that weeds are a more serious problem in the dry zone than wet zone, which could be related to the availability of water. A higher population density of *Isachne globosa* has resulted in 46% yield loss in rice (Witharana et al., 2014). Weeds have been reported to reduce crop yields by as much as 50%, in addition to quality of crop produce, thereby reducing the overall productivity of land and income of farmers, aside from adversely affecting the quality of the island's native biodiversity (Amarasinghe and Marambe, 1998; Bambaradeniya et al., 2001; Marambe et al., 2001, 2015; Rajapakse et al., 2012; Witharana et al., 2014).

In Bhutan, the aquatic weed *Potamogeton distinctus* alone caused yield loss of upto 37% (Nidup and Wangdi, 2000). Another aquatic species *Pistia stratiotes* lowered the availability of O_2 as well as pH of water, damaged rice crop and competed with rice for nutrients and space (Hussain et al., 2000). *Echinochloa crus- galli* accounted for 90% of the collective losses caused by all weeds in rice in Pakistan (Irshad and Cheema, 2006). In a recent survey, farmers of Nepal reported increased weed infestation as a major problem in DSR (Dhakal et al., 2015).

Fourteen principal weeds are listed by Koehler et al. (1973) in Afghanistan, where serious weed infestations occur but weeds are considered normally as live-stock feed or fuel and not regarded as a deterrent to yield.

Weed competition and the grain yield losses due to weed competition would be less severe under transplanting method than those under direct-seeding (Dhakal et al., 2015; Rao et al., 2007; Rao and Nagamani, 2007; Singh et al., 2005) (Table 2). Rice yield losses due to uncontrolled weed growth and weed competition were least (12%) in transplanted rice (Singh et al., 2011) and losses were the highest in aerobic direct- seeded rice on a furrow-irrigated raised bed systems (Singh et al., 2008) and in dry-seeded rice sown without tillage (Singh et al., 2011).The rice grain yields were comparable across all establishment methods of rice when weeds were managed (Singh et al., 2008). Thus, weed management is the major prerequisite for improved rice productivity and production using different methods of rice establishment (Rao et al., 2007).

In this Chapter, an effort has been made to collate the information on weeds and weed management in rice producing countries of South Asia and to suggest future research needs for continued sustainable production of rice in South Asia.

2. Weed Species infesting Rice in South Asia

The extent of weed infestation in rice depends on several factors such as weed seed bank, tillage practices, cultivar used, planting season, fertilizer and water management (Mahajan and Chauhan, 2013; Rao et al., 2007). In Sri Lanka, more than 142 weed species have been identified in rice fields. Of these, more than 78 species are grasses, with 52 species being sedges while broadleaf species account for 10-15 (Abeysekera, 2015; Amarasinghe and Marambe, 1998).

Table 2. Yield Loss due to Weeds in Rice Established by Different Methods in Major Rice Growing South Asian Countries

Country	Yield loss (%)		References
	Transplanted rice	Direct-seeded rice	
Bangladesh	15 to 40	40 to 100	Ahmed and Chauhan 2014; Ahmed et al., 2006; Karim et al., 1998; Mazid et al., 2001.
Bhutan	Up to 50	--	Nidup and Wangdi, 2000; Tshewang et al., 2016.
India	12 to 69	17 to 98	Kathirvelan, and Vaiyapuri, 2003; Rammohan et al., 1999; Singh et al., 2011.
Nepal	7 to 70	14 to 93	Pandey, 2009; Ranjit et al., 1989.
Pakistan	24 to 56	80	Akbar et al., 2011; Hussain et al., 2008; Jabran et al. 2012; Khaliq et al., 2011.
Sri Lanka	20 to 40	20 to 40 or higher (WSR)	Chauhan et al., 2013; Marambe 2009; Marambe et al. 2015.

The major weeds that infest different types of rice cultures in India are presented in Table 3. Weeds that infest rice in Bangladesh and in Sri Lanka are listed in Table 4, 5 and 6.

Echinochloa crus-galli, *Echinochloa colona*, *Cyperus rotundus*, *Cyperus iria* and *Cyperus difformis* were reported as major weeds in Pakistan (Hassan and Marawat, 2015), India (Rao, 2010) and Nepal (Bhurer et al., 1989). In addition to these, red rice (*Oryza sativa*), *Leptochloa chinensis*, *Paspalum distichum*, *Dactyloctenium aegyptium*, *Cynodon dactylon*, *Eleusine indica* and *Fimbristylis miliacea* were also reported as major weeds of rice in Pakistan (Hassan and Marawat, 2015) and India (Rao, 2010). In Afghanistan, *E. colona* was reported to occur (Clayton et al., 2014).

In the lowland rice of Bhutan, the most commonly occurring weeds are *Blyxa aubertii*, *Schoenoplectus juncoides*, *E. crus-galli*, *C. difformis*, *Monochoria vaginalis*, *P. distichum* and *Commelina benghalensis* (Dorji et al., 2013). In the upland system, weeds such as *Ageratum conyzoides*, *Galinsoga parviflora*, *Fagopyrum dibotrys* and *Persicaria runcinata* are also among the most dominant weeds, though grass weeds too are observed (Tshewang et al., 2016). Weed flora in the DSR systems is floristically diverse and higher in abundance than in transplanted rice (Mazid et al., 2001).

Table 3. Major Ten Weeds in Different Methods of Rice Establishment in India

Order of reporting (1 = Most reported)	Major weeds		
	Transplanted rice	**Wet-seeded rice**	**Dry-seeded rice**
1	*Echinochloa colona* (L.) Link	*Cyperus iria* L.	*Echinochloa colona*
2	*Echinochloa crus-galli* (L.) Beauv.	*Echinochloa colona*	*Cyperus rotundus*
3	*Cyperus iria* L.	*Echinochloa crus-galli*	*Cyperus iria*
4	*Cyperus difformis* L.	*Cyperus difformis*	*Commelina benghalensis* L.
5	*Fimbristylis miliacea* (L.) Vahl.	*Eclipta alba*	*Cynodon dactylon* (L.) Pers.
6	*Eclipta alba* L.	*Ludwigia Parviflora*	*Echinochloa crus-galli*
7	*Cyperus rotundus* L.	*Ammannia baccifera*	*Eclipta alba*
8	*Ammannia baccifera* L.	*Fimbristylis miliacea*	*Digitaria sanguinalis* (L.) Scop.
9	*Ludwigia parviflora* Roxb.	*Cyperus rotundus*	*Cyperus difformis* L
10	*Monochoria vaginalis* (Burm. f.) C. Presl	*Marselia quadrifolia*	*Eluesine indica* (L.) Gaertn.

In Bangladesh, aquatic weeds were dominant in rice fields earlier when rice was cultivated under intensive wet tillage (puddling) conditions mainly in lowland and medium lowland areas where water from ponds were continuously available. However, since the last decade, many upland weeds that do not infest rice became prominent in rice fields when tillage systems were changed to enable growing the crop in all types of topographical lands. The dominant weeds found in rice in the past and at the present time are presented in Tables 4,5 and 6. These suggest a major shift in weed spectrum and population.

The change in the method of rice cultivation has also caused changes in weed flora in Pakistan. There was a significant increase in the occurrence and persistence of weeds such as *Cynodon dactylon*, *Commelina diffusa*, *Cyperus rotundus*, *C. iria*, and *Trianthema portulacastrum* in DSR systems. In most of the cases, *T. portulacastrum* caused complete failure of rice crop (Farooq et al., 2009).

The change in rice establishment method from transplanting to direct-seeding rice, for saving cost and resources in South Asia, has resulted in increased weed competition and weed dynamics change (Matloob et al., 2015). In Sri Lanka, the spectrum of weed flora in wet-seeded rice has shifted from annuals to perennials (Abeysekera et al., 2006). The annual grass *E. colona* is a troublesome weed in

Table 4. Seasonal Variation of Weed Flora of Rice in Bangladesh

Weed species	**Season**		
	Spring (*boro*) rice	**Autumn (*aman*) rice**	**Summer (*aus*) rice**
Commelina benghalensis L.	++	++	
Cynodon dactylon (L.) Pers.			+++
Cyanotis axillaris R. & S.	+	+	
Cyperus diffusa Burn. f.		+	
Cyperus difformis L.			++
Cyperus iria L.		+++	++
Cyperus rotundus L.			+++
Digitaria sanguinalis (L.) Scop.			+
Echinochloa crus-galli (L.) P. Beauv	+++		+++
Echinochloa colona (L.) Link		+++	+++
Eclipta prostrata (L.) L.			+
Eleusine indica (L.) Gaertn.			+++
Fimbristylis littoralis Gaud.			++
Fimbristylis miliacea (L.) Vahl.		+++	
Jussieua decurrens (Watt.) D.C. .	++	+	
Leersia hexandra Sw.	++	++	
Murdania nudiflora (L.) Brenan			+
Marsilea quadrifolia L.	+		
Leptochloa chinensis (L.) Nees.	++	++	
Ludwigia prostrata Roxb		++	
Monochoria hastata (L.) Solms.		++	
Murdania nudiflora (L.) Brenan		++	
Nymphaea spp.	++		
Oryza rufipogon L.	+++		
Paspalum commersoni Lamk.			++
Pistia stratioites L.	+++		
Sagittaria spp.	++		
Sagittaria guanensis H.B.K.		++	
Salvinia natans Hoffm.	++		
Scirpus mucronatus L.		+++	

* + = occurs as a component of weed flora but not a serious problem by itself. ++ = occurs as a weed of considerable importance
+++ = occurs as a serious weed at one or more locations

Table 5. Weeds of National Significance for Rice as Identified by the Sri Lankan Council for Agricultural Research Policy of Sri Lanka

2008	2011	2017
Echinochloa crus-galli	*Echinochloa crus-galli*	*Echinochloa crus-galli*
Leptochloa chinensis	*Leptochloa chinensis*	*Leptochloa chinensis*
Cyperus rotundus	*Ischaemum rugosum*	*Echnochloa colona*
	Isachne globosa	*Ischaemum rugosum*
	Ludwigia spp.	*Paspalum distichum*
	Oryza sativa f. *spontanea*	*Isachne globosa*
		Fimbristylis miliacea
		Fimbristylis dochotoma
		Cyperus iria
		Cyperus difformis
		Cyperus rotundus
		Oryza sativa f. *spontanea*

aerobic rice (Gunawardena et al., 2013) where weed control increased the grain yield by 3.92 to 7.84 fold as compared to an unweeded situation. Increased and incorrect use of herbicides was suspected to cause shifts in weed spectra in favour of perennials such as *Isachne globosa*, *Paspalum* spp. etc. (Abeysekera et al., 2015). Switching to quinclorac for grass weed control in the late 1990s has resulted in dominance of *Ischaemum rugosum* (Amarasinghe et al., 1999) while *Leptochloa chinensis* became a dominant weed consequent to using bispyribac sodium (Marambe, 2002) in lowland rice.

In the Cauvery Delta region of Tamil Nadu, India, *L. chinensis* and *Marsilea quadrifolia* became predominant in rice fields by replacing *Echinochloa* spp. due to growing rice under alternating flooding regimes and residual soil moisture conditions (Yaduraju and Kathiresan, 2003). In the eastern Indo-Gangetic Plains, adoption of zero tillage has resulted in an increase in the population of the perennial weeds such as *Cyperus rotundus* and *Cynodon dactylon* due to the option of zero tillage in the eastern (Kumar et al., 2013; Malik and Kumar, 2014).

Weedy rice (*O. sativa*) has become a serious problem in India, and its spread is largely through the use of contaminated rice seeds (Chauhan and Mahajan, 2012; Rao and Chauhan, 2015). Growing rice with the genotypically similar weedy rice (*O. sativa* f. *spontanea*) (Abeysekera et al., 2010; Marambe, 2009; Marambe and Amarasinghe, 2000; Subasinghe et al., 2007) has created a serious problem in rice growing areas, threatening the food security of different countries in South Asia. The weed flora needs to be monitored continuously to assess the emerging weed problems and plan weed management strategies accordingly.

Table 6. Major Weed Species in Rice in Past, Present and Weed Shifs in Bangladesh (Ahmed and Chauhan 2014, 2015; Ahmed et al. 2015; Mamun et al. 1990, 1993, 2013; Mazid et al. 2001, 2005; Rashid et al. 2012)

Past	Present	Shift in weed population (The weeds which were not associated with rice earlier and which currently are weeds in rice)
Echinochloa crus-galli (L.) P. Beauv.	*Echinochloa colona*	*Cyperus rotundus*
Cyperus difformis L.	*Cyperus rotundus* L.	*Digitaria ciliaris*
Scirpus juncoides Roxb.	*Panicum repens* L.	*Dactyloctenium aegyptium*
Leersia hexandra Sw.	*Leersia hexandra* L.	*Eleusine indica*
Panicum repens L.	*Cyperus difformis* L.	*Anagalis arvensis*
Ludwigia hissopifolia (G.Don) Exell	*Ludwigia hissopifolia* (G.Don) Exell	*Cleome rutidosperma*
Cyperus iria L.	*Leptochloa chinensis* L.	*Galinsoga ciliate*
Leptochloa chinensis (L.) Nees	*Cynodon dactylon* (L.) Pers.	*Phyllanthus niruri*
Alternanthera sessilis (L.) R.Br. ex DC.	*Alternanthera sessilis*	*Celosia argentea*
Eclipta prostrata L.	*Fimbristylis miliacea*	*Murdannia nudiflora*
Marsilea minuta L.	*Digitaria ciliaris* (Retz.) Koel.	*Aeschynomene indica*
Echinochloa colona (L.) Link	*Scirpus juncoides* Roxb.	*Ageratum conyzoides*
Fimbristylis miliacea (L.) Vahl	*Cyperus iria*	*Physalis heterophylla*
Sagittaria guyanensis H. B. K.	*Eclipta prostrata*	
Sphenoclea zeylanica Gaertn.	*Dactylocteniu maegyptium* (L.) Willd.	
Enhydra fluctuans Lour.	*Eleusine indica* (L.) Gaertn.	
Monochoria vaginalis (Burm. f.) C. Presl.	*Anagalis arvensis* L.	
Commelina benghalensis L.	*Commelina benghalensis*	
Oxalis europea L.	*Monochoria vaginalis*	
Cynodon dactylon (L.) Pers.	*Sphenoclea zeylanica*	
	Cleome rutidosperma DC.	
	Galinsoga ciliate Blake,	
	Phyllanthus niruri L.	
	Celosia argentea L.	
	Murdannia nudiflora (L.) Brenan	
	Marsilea minuta	
	Oxalis europea	
	Aeschynomene indica L.	
	Ageratum conyzoides L.	
	Sagittaria guyanensis	
	Physalis heterophylla L.	

3. Methods of Weed Control

The diversity and plasticity of weed communities associated with rice in South Asia necessitates diverse approaches of weed management.

3.1. Manual

The traditional methods of weed control practices of smallholders is hand weeding by hand held hoe and hand pulling in Bangladesh (Alam et al., 2002; Hasanuzzaman et al., 2009), Bhutan (Karma and Ghimiray, 2006), Nepal (Dangol and Gurung, 1988; Dangol, 2015), India (Yaduraju et al., 2015) and Pakistan (Ali et al., 2017; Khaliq et al., 2013; Matloob et al., 2015). Depending upon the nature of weeds, their intensity of infestation and the nature of the crop grown, two or three hand weedings are done usually for growing a rice crop. Generally, one weeding requires 25-35 man days ha^{-1}, depending on the type of land and method of raising a crop. Without herbicide application, manual weeding in DSR systems needed to be performed three to five times to maintain the crop completely weed free (Chauhan and Opeña, 2013). More labour is needed for weeding upland direct-seeded rice field than lowland transplanted rice field (Dangol, 2015). The nonavailability of labour during the peak period time of the labor crisis and resulting delay in weeding causes drastic rice grain yield losses (Ahmed and Chauhan, 2014). In addition, hand weeding becomes more tedious and difficult in DSR as seedlings of grassy weeds (e.g. *E. crus-galli*) look similar to rice seedlings (Rao and Moody, 1988). Due to industrialization in South Asian countries, migrating from rural to urban areas is occurring resulting in workers shortages for hand weeding and increased labor cost even if labour is available. Thus, farm labour wage rates have steadily increased (Rao and Ladha, 2014). Thus, rice farmers of South Asia are preferring methods other than hand weeding or using hand weeding, to limited extent, along with other methods of weed control to reduce the cost of cultivation (Rao and Ladha, 2011).

3.2. Mechanical

Mechanization of agriculture is essential in order to enhance rice productivity, make agriculture attractive and sustainable to future generations. Besides, mechanization will allow farm operations like weeding timely faster and less drudgery (Kabir et al., 2015). Availability of labour for agriculture is on a decreasing trend due to shifting from low productivity to its shifting to high productivity sectors in different countries (BBS, 2016; Rao and Ladha, 2014). Weeders were reported to reduce 74% of the need for labour and 72% of the cost (Islam et al., 2016). In transplanted rice, Japanese rotary weeder, viz. BARI weeder or BRRI weeder, is being used for inter row weeding in Bangladesh (Karim, 2015). In Afghanistan, rotary weeding (using star weeder) 2 to 4 times, immediately after irrigation, was found to manage weeds more effectively (Norwegian Embassy, 2013). Manual weeders are used widely, with about 200,000 of them being used in Bangladesh (Islam, 2009). In different South Asian countries, the Departments of Agriculture have been promoting mechanization in rice farming, with a special emphasis on the use of weeders for effective weed control. In Karnataka, India, rice power weeders were demonstrated under the Bhoosamrudhi program. Finding the advantage of power weeders, farmers have adopted them in machinetransplanted and row-transplanted rice cultures. In other states of India, power weeders are being distributed on subsidy basis as a part of National Food Security Mission - Rice (GOI, 2014).

3.3. Tillage

The traditional transplanting method of rice culture in South Asia involves continuous submergence and puddling the soil by repeated tillage practices. Weed control is the main reason for flooding and transplanting of rice. The land preparation's tillage operation comprises of two to three dry tillages and two to three wet tillage (puddling) operations. It results in a soft mud that forms a saturated root zone, for the transplanted rice seedlings establishment, above a compacted subsoil layer that reduces seepage of standing water. The puddling and transplanting operations require a huge amount of water and labor, which are becoming scarce along with rising input costs. Hence, the farmers are showing interest on non-puddled (zero or minimum till) direct-seeded rice in South Asia (Gathala et al., 2013; Rao et al., 2007). However, weeds are the main constraint to the production of dry-seeded rice due to the absence of standing water at crop emergence to suppress weeds and the absence of a seedling size advantage between rice and weed seedlings since both emerge simultaneously in these production systems (Chauhan and Opeña, 2012).

In zero tilled rice, uncontrolled weeds caused grain yield loss of up to 98% (Chauhan and Abugho, 2013). The weed spectrum changes in the absence of puddling and flooding. Some of the weed species that appear in dry-seeded systems do not adapt well in conventional tillage system. Kumar and Ladha (2011) observed that grasses and broadleaf weed species under conventional tillage were 6 and 4 respectively, while in dry-seeded rice there were 15 grass species and 19 broad leaf species. Successful cultivation of direct-seeded rice requires intensive use of herbicides (Chauhan, 2012). PRE and POST emergence herbicides are a necessity to keep weeds under check in direct-seeded rice. A variety of herbicides have been found effective for preplant (burndown), preemergence and postemergence weed control in dry direct drill-seeded rice systems, including under zero tillage conditions (Chauhan et al., 2012; Gathala et al., 2013). The use of herbicides gives selective and effective control of weeds and allows the crop to emerge in a relatively weed free environment (Chauhan and Abugho, 2013; Mishra and Singh, 2012). Rice yields without tillage are higher than in conventional puddled transplanted systems because of proper weed management through use of suitable herbicides (Jat et al., 2014).

3.4. Mulching

Mulching is one of the methods to manage weed problems in rice. Crop residues may be used as mulch in tilled (Bijay-Singh et al., 2008) and untilled rice (Chauhan et al., 2012) for suppressing weeds growth. In addition to weed management, mulching also helps to maintain optimum surface soil moisture for germination and rooting of the crop and protects seeds from birds (Gaire et al., 2013). Organic mulch such as straw, hay, dry sugarcane leaves, FYM, rice hulls, saw dust and bark dust provides stronger mechanical barriers to all kinds of germinating weeds (Gurung, 2006). Singh et al. (2007) found that the density of grass weeds was low in mulched rice field at all stages of crop growth. Application of wheat residue mulch (4 t ha^{-1}) and intercropping of *Sesbania* for 30 days were equally effective in controlling weeds associated with dry-seeded rice (Singh et al., 2007a).

The weed, *Eupatorium* was found to be a source of good organic matter and weed suppressor for several upland crops including DSR in Himachal Pradesh, India (Acharya et al., 1998). Mulching with *Eupatorium* or wheat straw (5t ha^{-1}) one day after DSR resulted in effective weed management (Gaire et al., 2013). However, mulching alone may not be sufficient to manage weeds in DSR because weed suppression by mulching depends on rainfall, thus necessitating the use of herbicides or hand weeding to manage weeds effectively in rice (Adhikari et al., 2007). The combinationof herbicide (butachlor or pretilachlor 1 kg a.i. ha^{-1}) followed by brown sarson straw mulching at 3-5 days after transplanting was found effective in managing weeds in transplanted rice (Singh et al., 2009). Mulching by rice straw has been proposed as a successful weed control strategy in rice (Devasinghe et al., 2011).

3.5. Crop Diversification and Rotation

Crop diversification of the rice systems ameliorates family incomes, minimizes peak labour demands and facilitates easier weed and nitrogen management for better yields (Gupta et al., 2003). A legume crop (e.g. sesbania, sunhemp, mungbean, guara and cowpeas) that suppresses weeds and exhibits good nodulation activity is preferable in crop rotations because it provides a supply of balanced nutrients and enhances soil organic matter (Ali et al., 2012).

Mollah et al. (2015) observed lower rice yield in Wheat-Fallow-Rice cropping programme because of high weed infestation when field was left fallow after wheat. In Wheat-Mungbean-Rice cropping system, there was very low weed infestation in DSR as against in Wheat-Fallow-Rice cropping pattern, suggesting that inclusion of mungbean in rice-wheat cropping system is an effective measure in controlling weeds in DSR (Mollah et al., 2015).

3.6. Competitive Rice Cultivars

Competitive crop cultivar use is a low monitory input needed cultural weed management method, which has been in use for decades in South Asia. Improved crop competitiveness can be achieved by growing weed-competitive cultivars (e.g. early growth vigor, fast ground coverage and light interception, allelopathic nature) (Mahajan et al., 2014); seeding time (Mubeen et al., 2014); closer spacing (Chauhan and Johnson, 2011; Nayak et al., 2014); planting pattern (Mahajan and Chauhan, 2011) and geometry (Joshi et al., 2015); use of optimal crop density (Kaur and Singh, 2014), seed rate (Walia et al., 2009); and direction of planting (Mahajan et al., 2011). Competitive cultivars enable efficient use of resources such as space, light, moisture, nutrients etc. by the crop rather than weeds.

3.7. Allelopathy

Allelopathy was recognized as one of the means of natural weed management (Cheema et al., 2010; Rice, 1995). However, it was not yet demonstrating beyond doubt that isolated chemicals are responsible for observed allelopathy under field conditions (Bhowmick and Inderjit, 2003; Rao et al., 2007).

Marambe (1998) reported that the knowledge on rice plant allelopathy would offer an attractive alternative for weed control in rice-based cropping systems of Sri Lanka. Furthermore, Abeysekera et al. (2004, 2005, 2009) reported that the allolepathic potential of weeds offers an alternative option for weed control in rice. Wathugala and Ranagalage (2014) recorded the alleopathic activity by traditional Sri Lanka varieties like Herathbanda, Batapolael and Sula, and opined that allelopathic rice varieties might reduce the application of herbicides by the farmers as those varieties may serve as a natural source of herbicides.

In Bangladesh, varieties of Boterswar, Goria, Biron and Kartiksail were observed as the most allelopathic among the tested 50 indigenous Bangladeshi rice varieties, which may be used for the isolation and identification of allelochemicals and to further develop new varieties that are tolerant to weeds (Masum et al., 2016). Allelopathic potential of 102 Bangladeshi rice varieties was evaluated against cress (*Lepiun sativum* L.), lettuce (*Lactuca sativa* L.), barnyardgrass (*Echinichloa crus-galli*) and Jungle rice (*Echinochloa colona*). Fifty nine percent growth inhibition of the test weed species was recorded with allelopathy of rice cultivar BR17 possessing allelochemical 9-hydroxy-4-megastigmen-3-one. It inhibited root and shoot growth of these weed species at concentrations greater than 0.03 µM and 3 µM, respectively (Kato-Noguchi et al., 2009, 2010; Salam and Kato-Noguchi, 2010).

3.8. Intercropping

Intercropping, involves cultivation of two or more crops in the same space and time, is a traditional and commonly used cropping practice of South Asia. Intercropped *Crotalaria juncea*, *Vigna sinensis*, *Glycine max* or *S. rostrata*, could replace herbicide application (Angadi et al., 1993). Intercropping of lowland rice with green manures in combination with intercultivation was found to suppress the weeds effectively and increase rice yield while increasing the fertility status of the soil due to legume (Vennila et al., 2008).

In dry-seeded rice, the possibility of use a green manure such as *Sesbania rostrata* as an intercrop to manage weeds was tested (Singh et al., 2007a) as the *Sesbania* option provides an alternative to crop residue. Brown manuring (BM) is a no-till version of green manuring (Gaire et al., 2013), in which selective herbicide 2,4-D @ 400-500 g ha^{-1} is applied to knock down and desiccate the BM materials like *Sesbania* 30-40 days after seeding along with rice. When wheat straw is not readily available, farmers can opt for growing *Sesbania* with dry-seeded rice up to 30 DAS (Singh et al., 2007a). The effective control of weeds in DSR by brown manuring of *Sesbania* (Bhattarai et al., 2016) or *Crotolaria* (Gaire et al., 2013) was reported in India (Singh et al., 2007a) and Nepal (Bhattarai et al., 2016). Brown manuring was considered as a potential alternative to herbicide application to increase rice productivity with reduced cost of production (Gaire et al., 2013).

3.9. Preventive Measures

The prevention method as a pillar of integrated pest management (IPM) (Norris et al., 2003) and is the most cost-effective approach that a farmer can use. But, it is complex and involves the integration of a number of practices and policies that avoids introduction, infestation, or dissemination of weed species to fields free of those. Prevention measures should be adopted at all stages of crop production, from the use of machinery, seed, water and fertilizers, to crop harvest and processing. Preventive measures such as avoiding seed or propagule movement from field to field and use of clean crop seeds and machinery are much cheaper and easier options in reducing weedy rice infestation rice ecosystems. The integration of prevention as a component of integrated weed management is essential for economic and effective weed management (Rao et al., 2017) in rice of South Asia.

3.10. Herbicides

A number of herbicides were found to be effective for pre-emergence and post-emergence control in transplanted and direct-seeded rice methods of establishments in South Asia (Table 7). The optimal productivity of rice established by direct-seeding is possible only with proper weed management and hence all rice farmers who practice direct-seeding adopt herbicides (Ho, 1996; Mazid et al., 2006; Rao et al., 2007).

The herbicide use has increased, during 2005 to 2015, by 2.5 times from 60 thousand to 150 thousand tons of formulated herbicides (Das Gupta et al., 2017) and the Indian herbicides market was projected to grow about 40% annually over the next 5 years (Glanessi, 2013). Rice consumes a major share of herbicides used in India. In India, thiobencarb, butachlor, 2,4-D and anilophos have been used in the past in rice (Mukhopadhyay, 1993). Currently, bis-pyribac sodium, butachlor, fenoxaprop, chlorimuron + metsulfuron, ethoxy-sulfuron, oxadiargyl, pyrazosulfuron, pretilachlor and 2,4-D are more favoured by rice farmers (Bhullar et al., 2016; Rao and Chauhan, 2015).

Manual weeding and submergence are the main weed control techniques adopted in Sri Lanka until early 1960s where transplanting of rice was the main method of crop establishment. However, due to increase cost and scarcity of labour resulting in a shift of the crop establishment techniques to broadcasting over the years, herbicides have started performing major role in weed control in rice. Of the total amount of herbicides imported to Sri Lanka prior to 2016, more than 50% have been used in rice cultivation. In 2015, 39 different molecules of pre-emergence and post-emergence herbicides with 11 modes of actions are being traded in Sri Lanka under more than 200 brand names. More than 85% of the land extent cultivated to paddy has been using herbicides until ban or restriction was imposed on three most widely used herbicides. The government of Sri Lanka banned the importation and use of paraquat in 2014 (gazette No. 1854/47 of 21 March 2014) and glyphosate in 2015 (gazette No. 1918/22 of 11 June 2015 and gazette No. 1937/35 of 23 October 2015) and prohibited the use of propanil in five major paddy growing districts in the country in 2014 (gazette No. 1894/4 of 22 December 2014). The latest information on the use of herbicides in paddy is thus not available. The change of herbicides have taken place due to shifts in weed flora became another major concern following heavy reliance on herbicides. At present, the government of Sri Lanka and the scientists and academia, including the pesticide industry are paying more attention towards “green pesticides”, “botanicals” and environmentally sound alternative measures to control weeds in rice fields.

Table 7. Major Herbicides found to be Effective in Managing Weeds and used in Rice Established by Different Methods in South Asia

Herbicide	**Rice establishment method and** (Rate in kg a.i/ha*)	**Method of application**	**Weeds controlled**
2,4-D	Transplanted and direct (wet- and dry-) seeded rice (0.850)	POE	Effective control of Broad-leaved weeds (BLW) and annual sedges(ASW)
Anilophos	Transplanted Rice – (300 - 450)	PRE	GW and some BLW
Azimsulfuron	Transplanted and direct (wet- and dry-) seeded rice (0.035)	POE	Broad-spectrum control of grasses (GW), BLW andparticularly, sedges (SW), including *Cyperus rotundus*
Bensulfuron methyl	Transplanted Riceand direct (wet- and dry-) seeded rice – (0.060)	PRE	BLW and SW
Benthiocarb/ Thiobencarb	Transplanted Rice (1.5)	PRE; EPOE	GW and some BLW
Bispyribac sodium	Rice Nursary (0.02); Transplanted Rice (0.02); direct (wet- and dry-) seeded rice (0.02)	POE	Broad-spectrum control of GW, BLW, AS
Butachlor	Transplanted Rice (1 to 2)	PRE; EPOE;	GW, BLW, AS
Chlorimuron Ethyl	Transplanted Rice (0.006)	POE	BLW and SW
Cinmethylin	Transplanted Rice(0.075 to 0.100)	PRE	
Cyhalofop Butyl	Transplanted Rice and direct (wet- and dry-) seeded rice (0.075 to 0.080)	PRE	Excellent control of annual GW but does not control BLW and SW
Ethoxysulfuron	Transplanted Rice and	POE	Effective on

Table 7. Continued.

Herbicide	**Rice establishment method and** (Rate in kg a.i/ha*)	**Method of application**	**Weeds controlled**
	direct (wet- and dry-) seeded rice (0.0125 to 0.015)		BLW and ASW
Fenoxaprop-p-ethyl	Transplanted Rice direct (wet- and dry-) seeded rice (0.056)	POE	Excellent control of AGW, BLW (SW not controlled)
Fluchloralin	Transplanted Rice (0.560 to 0.900);	PRE; PPI	
Glyphosate	Non cropped areas (0.82 to 1.23)	PWES; PCES	GW,BLW, ASW
Orthosulfamuron	Transplanted Rice (0.06 to 0.075)	POE	BLW, ASW
Oxadiazon	Transplanted rice (0.5)	PRE; POE	GW,BLW, ASW
Oxadiargyl	Transplanted Rice and direct (wet- and dry-) seeded rice (0.09)	PRE	GW,BLW, ASW
Oxyfluorfen	Transplanted Rice (0.150 to0.240)	PRE;	GW and some BLW
Paraquat dichloride	Non cropped areas (0.3 to 0.80	POE	Non-selective burn down herbicide
Pendimethalin	Transplanted Rice and dry-direct seeded rice (1-1.5)	PRE	Most of the GW, certain BLWand ASW
Pretilachlor	Transplanted rice (0.5 to 0.75)	PRE; EPOE	GW, BLW, AS
Propanil	Transplanted Rice direct (wet- and dry-) seeded rice (2-3)	POE	GW
Pyrazosulfuron Ethyl	Transplanted Rice direct (wet- and dry-) seeded rice (0.010 to 0.015)	PRE POE	Broad-spectrum control of GW,BLW and SW including *C. rotundus* (Poor on GW such as

Table 7. Continued.

Herbicide	Rice establishment method and (Rate in kg a.i/ha*)	Method of application	Weeds controlled
			L. Chinensis and *Dactyloctenium aegyptium*)
Herbicide combinations			
Anilofos 24% + 2,4-D ethyl Ester 32% EC	Transplanted rice(0.24+ 0.32) to (0.36 + 0.48)	PRE	GW,BLW, SW
Bensulfuron methyl 0.6% + Pretilachlor 6% GR	Transplanted Rice (0.060+0.600)	PRE	GW,BLW, SW
Clomazone 20% + 2,4-D EE 30% EC	Transplanted Rice (0.250-0.375)	POE	GW,BLW, SW
Metsulfuron Methyl 10% + Chlorimuron ethyl 10% WP	Transplanted Rice direct (wet- and dry-) seeded rice (0.004)	POE	Effective on Broad-leaved and annual sedges weeds
Pretilachlor6% + pyrazosul-furon Ethyl 0.15%(H)	Transplanted Rice (0.600+0.015)	PRE	GW,BLW, SW
Fenoxaprop + ethoxysulfuron	Transplanted Rice direct (wet- and dry-) seeded rice (0.060+0.018)	POE	GW,BLW, SW

Basic data source: Directorate of Plant Protection, Quarantine & Storage, Fariabad.
PRE = Pre emergence spraying
EPOE = early post-emergence spraying
POE = post-emergence spraying
PPI = pre- plant incorporation
PWES = Post-weed emergence spraying
PCES = pre-crop emergence spraying

Manual weeding is common in Bangladesh. Due to the high price of labor, manual weeding is becoming expensive and, in the near future, it will be difficult to find labor for manual weeding (Ahmed and Chauhan, 2014). In Bangladesh, pre-emergence herbicides in rice are 38–46% cheaper than one hand weeding (Mazid et al., 2000). Economic analysis of rice production in Bangladesh revealed that net income from herbicide application was 116% higher than hand weeding owing to increased yield and lower cost (Rashid et al., 2012). About 30% of farmers were estimated to be losing in excess of 500 kg ha^{-1} in the absence of herbicides use (Ahmed et al., 2001). Thus, in the 1980s, herbicides have been introduced in rice. Currently, about 2 million ha are under herbicide-based weed control in Bangladesh (Ahmed et al., 2011). Pretilachlor, butachlor and MCPA-500 were the most used pre-emergence herbicide in last few decades in Bangladesh but recently farmers are using mostly Bensulfuron methyl + acetachlor, bensulfuron methyl + mefenacet, pyrazosulfuron ethyl + pretilachlor etc. Post-emergence herbicides are not very common for transplanted rice in Bangladesh; however, in direct seeding, few farmers are using penoxsulam and bis-pyribac sodium. It is projected that in near future both herbicides will gain popularity because of post-emergence herbicides use in rice are increasing in Bangladesh.

Farmers generally use butachlor, in Bhutan, following a rate of 1-2 kg a.i. ha^{-1} recommended by national research program, as it is the most economical and effective dose (Centre for Agriculture Research and Development, 1988). But the use of herbicide, butachlor, as a control measure is limited to as low as 11.8% farmers (Karma and Ghimiray, 2006). Non-availability of the herbicides on time is the main reasons cited by farmers for its limited use.

3.11. Integrated Weed Management (IWM)

Single weed control approach may not be able to keep weeds below an economic threshold level (Rao et al., 2007; Shultana et al., 2016). The escalating problems of herbicide persistence and resistance in weeds associated with the herbicide use have lead to the emphasis on integrating herbicides with the physical, cultural, and biological weed management practices for reducing the reliance on herbicides alone (Buhler, 2002; Rao et al., 2007).

The application of pre- (PRE) and post-emergence (POST) herbicides like Pyrazosulfuron (pre) @ 20 g a.i ha^{-1} fb bispyribac (post) @ 25 g a.i. ha^{-1} fb 2, 4-D (Bhurer et al., 2013; Bhattarai et al., 2016) was not enough to achieve adequate weed control in DSR (Chauhan et al., 2015). Therefore, an integrated weeds management approach is needed. Pyrazosulfuran ethyl applied at 2-3 leaf stage of weed integrated with hand weeding (HW) at 45 days after seeding (DAS) or BRRI developed rice weeder application at 20 and 45 DAS with 120:26:33 kg NPK ha^{-1}, resulted in higher wet-seeded rice yield (Shultana et al., 2016). Application of pyrozosulfuran-ethyl at 6-7 days after transplanting (DAT) with one supplement hand weeding (30 DAT) (Bhuiyan et al., 2015) was found effective in managing weeds and increasing yield of transplanted rice.

Balanced nutrient management integrated with weeds management was reported to reduce losses due to weeds, increased fertilizer use efficiency and the grain yield (Rana et al., 2000). Ahmed et al. (2015) observed that pendimethalin fb ethoxysulfuron fb one HW with 120 kg N ha^{-1} is the best option to control weeds and obtain higher yield and net profit. However, if farmer prefers to avoid hand weeding after the application of herbicides (pendimethalin fb ethoxysulfuron) due to non- availability of labor, there is a need to increase the N rate (160 kg ha^{-1}) to obtain high yield. Direct-seeded rice culture using herbicide pyrazosulfuron ethyl, applied at 2-3 leaf stage of weed with one hand weeding and 120:26:33 kg NPK ha^{-1} was found as an option for reducing production cost and attain higher grain yield (Shultana et al., 2016).

The rice variety BRRI dhan 30 planted at spacing of 25 cm x 15 cm with nitrogen dose of 80 kg N ha^{-1} was more competitive against weeds and resulted in higher yield (Karim et al., 2014).The BRRI dhan 34 in combination with ethoxy-sulfuron (PRE) recorded highest grain yield due to better weed management (Chowdhury et al., 2015). About 66 to 75% reduction in of predominant barnyardgrass density and biomass was observed with tank mixing of the extracts of sorghum, sunflower or rice (15 L ha^{-1}) with one half of the recommended rates of three pre-emergence herbicides butachlor, pretilachlor or ethoxysulfuron ethyl (Rehman et al., 2010).

Integration of different weed management methods such as appropriate tillage, stale seedbed, residue mulching, brown manuring by sesbania coculture, competitive crop cultivars, appropriate crop management practices, including high quality weed seed free crop seed, optimal seed rate, crop geometry, crop establishment methods, water and nutrient management, and strategies to reduce weed seedbank by minimizing seed input and increasing mortality of seed, can reduce weed infestations and hence herbicide use in rice production systems of South Asia.

4. Herbicide Resistance in Weeds in South Asia and Their Management

Herbicide resistance among weeds was not reported in India, Bangladesh, Nepal and Pakistan, yet. In Sri Lanka, the first record of herbicide resistant weeds was made in 1997 (Marambe et al., 1997) when several biotypes of barnyardgrass (*E. crus-galli*), the major trouble some grass weed in lowland rice cultivation, developed resistance to propanil. This was later confirmed by Marambe and Amarasinghe (2002) who also found that the resistant biotype was four times more resistant to propanil than the susceptible biotype of *E. crus-galli.* This propanil resistant barnyard grass biotype was recommended to be controlled by herbicides such as quinclorac and bispyribac sodium having different modes of actions to that of propanil, and the premixed formulation of oxadiazone + propanil (Marambe and Samita, 2002). The rice farmers of Sri Lanka are complaining about the non-control of *I. rugosum* by bis-pyribac sodium and *C. iria* by MCPA. Studies are ongoing to see whether there is a resistance build up in these weeds against the widely used herbicides. Best management practices suggested for reducing the risk of herbicide resistant weeds (Norsworthy et al., 2012) are applicable to South Asian countries too.

5. Herbicide Tolerant (HT) Rice the Current Status and Potential

The use of HT rice can help improve control of weeds, including weedy rice, and reduce weed control costs and the labor associated with manual removal of weeds. In South Asia, herbicide tolerant rice is yet to be made available to rice farming community. In Sri Lanka, The National Biosafety Policy of Sri Lanka (2005) is in place and regulations in this regard are currently being prepared. It is highly unlikely that Sri Lanka will grant permission to cultivate herbicide tolerant rice (paddy). As for National regulations rice (de-husked paddy) can be imported to Sri Lanka but importing paddy is prohibited by law. The countries of South Asia may consider the introduction of HT rice after a thorough scientific investigation of available technologies and adequately educating farmers on the proper use of HT varieties to avoid any ill effects, if any.

6. Future Research Needs of the South Asia in Managing Weeds in Rice

The South Asian farmers are combating with weeds to ensure higher crop productivity, production and profitability. Effective weed control strategies have received attention of all farmers. However, newly emerging weeds, herbicide resistant biotypes of weeds, and environmental and human health issues related to herbicide use have become major challenges faced by policy makers, scientists and farming communities in the recent past.

- **Scientific quantification of yield loss due to weeds in rice:** Rice grain yield losses due to weeds in rice, established by different methods in farmers' fields, is yet to be quantified systematically in South Asia. Hence, to plan weed management strategies, it is essential to carry out a systematic study on yield losses caused by weeds and the weeds that are causing losses in different agroecological zones in different countries of South Asia.
- **Developing competitive rice cultivars with higher competitive ability against weeds:** Improved rice cultivars with higher competitive ability against weeds should be developed to include them as a component of IWM in rice established by different methods.
- **Mechanization of weed management:** Mechanical weeders are to be improvised to suit to the needs of the farmers growing rice with different establishment methods. Indigenously developed robotic weed control tools, capable autonomous vehicles capable of inter-row weeding are to be evolved. The indigenous methods are to be looked into to use sensors for tractor drawn weed management tools or cultivators such as the rotary hoe should be studied to enhance their functional efficacy.

- **Biological control of weeds:** The biocontrol agents need to be identified for major weeds of rice including weedy rice for using it as a component of IWM.
- **Preventive weed management methods identification and use as a component of IWM:** Identifying preventive weed management methods like use of weed seed-free rice seed, stale seed bed technique, crop rotations and cropping systems that reduce weed seed bank development in rice agroecosystems should be identified and incorporated in weed management strategies as a component of IWM. Economic options should be evolved for managing the soil-seedbank by decreasing weed seed inputs and providing conducive environment for seed predation enhancement and weed seed decay and thus lessen the weed establishment probability. Research on weed ecology, biology, weed seedbank and weed population dynamics are needed for evolution of effective preventive weed management strategies.
- **Need for IWM strategies and methods and technologies to minimize evolution of herbicide resistant weeds:** The cultural, mechanical and chemical weed management options for different types of rice establishment methods under different agro-ecological zones in rice growing countries of South Asia should be developed and fine-tuned to suit to location specific needs of farmers and to minimize herbicide resistant weeds evolution.
- **Improving spraying technology and educating farmers on the safe use of herbicides:** The safe use of herbicide should be popularized among the rice farmers. The recent technologies like use of drones and other remote-sensing devices for surveillance and herbicides applicationbased on presence or absence of weeds should be developed/improved/popularized (Rao et al., 2014) for systemic monitoring and using in site-specific weed management.
- **Weedy Rice:** Weedy rice is a C_3 weed in rice in many South Asian countries. The competition impact of weedy rice on rice in future may be greater due to greater physiological plasticity and genetic diversity among weedy rice relative to cultivated rice under increased atmospheric CO_2 (Ziska and Mc Clung, 2008). Hence, weedy rice management is critical and would thus become a major issue in years to come.
- **Climate Change:** Changing and variable climates over the years have brought in new dimensions to the agro-biodiversity, floristic composition and dynamics in weed competition, thus making agriculture more difficult to manage in a profitable manner (Marambe and Silva, 2016). Though a clear linkage on occurrence of weeds in rice fields and climate change has not been established yet (Sathischandra et al., 2014), further research is required to determine the impact of climate change and climate variability on changes in weed flora and thereby the impact on production and productivity of rice, with special focus on invasive alien species.

Although greater reliance on external inputs, including herbicides, increased the productivity and crop production, it brought many questions to the fore. These include the resistance of weeds to herbicides, residues in economically important crops and food chain, changes in weed flora, negative effects on human and environmental health and sustenance of the agricultural operations. Weed management technologies should aim at overcoming the negative effects of climate change and improving the sustainability of rice production systems. Research need to be focused on these lines and also to identify more environmentally friendly, but still economically viable weed management strategies.

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WEED MANAGEMENT IN RICE
IN THE ASIAN-PACIFIC REGION

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