Integrated weed management in direct seeded rice in Trans Indo-Gangetic plains of India- A review

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Abstract
In the Indo-Gangetic Plains (IGP) of India, rice (Oryza sativa L.) is taken by conventional tilled puddled transplanted (CT-PTR) method. CT-PTR requires a lot of water (2000-2500 mm) which comes mainly from groundwater. Due to declining water table and changing climate, the sustainability of CT-PTR rice is under immense pressure. The alternative to CT-PTR could be direct seeded rice (DSR) which requires less water, labor, initial cost and energy than CT-PTR. But direct seeded rice is heavily infested with weeds which cause severe loss to the grain yield. Thus, the success of aerobic rice depends on effective and timely weed control. As a single weed control method may not be successful on a long term basis, weed problem in direct seeded rice needs to be solved by integrated approach. Integrating cultural, mechanical and chemical methods along with highly competitive cultivars with effective allelopathic properties, effective weed management on long term sustainable basis can be achieved.

Keywords: Aerobic rice, Allelopathy, Competitive Cultivars, Direct seeded rice, Puddled transplanted rice

INTRODUCTION
Rice (Oryza sativa L.) is the most important cereal crop of India and feeds the belly of more than 800 million Indians. It has a share of 41.33% in total food grain produced and 55% of cereals produced in the country, contributing 20-25 % to Agricultural GDP (Anonymous, 2016). In India, rice is grown on nearly 43.49 m ha with total production of 104.4 m t and productivity of 2400 kg/ha (Anonymous, 2016).

In India, the IGP cover about 20% of the total geographical area (329 Mha) and about 27% of the net cultivated area, and produce about 50% of the total food consumed in the country (Dhillon et al., 2010). It is spread across five Indian states, Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal. Trans Indo Gangetic Plain (TIGP) in India is spread across Punjab and Haryana. TIGP constitutes a highly productive RW zone contributing about 69% of the total food output in the country (about 84% wheat and 54% rice) and this region is called the “food bowl of India.” This region has played a vital role in sustaining the food security of India by contributing about 40% of wheat and 30% of rice to the central stock of India every year during the last four decades (Hira and Khera, 2000).

In the Indian perspective, a target production of 130 MT (Million tonne) of rice has to be achieved by 2020-2021, which means 5-6% increase in total production annually, to feed ever increasing population. The possibility of increase in area in the near future is very limited mainly due to fast urbanization, utilization of productive land for non-agricultural purposes and land degradation. Therefore, the extra rice needed must come from gain in productivity. The main hindrance in achieving this target are: (1) inefficient use of inputs (fertilizer, water, labour); (2) less availability of water and labour; (3) climate change; (4) the emerging crisis of energy and rising fuel prices; (5) the rising cost of cultivation; and (6) other problems like rapid urbanization, labbour migration to cities (Ladha et al., 2009).

In India, mainly puddled transplanted rice is taken. In transplanted rice, first rice nursery is raised and thereafter 20-30 days old seedlings are transplanted into puddles soil. Puddling makes an impervious layer which reduces percolation loss, creates anaerobic conditions to increase availability of nutrients and suppresses weeds (Bhurer et al.,...
But repeated puddling destroys soil aggregates, thereby decreasing permeability in sub-surface layers and forming hard-pans (Aggarwal et al., 1995; Sharma and Datta, 1985; Sharma et al., 2003), all of these prove detrimental to succeeding crop usually wheat in IGP (Hobbs and Gupta, 2000).

Moreover, puddling requires additional water (~200 mm) which is becoming scarce day by day and labour which becoming costlier each day. So, with increasing cost of cultivation paddy production is become less profitable to the farmers. In India per capita water availability decreased by 72.3 % between 1951 and 2005 (5831 m²and 1611 m² in 1951 and 2015 respectively) and is likely to decline by 77.8 % by 2050 (1292 m² in 2050). So scarcity of water, less availability of labour acts as driving force for direct seeding (Kumar and Ladha, 2011). All these above factors demand a major shift from conventionally tilled-puddle transplanted rice (CT-TPR) to direct seeding of rice (DSR).

Pandey and Velasco (2002) argued that transplanted is prevalent in areas where wages rates are low and water availability is enough whereas high wage rates and less availability of water favours adoption of direct seeded rice. So, aerobic rice could replace puddled transplanted rice. Direct seeded rice matures 7-11 days earlier than transplanted rice allowing timely sowing of next crop (Giri, 1998; Singh et al., 2006).

Other benefits of DSR include easier planting by direct seeded machine, improvement of soil structure, higher tolerance to water deficit, less emission of methane and often higher profit in areas with an assured water supply (Datta, 1986). Both Dry and Wet-DSR have the potential to reduce the water and labour use compared with CT-TPR.

Tabbal et al., (2002) under on-farm trials in Philippines observed on an average 67-104 mm of saving in irrigation water in Wet-DSR compared with puddled-transplanted rice when irrigation application criteria was same for both establishment methods. Other than saving water, DSR reduced total labour requirement 11%-66% depending on season, location and type of DSR compared with CT-TPR (Kumar et al., 2009; Rashid et al., 2009). Labour requirements for crop establishment decreased by more than 75% with direct seeding compared with transplanting (Dawe, 2005; Pandey and Velasco, 2002).

But direct seeded rice are heavily infested with weeds, so success of DSR depends on effective weed management (Chauhan and Yadav 2013; Singh et al., 2006a; Rao et al., 2007; Singh et al., 2007). Many studies have reported the potential for DSR as a replacement for transplanted rice if weeds are controlled effectively (Singh et al., 2007). Aerobic systems are subjected to much higher weed pressure than CPTR (Rao et al. 2007) in which weeds are suppressed due to prevailing anaerobic environment in flooded conditions and by 25-30 days old transplanted seedlings which have an edge over germinating weed seedlings (Moody, 1983).

So managing weeds effectively is the major challenge in DSR, as failure to manage weeds results in very low or no yield (Singh et al., 2008; Moody and Mukhopadhyay, 1982). In DSR first 30-45 days after sowing is critical period and weeds must be managed effectively in this period otherwise there will be much loss in the yield. Maity and Mukherjee (2008) reported that uncontrolled weeds reduced the yield by 96% in dry-DSR and 61% in wet-DSR.

So the success of DSR depends largely on effective weed management especially the integrated approach. As a single method may not provide adequate control and for long term sustainability, integrated approach is the best option.

**Weed flora of DSR:** Direct seeded rice is infested by complex weed flora including various grasses, broadleaf and sedges. Singh et al. (2017) reported Echinochloa glabrescens, Leptochloa chinensis, Cyperus spp. Ammania baccifera, Eclipta alba as predominant weed species in direct seeded rice at Kaul (Kaithal) Haryana. Saha (2006) reported that DSR was mainly infested by sedges including Cyperus difformis (30.2%), Fimbristylis miliacea (27%) followed by BLW Ludwigia parviflora (17.5%) Sphenochlaea zeylanica (15.8%) and grasses Echinochloa colona (9.5%). However, Mishra and Singh (2008) reported that direct seeded rice was infested mainly by BLW including Phylanthus spp.(26.5%), Commelina communis (17.8), Physlis minima (1.8%), Alternanthera sessilis (5.9%), Caesalia axillaris(1.2%), nongrasses Echinochloa colona (31.8%) and sedges Cyperus iria (9.9%). So the composition and species of weed vary from region to region.

**Losses caused by weeds:** The productivity of crops to a greater extent depends upon efficient resource management. Among many factors responsible for low yield in Indian agriculture, problem of weed is one of the major factors causing losses in crop yield in general and under direct seeded rice in particular. Heavy weed infestation and poor weed management contribute to poor yield in aerobic rice (Bhurer et al., 2013).

Crop-weeds competition depends on a number of factors such as the weed species, type of rice culture, methods of planting and cultural practices. Rice crop suffers more if weeds compete for resources during initial crop growth period and competes for a longer period. This results in poor growth of rice plants which eventually leads to poor yield. Weeds heavily repress the growth of rice during initial 30-40 days.

The slow initial seeding establishment and growth
of young seedlings are more sensitive to weed competition in direct seeded rice and yield loss up to 57.6 % due to uncontrolled weed growth has been reported by Singh (2017).

Aerobic conditions along with alternate wetting and drying favours the germination and growth of weeds in direct seeding which causes yield loss up to 50-91% (Bhurer et al., 2013; Singh and Chinnusamy, 2006).

Bhurer et al. (2013) claimed that weeds are supposed to be the foremost factor that causes heavy yield reduction varying from 40 to 76 % in broadcast seeded, 20 % in drill seeded and 11 to 20 % in transplanting in puddled fields. Malik et al. (2002) reported that uncontrolled weeds in rice can cause grain yield loss up to 89.9% as compared to weed free.

Yield loss of rice due to uncontrolled weeds was 96 % in dry DSR, 61 % in wet DSR and 40 % in the machinery-transplanted crop (Kim and Pyon, 1998). Choubey et al. (2001) also reported that weeds are the major biotic constraints to crop production and in direct seeded rice they reduce the yield by 40 to 100 %. Yield losses without proper weed management can reach to 70-100 % in dry seeding versus only 10-35 % for machine-transplanted rice (Lee et al., 2002). The loss of yield in unweeded direct-seeded rice has been estimated to be 45-66 %, whereas it was 13% in transplanted rice (Thakur, 2006).

Reported yield losses from weeds in DSR ranged from 20 to 88 % (Rao and Moody, 1994). Yield reduction upto 50 to 60 % and sometimes complete failure of the rice crop due to heavy infestation of weeds under direct seeded upland conditions has been reported by various researchers (Singh, 1988; Singh et al., 2002; Raju and Gangwar, 2004; Singh et al., 2005b; Singh et al., 2017).

Methods of weed control: Integrated weed management (IWM) is desirable for effective and sustainable weed control in Dry-DSR (Rao and Naganmani, 2007; Rao et al., 2007). Tools available for IWM can be categorized broadly into (a) cultural, (b) chemical, (c) mechanical, and (d) allelopathic approach for weed control.

Cultural methods of weed control

Land levelling: Proper land preparation helps in reducing weed infestation by providing a weed free seed bed at the time of sowing. To achieve uniform crop stand the field should be levelled before crop sowing.

In Indo-Gangetic plains, a deviation of 8-15 cm in field level is observed due to traditional levelling. This results in poor crop establishment of rice due to unequal distribution of water in soil profile and inundation of newly germinating seedlings (Gopal et al., 2010). Laser land levelling ensures better crop establishment (Jat et al., 2009), precise water control and increased herbicide use efficiency (Chauhan, 2012).

Time of sowing, seed rate and spacing: In northern India, rice is grown during the kharif season before onset of monsoon. To optimize the use of monsoon rain, the optimum time for sowing DSR is about 10-15 days before onset of monsoon (Gopal et al., 2010; Kamboj et al., 2012; Kumar and Ladha 2011; Gopal et al., 2010). A seed rate of 81 kg/ha has produced the best result in the area of study.

Table 1. Different type of mulches, their suppressive ability on particular weeds and increase in yield.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of mulch</th>
<th>Rate (t/ha)</th>
<th>Weeds</th>
<th>Weed suppression (%)</th>
<th>Increase in yield (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wheat mulch</td>
<td>4</td>
<td>Grass and BLW Complex</td>
<td>54</td>
<td>22</td>
<td>(Singh et al., 2007)</td>
</tr>
<tr>
<td>2</td>
<td>Plastic mulch</td>
<td></td>
<td>Complex</td>
<td>69-77</td>
<td>45</td>
<td>(Mohtisham et al., 2013)</td>
</tr>
<tr>
<td>3</td>
<td>Paper mulch</td>
<td>5</td>
<td>Echinochloa spp., Schoenoplectus mucronatus</td>
<td>61-97</td>
<td></td>
<td>(Wentao et al., 2003)</td>
</tr>
<tr>
<td>4</td>
<td>Maize mulch</td>
<td></td>
<td>Complex</td>
<td>48-56</td>
<td>32</td>
<td>(Mohtisham et al., 2013)</td>
</tr>
<tr>
<td>5</td>
<td>Sugarcane trash mulch</td>
<td>5</td>
<td>Complex</td>
<td>26-32</td>
<td>16</td>
<td>(Mohtisham et al., 2013)</td>
</tr>
<tr>
<td>6</td>
<td>Alfalfa</td>
<td>1</td>
<td>E. phyllopon, Monochoria vaginalis</td>
<td>~90</td>
<td>81</td>
<td>(Xuan et al., 2003)</td>
</tr>
</tbody>
</table>

Table 2. Common pre-emergence herbicides used in direct seeded rice in India.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Name of the herbicide</th>
<th>Dose (kg/ha)</th>
<th>Time of application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Pendi...ermalin</td>
<td>0.75-1.0</td>
<td>PRE</td>
<td>(Singh et al., 2016; Singh et al., 2017; Gopal et al., 2010)</td>
</tr>
<tr>
<td>2.</td>
<td>Oxidi...lapy</td>
<td>0.09-0.10</td>
<td>PRE</td>
<td>(Singh et al., 2016; Singh et al., 2017)</td>
</tr>
<tr>
<td>3.</td>
<td>Pyrazosulfuron</td>
<td>0.015-0.020</td>
<td>PRE</td>
<td>(Singh et al., 2016; Kaur and Singh, 2015)</td>
</tr>
<tr>
<td>4.</td>
<td>Butachlor</td>
<td>1.0-1.50</td>
<td>PRE</td>
<td>(Singh et al., 2016; Kaur and Singh, 2015)</td>
</tr>
<tr>
<td>5.</td>
<td>Penoxsulam</td>
<td>0.030</td>
<td>PRE</td>
<td>(Singh et al., 2016; Kaur and Singh, 2015)</td>
</tr>
<tr>
<td>6.</td>
<td>Preti...lachlor</td>
<td>0.40-0.75</td>
<td>PRE</td>
<td>(Singh et al., 2016; Kaur and Singh, 2015)</td>
</tr>
<tr>
<td>7.</td>
<td>Thio...encarb</td>
<td>1.25</td>
<td>PRE</td>
<td>(Singh et al., 2016; Kaur and Singh, 2015)</td>
</tr>
<tr>
<td>8.</td>
<td>Flufenac...et</td>
<td>0.08</td>
<td>PRE</td>
<td>(Singh et al., 2016; Kaur and Singh, 2015)</td>
</tr>
<tr>
<td>9.</td>
<td>Anilofos</td>
<td>0.375</td>
<td>PRE</td>
<td>(Singh et al., 2016; Kaur and Singh, 2015)</td>
</tr>
</tbody>
</table>
of 20–25 kg/ha has been found optimum for basmati rice cultivars with a spacing of 20 cm (Yadav et al., 2007). High seed rates results in excessive vegetative growth thereby utilizing most of the resources before anthesis and less accumulation of dry matter after anthesis (Wellis and Faw, 1978). This results in lower N content in foliage (Dingkuhn et al., 1990) and results in sterility of spikelet and less grains per panicle (Kabir et al., 2008). Moreover, dense plant populations at high seed rates can create favourable conditions for diseases, e.g., sheath blight (Guzman and Nieto 1992; Mithrasena and Adikari 1986) and insects (e.g., brown plant hoppers) and make plants more prone to lodging due to weak stem (Islam et al., 2008).

Lower seed rate can be used for high-tillering varieties and a little higher seed rate for medium-tillering varieties (Soo et al., 1989).

Seeding depth is another important aspect which must be kept in mind. In DSR, seeding should be done with precision planters having depth control wheels. Seed depth plays an important role in germination and seedling emergence in DSR. Semi-dwarf varieties are highly sensitive to seeding depth due to their shorter mesocotyl as compared to conventional tall varieties (Blanche et al., 2009).

The germination of seedling is decreased when seed is placed too deep or at shallow depth. When the seed is placed too deep, there are chances that the shoot tip will be damaged due to weak coleoptile, while if seeds are placed near surface, germination is affected by rapid drying of soil surface and high temperature near soil surface due to incoming solar radiation (Gopal et al., 2010). Maximum depth up to which rice seeds can be drilled is 2.5 cm, deeper than 2.5 cm results in uneven crop establishment (Kamboj et al., 2012).

**Stale seed bed technique**: Stale seedbed technique can be used to decrease weed seed bank from soil where a particular cropping system is followed year after year. This could be very useful in IGP where rice-wheat is the major cropping system. It depletes 5-10% of weed seeds present in soil.

In stale seedbed after tillage, light irrigation is applied to facilitate proper germination and emergence of weed seedlings. Single irrigation is given 15 days before sowing to maximize weed germination and after that soil moisture is maintained at optimum level. A non-selective herbicide (glyphosate or paraquat) or mechanical method is used to kill emerged weeds (Anonymous, 2017). Stale seedbed can be very effective when weed species have low dormancy, are placed near soil surface (in Zero-tillage) and favourable environmental conditions (light, optimum temperature) are present (Chauhan, 2012).

Singh et al. (2009b) reported that using stale seedbed technique in direct seeded rice, weed density can be reduced by 53% over control. Chauhan and Johnson (2010) observed better weed control when stale seedbed with paraquat is used with zero-till because weed seeds placed deeper than 1 cm do not emerges.

Combined use of stale seedbed along with pendimethalin gave effective control of weeds in DSR in large-scale farmer participatory trials in India (Singh et al., 2005c).

**Mulching**: Applying mulch on soil is another of controlling weeds in direct seeded rice. Besides conserving moisture mulch suppresses weeds, prevents soil erosion, add organic matter to soil, improve soil health and decrease fluctuations in diurnal temperature (Qin et al., 2010). Mulches are though to suppress weeds by physical obstruction to germinating weed seeds, block incoming sunlight and by release of certain allelochemicals. Kumar et al. (2013) reported that problematic weeds of DSR such as Echinochloa crusgalli, E. colona, Dactyloctenium aegypitium and Eclipta alba were sensitive to wheat straw used as mulch.

Batish et al. (2007) claimed that when residue of Tagetes minuta L. was used as mulch it suppresses growth of E. crus-galli and C. rotundus. Hong et al. (2004) reported through allelopathy certain plants like with Clerodendrum trichotomum Thunb., Datura stramonium L., Desmodium triflorum (L.) DC. and Melia azedarach L. were found to suppress weeds in rice by 70-90%.

Singh et al. (2007) studied the effect of weed suppression ability of crops with wheat straw 4 t/ha spread uniformly at SVBPU and T and found that during early stage (30 DAS) mulch resulted into highest reduction in total weed density (54%) which may be due to inhibitory effect of allelochemicals released by wheat on weed seed germination. Also wheat straw results in better weed control and gain in grain yield of rice. Wheat straw reduced grasses and BLW by 46% and 71% respectively, and increases grain yield of rice by 22%. This result in higher economic returns compared to control (Singh et al., 2007).

Hamdi et al. (2001) reported that suppressive effect of wheat straw on ryegrass may be through release of leachates and organic molecules may be involved.

The straw generated in wheat crop can be best utilised by spreading over the surface. This will also solve the problem of straw management as burning straw in the IGP is another serious issue. Encouraging results with the use of straw mulch from previous crop have been reported by Talukder et al. (2006). Straw mulch from previous crop along with post emergence herbicides could be promising strategy to control weeds in direct seeded rice.

Table 3. Common post-emergence herbicides used in direct seeded rice in India

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Name of the herbicide</th>
<th>Dose (kg/ha)</th>
<th>Time of application (DAS)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Bispyribac-sodium</td>
<td>0.025</td>
<td>25-30</td>
<td>(Kaur and Singh, 2015; Walia et al., 2008)</td>
</tr>
<tr>
<td>2.</td>
<td>Fenoxaprop-p-ethyl</td>
<td>0.06-0.075</td>
<td>25-30</td>
<td>(Upasani and Barla, 2014)</td>
</tr>
<tr>
<td>3.</td>
<td>Ethoxy sulfuron</td>
<td>0.015-0.175</td>
<td>25-30</td>
<td>(Upasani and Barla, 2014)</td>
</tr>
<tr>
<td>4.</td>
<td>Chlorimuron-ethyl+ met-sulfuron-methyl</td>
<td>0.002-0.004</td>
<td>25-30</td>
<td>(Singh et al., 2010; Singh et al., 2017)</td>
</tr>
<tr>
<td>5.</td>
<td>Acifluorfen</td>
<td>0.60</td>
<td>20-30</td>
<td>(Sankula et al., 1997)</td>
</tr>
<tr>
<td>6.</td>
<td>2,4-D</td>
<td>1.0</td>
<td>30</td>
<td>(Angiras and Attri, 2002)</td>
</tr>
</tbody>
</table>

Weed competitive cultivar: Weed-competitive cultivars can be a low cost but promising strategy to get higher yield and economic returns (Andrew et al., 2015). Varieties having good mechanical strength of coleoptile for rapid germination and higher seedling vigour to compete weeds are best suited for direct seeding (Jannink et al., 2000; Zhao et al., 2006). Ranasinghe (1995) conducted field experiments to identify morphological traits which provide competitive ability to rice plants against weeds. He found that rice-barnyard grass competition varies significantly with the morphology of rice cultivar. Cultivar which attains more plant height, leaf area and higher dry matter accumulation during seedling stage and more plant height and leaf area at the time of maturity offers more competition to the weeds. Better developed roots, high leaf area index and tillering capacity were the characters associated with weed suppressive rice cultivars (Fofana and Rauber, 2000). Perera et al. (1992) observed that under high crop-weed competition the root growth, root biomass and nutrient uptake is reduced in rice cultivars. Gealy and Moldenhauer (2012) reported that weed suppressive rice cultivars have twice root biomass than those of non-suppressive types. Due to higher root biomass and root proliferation, weed suppressive cultivars competed better for resources with weeds and reduced weed loss by 44% and weed prevalence by 30% as compared to non-suppressive cultivars (Gealy and Moldenhauer, 2012).

Therefore varieties suitable for direct seeded require characters like efficient root system for better anchorage and to draw moisture from deeper soil layers during peak evaporation demands (Clark et al., 2000; Pantuwan et al., 2002) and a wider window of sowing time. In Punjab and Haryana region, variety PUSA-1121, PR-115, PAU-201 etc. are suited for direct seeding.

Crop rotation: Crop rotation is very useful in controlling weeds. There are certain crop associated weeds which can be controlled simply by changing cropping system. Changing cropping system shifts the weed flora in which some weeds disappear and new weeds emerges. Singh et al. (2008) studied change in composition of weeds, weed density and weed dry weight when rice-wheat cropping sequence is changed. They found that minimum weed density was recorded in rice-wheat-green gram sequence followed by rice-wheat, rice-chickpea and rice-pea sequence. Changing rice-wheat rotation also helps in identification of weedy rice. By rotating rice with soybean, mungbean, Kharif maize or cotton etc., weedy rice can be controlled because other herbicides and cultural practices can be used which cannot be used in rice (Singh et al., 2013). Chhokar et al. (2008) reported that introduction of potato and pea in between rice and wheat can also improve weed control without herbicide applications.

Brown manuring: Brown manuring with sesbania in direct seeded rice can be a good option to control weeds, improve soil health and get higher yield. Seeds of sesbania 20 kg/ha can be drilled in between the rows of direct seeded rice 3 days after sowing of rice and sprayed with 2,4-D ethyl ester 0.50 kg/ha to produce sesbania brown manure. Nawaz et al. (2017) evaluated five different rice-wheat cropping systems and found that brown manuring in direct seeded rice with sesbania decreased weed density by 41-56 % and weed bio mass by 62-75% than sole direct seeded rice.

Seed priming: Seed priming are primarily aimed at hydration of seeds for a specific period of time to complete pre-germinative metabolic process but emergence of radicle is avoided. Priming may be done with water (hydro-priming), salt solution-NaCl (halo priming) or use of moist sand (sand matric priming). Priming increases germination percentage, gave uniform germination, improves resistance towards water and temperature stress, and increases the yield. Increased vigour in direct seeded Aeron 1 by different priming treatments was observed by Jurai mi et al. (2012). They reported primed seeds produced vigorous seedling with 50% higher vigour index than unprimed seeds. Anwar et al. (2012) claimed that primed seeds reduce weed dry weight by 22 to 27 % mainly due to good crop establishment with vigorous seedlings and quick canopy development. They also found that primed rice seeds produce 0.4/t/ha more yield over control.
Mechanical and manual methods of weed control: Controlling weeds through any physical activity that inhibits growth of weeds is mechanical control.

Mowing: Mowing is removing or cutting shoot of weeds by using sickle or mower. It is successful for controlling annual weeds while less practiced in case of perennial weeds because perennial weeds have stored food in below ground parts (rhizomes, stolones etc.) and come in several flushes. Mowing must be done before flowering or seed setting to prevent dispersal of seeds. Weed thus obtained should be buried deep or burnt to remove viability of weed seeds (Matloob et al., 2015).

Mechanical weeder: The mechanical methods control weeds and gave yield at par with chemical control provided they are done properly. Mechanical weeding is not practiced in IGP due to labour and economic constraint.

Muthukrishnan and Purushothaman (1992) reported that HW twice at 25 and 45 DAS effectively controlled the weeds, resulting in higher grain yield over un-weeded check. Mehta et al. (1993) observed that HW twice, at 20 and 30 DAS, produced rice grain yield of 3.2 t/ha at par with weed free (HW four times) yielding 3.3 t/ha and higher than one HW (2.5 t/ha) and weedy (1.0 t/ha).

Singh et al. (2003) reported from Pantnagar, India that pendimethalin at 1.0 kg/ha along with farm waste as mulch (7.5 t/ha) supplemented with one HW at 45 DAS decreased weed count, weed biomass with highest weed control efficiency (91.3%) which was comparable with HW thrice at 30, 60 and 90 DAS (farmers’ practice).

Manual weeding can be implemented only when weeds have reached a sufficient size to be pulled and it has an inherent opportunity cost. Manual weeding is therefore often practiced late as evident by yield loss comparisons of the effects of manual weeding at 21-30 DAS with those from the use of early post-emergence herbicides (Singh et al., 2005a).

Labour scarcity, high labour cost, poor weather conditions and the presence of perennial weeds that breaks down on pulling may all lead to lower efficiency of hand weeding.

Mechanical weeding using simple implements remains a practical and economic method for many small and marginal farmers of Asia and Africa. Mechanical weeding is almost universally practised on row-seeded rice since inter row cultivation with either hand tools or animal traction equipment reduces time in weeding and minimizes crop damage.

Sarma and Gogoi (1996) reported that in rain-fed upland rice in India, a manually operated peg-type dry-land weeder which is operated manually (with a straight-line peg arrangement) has shown excellent performance across a wide range of soil types with varying soil moisture levels and weed intensity providing a labour saving of ~ 57% compared with hand weeding (127 person-days/ha).

Chemical method of weed control: Labour unavailability, increasing labour costs, and the pressing need to raise yield and maintain profit on a progressively limited land base have been the major drivers for farmers to seek alternatives to manual weeding. Herbicides are one such alternative. Effective weed management practices are an important pre-requisite in DSR culture, with herbicide application seemingly indispensable (Azmi et al., 2005). The trend for an increase in herbicide use has been reinforced by the spread of DSR (Naylor, 1994).

Pre-emergence herbicides: Different pre-emergence herbicides are used for controlling weeds in direct seeded rice in India (Table 2). Among them, pendimethalin 1.0 kg/ha, oxadiargyl (0.10 kg/ha) and pyrazosulfuron (0.02 kg/ha) were found to give effective weed control (Gupta et al., 2006a; Rao and Nagamani, 2007; Singh et al., 2009; Gopal et al., 2010; Singh et al., 2017). Pendimethalin is a selective herbicide effective against most annual grasses and several annual broad leaves weeds. It belongs to chemical class of dinitroaniline. It acts via inhibition of microtubule formation, disrupting cell division and causing microfibril disorientation, so it’s a germination inhibitor. Pendimethalin controls Echinochloa spp. more effectively as compared to Cyperus spp. Pendimethalin at 0.90 kg/ha provided excellent control of weedy rice and best control of grassy weeds (Joseph et al., 1990), whereas Malik et al. (2002) reported that pendimethalin was effective only against Echinochloa spp., Cyperus iria and Commelina banghalensis. It shows poor efficacy against Leptochloa chinensis, another predominant weed in direct seeded rice (Singh et al., 2017).

Singh et al. (2016) evaluated three pre-emergence herbicides pendimethalin 1.0 kg/ha, butachlor 1.0 kg/ha and oxadiargyl 0.09 kg/ha and found weed density after application of these herbicides were 10-13, 15 and 16-23 plants/m² respectively compared to 51 plants/m² in weedy check at Taraori location. At Madhuban location, highest grain yield of direct seeded rice (3.43 t/ha) was obtained with pendimethalin 1.0 kg/ha PRE fb
bispyribac-sodium 0.025 kg/ha and azimsulfuron 0.0225 kg/ha POST which was comparable under weed free (3.5 t/ha).

Kaur and Singh (2015) evaluated seven pre-emergence (pendimethalin 0.75 g/ha, Butachlor 1.50 kg/ha, Thiobencarb 1.50 kg/ha, Anilofos 0.375 kg/ha, Pretiachlor 0.75 kg/ha, Oxadiargyl 0.09 kg/ha, Pyrazosulfuron-ethyl 0.015 kg/ha) herbicides for their efficacy against weeds in DSR. Application of pendimethalin 0.75 kg/ha PRE produced significantly lower weed density of Echinochloa spp. at 30 DAS than all other pre-emergence herbicides. Similarly, the density of Cyperus spp. was similar in all pre-emergence herbicides. However, the weed dry matter of Cyperus spp. in Pyrazosulfuron-ethyl 0.015 kg/ha treated plots was at par with unweeded at 30 DAS.

Post-emergence herbicides: In direct seeded rice, more than one flush of weeds occurs during crop duration. Pre-emergence herbicides gave effective control during early stage of crop growth and post-emergence herbicides during the second flush of weeds. If weeds were not controlled properly, they can cause significant qualitative and quantitative loss in grain yield. A single herbicide cannot give effective weed control throughout crop growth period so sequential herbicide application is done. A list of common post-emergence herbicides used in direct seeded rice in India is given in Table 3.

Walia et al. (2008) claimed that application of bispyribac-Na @ 0.025 kg/ha controlled all type of weeds in direct seeded rice and was found very effective against problematic weeds of DSR i.e. Echinochloa spp. and Cyperus spp. Also, Kaur and Singh (2015) reported that application of bispyribac-Na 0.025 kg/ha POST after six pre-emergence herbicides (butachlor, thiobencarb, anilofos, pretiachlor, oxadiargyl and pyrazosulfuron-ethyl) produced lower weed density than these six pre-emergence herbicides applied alone. Singh et al. (2017) at Kaul, Kaithal (Haryana) claimed that Leptochloa chinensis can be controlled effectively by fenoxaprop-p-ethyl 0.067 kg/ha having weed control efficiency (WCE) of 92% than bispyribac-Na 0.025 kg/ha with WCE of 38% in direct seeded rice (DSR). Singh et al. (2004) at Pantnagar also reported good control of L. chinensis by fenoxaprop-p-ethyl 0.056 kg/ha while its efficacy against Echinochloa spp. and Cyperus spp. was poor than bispyribac-Na with WCE of 40%. Singh et al. (2010) evaluated azimsulfuron 0.025-0.030 kg/ha at 25 DAS alone and tank mixed with chlorimuron-ethyl+ metsulfuron-methyl 0.004 kg/ha and reported that tank mixing of chlorimuron-ethyl+ metsulfuron-methyl 0.004 kg/ha does not improve the efficacy of azimsulfuron 0.025-0.030 kg/ha against grasses weeds. Azimsulfuron 0.025-0.030 kg/ha alone at 25 DAS gave effective control of BLW (Broad leaf weeds) and sedges especially Cyperus rotundus but poor control of grasses.

Mishra and Singh (2008) evaluated two pre-emergence herbicides i.e., pendimethalin 1.0 kg/ha and pretilachlor 0.75 kg/ha followed by 1 HW at 30 DAS or 2, 4-D (0.05 kg/ha) + fenoxaprop (0.07 kg/ha) and reported that these treatments being at par were effective against weeds and gave significantly higher grain yield (3.07, 3.25, 3.23 and 3.14 t/ha, respectively) and benefits (B:C ratio of 1.75, 1.75, 1.86 and 1.71, respectively) than weedy check (1.36 t/ha and 0.95).

Singh et al. (2006) studied efficacy of herbicides in direct seeded rice cultivated in FIRBS (furrow irrigated raised bed planting system) and reported that application of fenoxaprop 0.050 kg/ha + ethoxy sulfuron 0.018 kg/ha at 21 DAS and pendimethalin 1.0 kg/ha PRE fb chlorimuron-ethyl+ metsulfuron-methyl 0.004 kg/ha at 21 DAS were effective against mixed weed flora (WCE of 90 and 84%, respectively) and economical also (Net income of 115 and 97 US $, respectively). Mahajan et al. (2009) reported that application of bispyribac-Na 0.025 kg/ha and penoxsulam 0.025 kg/ha effectively controlled all the weeds in aerobic direct seeded rice (ADSR) with WCE of 85 and 67%, respectively and grain yield were similar with conventional puddled transplanted rice (CPTR) (25.69 and 20.76 q/ha under ADSR and 30.02 and 28.58 q/ha under CPTR).

Mahajan and Timisina (2011) claimed that application of pendimethalin 1.0 kg/ha PRE fb bispyribac-Na 0.030 kg/ha 18 DAS or pendimethalin 1.0 kg/ha PRE fb bispyribac-Na 0.030 kg/ha 18 DAS + HW 45 DAS gave better weed control (WCE of 81 and 91%, respectively compared to pendimethalin 1.0 kg/ha PRE fb + HW 45 DAS), higher grain yield (5.32 and 6.11 t/ha, respectively), higher water productivity and profitability in direct seeded rice. Walia et al. (2008) reported that application of pendimethalin 0.75 kg/ha PRE followed by bispyribac-Na 0.25 kg/l or azimsulfuron 0.020 kg/l or 2, 4-D 0.50 kg/ha at 30 DAS resulted in better weed control (WCE of 87, 84 and 78%, respectively) and higher grain yield of rice (5618, 4747 and 4675 kg/ha, respectively). Application of pendimethalin 0.75 kg/ha PRE fb bispyribac-Na 0.025 kg/l ha resulted in 372 % increase in grain yield as compared to unweeded control (1191 kg/ha). Application of pendimethalin provided effective control of non-predominant paddy weeds, whereas bispyribac-Na controlled typical predominant paddy weeds including Echinochloa colona and all Cyperus spp.

Singh et al. (2017) reported that pendimethalin 1.0 kg/ha fb bispyribac-Na and chlorimuron-ethyl+ metsulfuron-methyl 0.004 kg/ha gave effective weed control (WCE of 75.4%) with higher grain yield and profitability at par with weed free (3.97
and 4.12 t/ha and 2.37 and 2.01, respectively).

**Allelopathy:** Recent studies showed that rice plants and weeds also compete through allelopathy. Olofsdotter (2001) studied allelopathic potential of 111 rice cultivars on weeds in Philippine’s and reported that dry weight of weeds reduced up to 34 % after 8 weeks of seeding. The reduction in weeds dry weight is due to allelochemicals released by these rice cultivars (Olofsdotter et al., 2002). Kato-Noguchi et al. (2011) identified 3-hydroxy-6-ionone and 9-hydroxy-4-megastigmen-3-one (Fig. 1) as main allelochemicals in Kartikshail and BR 17, two high yielding rice cultivars of Bangladesh.

Allelopathic potential of many rice cultivars like BR17 against *Echinochloa crus-galli* and *E. colo- num* had already been reported in various studies (Farooq et al., 2008; Farooq et al., 2011; Jabran and Farooq, 2013). Several rice cultivars through release of allelochemical had been found to suppress predominant weeds of rice, such as *E. crus-galli* (Jensen et al., 2001; Seal and Pratley, 2010), *Cyperus difformis* (Seal and Pratley, 2010), * Sagittaria montevidensis* (Seal and Pratley, 2010; Seal et al., 2004).

Seal and Pratley (2010) evaluated the allelopathic multi-weed suppression of 27 different rice cul- timers against five major aquatic weeds of Australia and found that cultivar Amaroo inhibited Alisma- taceae weeds by an average of 97%, whereas *Echinochloa crus-galli* was inhibited by 72%. A non allelopathic cultivar, Langi stimulated root growth of *E. crus-galli* by almost 20 %.

In India not much work is done to exploit the rice’s allelopathic property for weed control in direct seeded rice. Cultivars with improved allelopathic potential can be developed which compete better with weeds and lowers the dependence on herbi- cides. So, there is wide scope to identify, develop and exploit cultivars with higher allelopathic poten- tial in proper cropping systems.

**Conclusion**

Weeds are the major biotic factors which hinder the growth and yield of direct seeded rice. Con- trolling weeds is pivotal for getting good grain yield of rice. Not a single weed control method is ecological viable and sustainable both ecologically as well as economically. Therefore, integrating different weed control methods on the basis of climatic conditions, edaphic factors, weed flora present and cultivars, effective weed management on a long term sustainable basis can be achieved. New weed control approach like allelopathy can be used along with other weed control methods to further reduce the losses caused by the weeds in direct seeded rice.

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