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PERSPECTIVE ARTICLE

The scenario of herbicide-resistant weeds: Management challenges and perspectives

Vipin Kumar[1*], Mandeep Singh[1], Ramandeep Kaur[1], Amit J. Jhala[2]

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ABSTRACT

The evolution of herbicide-resistant (HR) weeds is becoming a challenge for sustainable food production. As of March 2023, 267 weed species have been confirmed resistant to one or more herbicides globally. The objectives of this review were to summarize the status of herbicide-resistant weeds, their mechanisms of resistance, herbicide resistance dispersal mechanisms, management options, and future perspectives on herbicide-resistant weeds. Target site resistance (TSR) and non-target site resistance (NTSR) are two mechanisms for the evolution of HR weeds. TSR results from changes in the specific target site/enzyme for the herbicide, whereas NTSR includes physiological processes that reduce herbicide concentration at the target site. Once an individual weed evolves resistance, the resistance can disseminate through seed-mediated gene flow, pollen-mediated gene flow, or vegetative propagules. Widespread dispersion of HR weeds threatens crop production, and effective steps need to be taken to restrict this dispersion. A widespread occurrence of HR weeds, particularly in developed countries, requires a systemwide, integrated, holistic approach for their effective management that can reduce reliance on herbicides and integrate non-chemical control techniques, including cultural practices, cover crops, conservation tillage and residue retention, harvest weed seed control, and mechanical weed control. Multiple herbicide-resistant crops and herbicide premixes with multiple sites of action are widely used for HR weed management; however, their long-term sustainability is questionable. Moreover, new herbicides with novel site of action and other non-chemical weed management strategies need to be developed that can be adopted by growers. Thus, management of herbicide-resistant weeds is complex and requires a multidisciplinary approach.

Keywords: Conservation tillage, Herbicides, Herbicide-resistant, Weed control

INTRODUCTION

Although the first case of herbicide resistance was reported in Hawaii in 1957 (Hilton 1957), the first confirmed case of triazine resistance in *Senecio vulgaris* L. (common groundsel) was reported in 1960s in western Washington, USA (LeBaron 1989). As of March 2023, 267 weed species have evolved resistance to one or more herbicides (Heap 2023). Out of 267 weed species, 171 are resistant to acetolactate synthase (ALS) inhibitors, followed by photosystem-II (PS-II) inhibitor (87), atrazine (66), glyphosate (56), tribenuron-methyl (48), imazethapyr (44), imazamox (42), iodosulfuron-methyl- Na (40), metsulfuron-methyl (40), chlorsulfuron (38), fenoxaprop-ethyl (33), paraquat (31), simazine (31), thinfensulfuron-methyl (31), bensulfuron-methyl (29), mesosulfuron-methyl (27) and nicosulfuron (27) (Heap 2023).

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Wheat and maize are widely grown crops, and several herbicides are applied in different countries for weed control in these crops. A total of 83 weeds in wheat and 64 weeds in maize production fields have evolved resistance to at least one herbicide, followed by rice (54) and soybean (52) (Heap 2023). Weeds from the Poaceae and Asteraceae families have the highest instances of herbicide resistance, with more than 56 weed species showing resistance to multiple herbicides. In general, weeds with annual or biennial life cycles are more likely to evolve herbicide resistance compared with perennial weeds. *Lolium rigidum* Gaudin, *Poa annua* L., *Amaranthus palmeri* S. Watson, *Echinochloa crus-galli* (L.) P. Beauv., *Eleusine indica* (L.) Gaertn., *Lolium perenne* ssp. *Multiflorum* (Lam.) Husnot, *Amaranthus tuberculatus* (Moq.) J. D. Sauer, *Avena fatua* L., *Amaranthus hybridus* L., *Conyza sumatrensis* Retz., *Echinochloa colona* (L.) Link and *Raphanus raphanistrum* L. are examples of troublesome weed species that have evolved resistance to more than 6 herbicide sites of action (Heap 2023).

It has been estimated that more than 25 million hectares are infested with *L. rigidum, A. fatua, Phalaris* *minor* Retz., *Setaria* spp. and *Alopecurus myosuroides* Huds. in cereal crops globally. From an economic perspective, *A. palmeri* is the number-one herbicide-resistant weed in maize and soybean production systems and *Conyza* spp. are the most widespread (Heap 2023).

Herbicide-resistant weeds in India

In India, herbicides account for 16% of the total pesticide market (Bhullar *et al.* 2017). The first case of *P. minor* (little seed canarygrass) resistance to PS-II inhibitors and ACCase inhibitors was reported in 1991 and 1994, respectively, in wheat production fields in Haryana (Heap 2023). *P. minor* resistant to isoproturon in wheat in Haryana was first reported in 1995 (Malik and Singh 1995) due to an overreliance on substituting phenyl urea herbicides (chlortoluron, isoproturon, methabenzthiauron and metoxuron). Thereafter, aryloxyphenoxypropionates (fop-herbicides) including clodinafop and fenoxaprop were used for control of isoproutron-resistant *P. minor*, but it soon developed resistance against clodinafop, fenoxaprop, pinoxaden, sulfosulfuron, and tralkoxydim (Bhullar *et al.* 2017). By 2006, *P. minor* resistance to ACCase, ALS, and PS-II inhibitors had been confirmed (Rao *et al.* 2020). There are reports of *Avena ludoviciana* Durieu resistance to ACCase inhibitors, including clodinafop in Haryana. Chhokar *et al.* (2017) confirmed *Rumex dentatus* L. and *Polypogon monspeliensis* L. Desf. resistance to ALS inhibitors. Similarly, *Chenopodium album* L. has evolved resistance to ALS inhibitors (metsulfuron) (Bhullar *et al.* 2017) and Choudhary *et al.* (2021) reported that *Cyperus difformis* L. (smallflower umbrella sedge) has evolved resistance to ALS inhibitors (bispyribac sodium) in Chattisgarh and Kerala.

Evolution of herbicide-resistant weeds

The evolution of HR weeds follows the basic principles of natural selection and selection pressure. Selection pressure of an herbicide in a particular weed species refers to the ratio of resistant plants to susceptible plants following exposure to that herbicide (Gressel and Segel 1982). Herbicides do not cause weed resistance by themselves; rather, they select for individual plants with herbicide-resistant traits (Hanson *et al.* 2013). Repeated use of the same or different herbicide with the same site of action results in the selection of individuals that are not killed by that herbicide (Bhullar *et al.* 2017). These individuals then reproduce and grow in number over the years, resulting in a build-up of the HR weed population. However, the build-up of HR populations depends on numerous factors such as the initial frequency of resistant individuals, the reproductive ability of the respective weed species, and competition (Hanson *et al.* 2013).

The source of variation among individuals of a weed/plant species is mutation. Some mutations can be positive and may aid in the survivability of the plant, some may be lethal and lead to plant death and some may be neutral with no effect (Loewe and Hill 2010). Thus, mutations leading to the evolution of herbicide resistance can be considered positive mutations, as they aid in the survivability of the species following herbicide exposure. The rate of mutation is not constant within and between species; rather, it varies with plant age, the type of tissue involved, environmental factors, and the genome and locus involved (Christoffers 1999). Mutations can either affect the herbicide target site (target site herbicide resistance) or modify plant metabolic processes (non-target site herbicide resistance), resulting in either reduced herbicide uptake, reduced movement of the herbicide inside the plant system or increased herbicide detoxification (Hanson *et al.* 2013).

Mechanism of herbicide resistance

The mechanisms for herbicide resistance are primarily classified as target-site resistance (TSR) and non-target-site resistance (NTSR). In TSR, the target site of the herbicide is modified/mutated, causing the target enzyme or protein to become less sensitive to the herbicide, and requiring a higher concentration of herbicide to inhibit the enzyme activity (Jugulam and Godar 2013; Gaines *et al.* 2020). For this to occur in a weed plant, either change occurs in the sequence of amino acids or the overexpression of genes to produce a greater number of target enzymes that can be inhibited by the herbicide. Therefore, TSR occurs either due to mutation (point/double/deletion) or gene amplification. The target-site protein has a specific site for herbicide binding, and several amino acids exist nearby this site that, if substituted, can lead to TSR (Gaines *et al.* 2020). Hence, there are several possibilities for target-site mutations, though mutations usually occur in or near the binding site of the herbicide, with structural changes sometimes occurring at other places on the target protein (Délye *et al.* 2015; Gaines *et al.* 2020). A change in a single amino acid on the target-site protein can reduce the capacity of the herbicide to inhibit the enzyme without affecting the normal function of the protein (Gaines *et al.* 2020). The resulting resistance from amino acid substitution can vary from low to high levels depending on the mutation and herbicide molecule (Délye *et al.* 2015; Gaines *et al.* 2020). Mostly, TSR occurs due to point mutations and is frequently controlled by a single gene (monogenic), as herbicides are mostly meant to target specific enzymes/proteins. This also creates a relative ease in understanding the molecular mechanisms underlying TSR (Yuan *et al.* 2007). Monogenic resistance can spread rapidly within a population, as observed in the widespread occurrence of resistance to ALS-inhibiting herbicides conferred by a single nuclear gene (Tranel and Wright 2002).

NTSR mechanisms encompass all the physiological processes that reduce the concentration of active herbicide ingredients at the target site. NTSR includes a decrease in the uptake/translocation of herbicides, and/or an increase in sequestration, degradation, metabolism, or breakdown of herbicides to lesser toxic compounds compared to the parent material (Jugulam and Godar 2013). The reduced absorption of the herbicide is uncommon in the NTSR mechanism; differential absorption of foliar-applied herbicides is usually credited to differences in leaf anatomy (Gaines *et al.* 2020). However, it has been implicated as a mechanism of resistance in some cases such as glyphosate (Michitte *et al.* 2007) and atrazine (Svyantek *et al.* 2016), though it is usually deemed to confer low levels of resistance (Délye *et al.* 2013; Gaines *et al.* 2020). Herbicide resistance is sometimes conferred through reduced translocation, as the herbicide is trapped within the plant leaves due to vacuolar sequestration or changes in the activity of the plasma membrane transporter (Goggin *et al.* 2016; Gaines *et al.* 2020). For example, reduced translocation has been well-documented for imparting resistance to glyphosate (Ge *et al.* 2010; Gaines *et al.* 2019) and paraquat (Yu *et al.* 2010; Hawkes 2014).

The most important and researched NTSR mechanism is metabolic resistance, or enhanced herbicide degradation (Délye *et al.* 2013). Herbicide degradation is usually a three-phase process. In Phase I, the herbicide molecule is oxidized, hydrolyzed or reduced to modify it to a more hydrophilic metabolite. While in Phase II, this metabolite is conjugated, and in Phase III, the conjugated molecule is exported to the vacuole or cell wall for further degradation (Délye *et al.* 2013; Gaines *et al.* 2020). During this process, some enzymes have gained particular attention for conferring resistance by rapidly metabolizing herbicide molecules in resistant weed biotypes (Yuan *et al.* 2007). These enzymes are cytochrome P450 monooxygenases (P450s), which mediate Phase I of herbicide degradation, and glutathione S-transferases (GSTs) and glucosyltransferases (GTs), which mediate Phase II of herbicide degradation. Metabolic resistance can pose a challenge for weed management, as it can confer broad-spectrum resistance (cross-resistance) and even combine with reduced translocation and TSR mechanisms to provide a greater level of resistance (Gaines *et al.* 2020). Compared to TSR, NTSR mechanisms are more complex and difficult to understand (Délye *et al.* 2015). This is because NTSR mechanisms are usually controlled by many genes (polygenic) and can provide resistance to numerous herbicides with different sites of action, even herbicides that are not yet commercially available (Petit *et al.* 2010; Délye *et al.* 2013). Moreover, plants carry these genes as gene families, with P450s and GSTs being the most important. Hence, this involvement of gene families makes it more difficult to discover specific genes that are conferring resistance in a specific scenario (Gaines *et al.* 2020).

Discovering the exact mechanism(s) of herbicide resistance can be more complex, as TSR and NTSR can co-exist in the same population. For example, Nandula *et al.* (2013) reported both TSR (Pro-196 amino acid substitution) and NTSR (reduced translocation) mechanisms for glyphosate resistance in *A. tuberculatus* (waterhemp). Therefore, if herbicide resistance is suspected to be occurring due to one of the two mechanisms, it is important to test other mechanisms, because sometimes more than one mechanism might be conferring the resistance (Jugulam and Shyam 2019). As a result, genomics, metabolomics, proteomics, transcriptomics and next-generation sequencing technologies have become crucial for improved understanding of the biological, genetic, ecological and molecular basis of herbicide resistance during this critical time when weed populations are showing multiple-herbicide resistance (Gaines *et al.* 2020).

DISPERSAL OF HERBICIDE-RESISTANT WEEDS

When weed(s) evolve resistance to herbicide(s), the dispersal of the resistance plays an important role in the widespread occurrence of HR weeds across the region and at the landscape level. The importance of weed dispersal processes in shaping genetic structure has been difficult to evaluate because the relationship between genetic structure and gene flow is notably complicated in weed species due to the existence of three components of gene movement: (1) seed-mediated gene flow, (2) pollen-mediated gene flow and (3) gene flow through vegetative multiplication (Jhala *et al*. 2021a). The main evolutionary processes underlying gene flow dynamics rely on at least one of these three components of dispersal mechanism (Mallory-Smith and Zapiola 2008). For instance, hybridization is the result of pollen-mediated gene flow, whereas colonization of a new environment primarily occurs through seed-mediated gene flow (Jhala *et al*. 2008). Hybridization and introgression, although considered a form of gene flow, may also increase differentiation if admixture levels vary across populations (Jhala *et al*. 2008; Jhala *et al*. 2021a). To infer the level of pollen- and seed-mediated gene flow from patterns of genetic structure, it is important to monitor molecular markers that allow differentiation between seed and pollen movement (Sarangi *et al*. 2017).

Seed-mediated gene flow

Seed-mediated gene flow is the dispersal of weed species through the activity of seed(s). A number of factors play a role in seed-mediated gene flow such as seed viability, persistence, longevity, seed size, and seed dispersal mechanism (Oddou-Muratorio *et al*. 2001). A number of weed species such as waterhemp and *A. palmeri* (Palmer amaranth) are small seeded and prolific seed producers (Jhala *et al*. 2021b). For example, a single female plant of *A. palmeri* in central Nebraska, USA under ideal conditions can produce 5,00000 seeds (**Figure 1**). In contrast, large-seeded weed species such as *Ambrosia trifida* L. (giant ragweed) can produce about 10,000 seeds per plant. There are several ways that seeds can be disseminated from one field to another through equipment, transportation, water, animals or human activities. Seed-mediated gene flow is the most common type of dispersal mechanism once resistance has been evolved in weed species.

Pollen-mediated gene flow

Pollen-mediated gene flow (PMGF) is the dispersal of alleles through pollen via wind, insects, or other pollinators. Several factors influence the frequency and distance of pollen movement and gene flow, including reproductive biology of the weed species, the type and presence of pollination vectors, pollen viability and longevity, flowering synchrony and pollen production, wind speed and direction, and others. Pollen-mediated gene flow is a natural phenomenon not unique to weed species that has occurred since the existence of flowering plants. After the evolution of HR weeds, PMGF is believed to be an important avenue for the spread of resistance within and between weed species. The dissemination of herbicide-resistance alleles through pollen is more common in weed species that are dieocious (male and female plants are separate), such as Palmer amaranth and waterhemp. Certain weed species such as giant ragweed are prolific pollen producers; therefore, although giant ragweed is a monoecious species, pollen-mediated gene flow has been reported from glyphosate-resistant to susceptible giant ragweed (Ganie and Jhala 2017). Research has been conducted in Georgia, USA to determine whether the glyphosate-resistance trait can be transferred via PMGF from a glyphosate-resistant Palmer amaranth biotype to a glyphosate-susceptible biotype (Sosnoskie *et al*. 2012). Results from this study demonstrated that glyphosate-resistant Palmer amaranth could be dispersed up to 300 m under natural field conditions, and that the widespread occurrence of glyphosate-resistant Palmer amaranth is due in part to the movement of pollen between spatially segregated populations (Sosnoskie *et al*. 2012). A similar study is being conducted in Nebraska, USA to determine PMGF from glyphosate-resistant common waterhemp to glyphosate-susceptible common waterhemp under field conditions, with transgene movement detected at up to 50 m from the pollen source. Studies on PMGF from HR broad-leaved weeds (Jhala *et al*. 2021a) and grass weeds (Jhala *et al*. 2021b) have been reviewed and provide additional literature on this topic.

MANAGEMENT OF HR WEEDS

Weed management strategies that can reduce dependency on herbicides and herbicide selection pressure can aid in the management of HR weeds. Integrated weed management (IWM) is one such approach that can reduce the risk of evolution of HR weeds. IWM is a weed management strategy that integrates different weed management tools to help achieve effective weed control. The IWM approach aims at discouraging the introduction, spread and adaptation of weeds, and helping the crop to outcompete weeds. Some of the tools that can be used in IWM are listed below:

Cultural practices

Cultural practices are normally low-cost decisions that can serve as efficient weed management tools when integrated with herbicides or other weed management strategies. Cultural practices such as planting crops at the optimal time, using improved crop varieties, good quality seed material, optimal seed rate and row spacing, diversified cropping systems, the correct time and rate of nutrients and irrigation are very effective for weed management if integrated with other weed management practices (Kumar *et al*. 2021). Chhokar and Malik (1999) reported that wheat planted in October had a lower infestation of *P. minor* compared to wheat planted at later dates. Some weeds are prominent under cropping systems; for example, *P. minor* is common in rice-wheat cropping systems in the Trans Indo-Gangetic plains compared to other cropping systems because of favourable growing conditions, and crop rotation can help reduce infestation of this problematic weed (Rana *et al*. 2018). Reducing soybean row spacing from 76 cm to 38 cm also reduced weed biomass by three times (Harder *et al*. 2007). Similarly, a recent meta-analysis by Singh *et al.* (2023) concluded that narrow row spacing (< 76 cm) reduced weed biomass by 71% and improved weed control by 34%. Cultural practices can reduce the selection pressure of herbicides on weeds, but such practices alone cannot provide the desired level of weed control and need to be integrated with additional weed management practices.

Cover crops

Cover crops are generally planted in the off-season between two successive cash crops and are terminated/killed before (*i.e.*, planting brown) or after (*i.e.*, planting green) the planting of cash crops (**Figure 2**). Cover crops offer various advantages such as reducing soil erosion, improving soil organic matter, water infiltration, and many others. In addition, cover crops also help in suppressing weeds (Pittman 2020). During their active growth period, cover crops compete with weeds and thereby reduce their growth compared to growth occurring on bare ground (Smith *et al.* 2015). After termination, cover crop residue produces a mulching effect (Figure 2) and blocks sunlight from reaching the soil surface, discouraging the germination and growth of weeds (Huarte and Arnold 2003; Teasdale *et al*. 2007). Moreover, cover crop residue also has allelopathic effects on weeds (Kruidhof *et al.* 2009; Sias *et al*. 2021). Cornelius and Bradley (2017) observed a 68-72% reduction in density of *Stellaria media* (L.) Vill., *Thlaspi arvense* L. and *Lamium amplexicaule* L. by growing a cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) mixture as cover crops. Similarly, cereal rye and canola reduced total weed biomass by 91% and 74%, respectively, compared to no cover crop (DeSimini 2020). Therefore, if managed properly, cover crops have the potential to suppress HR weeds and reduce the HR weed seedbank (Bunchek *et al.* 2020).

Conservation tillage and crop residue retention

Conservation tillage has been defined as: "any tillage and planting system that covers 30% or more of the soil surface with crop residue, after planting, to reduce soil erosion by water" (CTIC 2002). While shifting from a traditional to a conservation tillage system may increase weed infestations during the initial years (i.e., the transition phase), the long-term adoption of conservation tillage practices can aid in weed management (Bhullar *et al.* 2016). The reduced disturbance of soil under conservation tillage prevents the mixing of weed seeds into the soil seed bank and reduces weed emergence (Nandan *et al*. 2020). Moreover, if weeds are managed effectively and discouraged from seed production during the initial years, the weed seed bank can be significantly reduced, as limited tillage reduces the movement of weed seed from the lower soil layer to the soil surface (Kumar *et al.* 2021). Furthermore, retaining residue from previous crops also helps improve weed control (Chauhan and Abugho 2013; Bana *et al.* 2020), soil health (Parihar 2020) and maintaining soil moisture (Jat *et al.* 2019). Retention of crop residue in direct-seeded rice (DSR) reduced weed biomass and weed density by 47% and 41%, respectively, compared to DSR without residue retention (Bana *et al.* 2020). Crop residue retention promotes the growth of soil micro-organisms, which can help in the predation of weed seeds (Nichols *et al.* 2015).

Harvest weed seed control (HWSC)

HWSC is the process/method of preventing the deposition of weed seed in the soil seedbank during crop harvesting, either by removing weed seeds along with crop residue, concentrating weed seeds in narrow lines or destroying weed seeds using impact mills (Walsh *et al*. 2017). Preventing weed seed deposition in the soil seed bank during crop harvest reduces dependency on herbicides. Somerville *et al.* (2018) reported that destroying 50% of seeds before their deposition in the soil seedbank can slow herbicide-resistance by approximately 10 years. HWSC can be achieved through several methods such as using chaff carts to collect chaff material and weed seeds, narrow window burning of chaff material containing weed seeds, bale direct systems, chaff tramlining and chaff lining, and the use of a weed seed destructor such as Harrington Seed Destructor (HSD) or RedekopTM seed control unit (Walsh *et al*. 2017; Shergill *et al.* 2020b). Several studies have been conducted on chaff carts and chaff lining indicating their success in controlling weeds; for example, the collection and removal of soybean residue after harvesting reduced Palmer amaranth density by 41-70% over three years (Norsworthy *et al*. 2016). However, removing crop residue also removes the nutrients present in the residue (Spoth *et al.* 2022), leaving the soil exposed to wind and water and resulting in soil erosion. Harrington Seed Destructor (HSD) and RedekopTM seed control unit are more advanced technologies that mechanically destroy weed seeds at the time of crop harvest without removing crop residue from the field (Walsh *et al.* 2017). It has been reported that HSD can destroy 85-100% of seeds from several weed species tested, including *A. artemisiifolia*, *A. hybridus*, *Abutilon theophrasti* Medik., *A. trifida*, *A. tuberculatus*, *C. album*, *Datura stramonium* L., *Ipomoea hederacea* Jacq., *Setaria faberi* Herrm., and *Xanthium strumarium* L. (Shergill *et al*. 2020a). Similarly, Walsh *et al.* (2012) recorded greater than 90% destruction of *Avena* spp., *Bromus* spp., L. *rigidum* and *R. raphanistrum* through the use of HSD.

Mechanical weed control

Mechanical weed control is an age-old practice. Before the discovery of herbicides, mechanical weed control was the most important weed management strategy, though with the increasing popularity of herbicides, mechanical weed control become obsolete, as it is a laborious and tedious task, as well as expensive due to the increased cost of fuel (Rueda-Ayala *et al*. 2010). Previously, mechanical weed control was performed by either tractor-driven cultivators or human managed tillers such as rototillers or handheld small equipment such as hoes. However, mechanical weed management has made numerous advances in recent years, with the development of robots that are capable of real time imaging and can identify and kill weeds using mechanical blades/cutters, laser lights, high temperatures or electric current (King 2017). Equipment such as the Weed Zapper™ has been developed in recent years to use electricity as a medium to control weeds. When the weeds come into contact with the electricity, the electric current travels through the plant system and to the soil, killing the plants (Moretti 2021). Electric weeders have the potential to be an effective mechanical weed management option if used at the correct crop and weed growth stage, especially under no-till organic crop production systems.

Stacked herbicide-tolerant crops and herbicide premixes

Stacking herbicide-tolerant crops refers to modifying a crop variety by breeding resistance to two or more herbicides; for example XtendFlex® soybean is resistant to dicamba, glyphosate and glufosinate (Striegel and Jhala 2022). Stacking or combining resistant traits in a crop expands the available herbicide options, as it allows for the rotation of different herbicides and hence, reduces the selection pressure against a single herbicide chemistry. Similarly, herbicide pre-mixes have different active ingredients mixed in a single herbicide, which aids in broad-spectrum weed control. Using herbicide premixes with different sites of action decreases the selection pressure exerted by an individual herbicide or an herbicide with the same site of action, thereby delaying the evolution of HR weeds (Norsworthy *et al*. 2012). Therefore, herbicide premixes reduce the possibility of survival and fecundity of weed species with resistance to a particular site of action herbicide (Norsworthy *et al.* 2012). Moreover, herbicide premixes can reduce application cost and are easy to use for farmers, as they do not have to buy different herbicides and can avoid herbicide tank-mixing complexities such as compatibility issues and calculating the herbicide rate of an individual active ingredient.

FUTURE PERSPECTIVES

Although diverse weed management strategies are the path to long-term sustainable weed management, herbicides are the central pillar of most weed management plans. Therefore, it is concerning that herbicide options are limited in the era of multiple HR weed populations. The discovery of herbicides with new sites of action is urgently needed (Dayan and Duke 2020), though in recent years, several herbicides with new potential targets have been discovered. For instance, fatty acid thioesterase (FAT) has been discovered as a target of cinmethylin with the potential for use in wheat, homogentisate solanesyltransferase (HST) has been discovered as a target of cyclopyrimorate with the potential for use in rice and dihydroorotate dehydrogenase (DHODH) has been discovered as a target of tetflupyrolimet with the potential for use in rice (Qu *et al.* 2021). For the future of herbicide discovery, several approaches have been introduced that can speed up the discovery process:

a. Develop active ingredients that inhibit dual or multiple target enzymes (Gressel 2020).
b. Use metabolomics to identify target enzymes, which on inhibition will accumulate (*in vivo*) phytotoxic metabolites or use proteomics to identify target sites that have low molecular concentration, allowing the use of low herbicide doses for killing weeds (Dayan and Duke 2020).

c. Develop molecules with binding sites on substrate recognition regions of the enzymes to create less frequent target site mutations or develop smart inhibitors that are self-adaptive and have conformational flexibility, which leads to lower vulnerability to resistance mutations (Qu *et al.* 2021).

d. Use innovative technologies, artificial intelligence, big data, *in vivo* and target-based high-throughput screening to identify novel herbicide molecules with the desired activity (Dayan 2019).

Weed management has become complex as weeds have evolved resistance to herbicides with multiple sites of action. With the prevalence of herbicide pre-mixtures and crops with multi-stacked herbicide-tolerant traits, the choice of herbicide and knowing which post-emergence herbicide to apply is critical. Therefore, it has become necessary to educate and guide farmers to make better decisions so they can effectively use available technology for long-term sustainability. Moreover, agronomists, crop advisors, and seed retailers who influence farmers' decisions should be trained about available herbicide options and weed management plans for specific scenarios in each farmer's field (Beckie *et al.* 2019). Additionally, farmers' feedback is crucial to tracking the occurrence of localized HR weeds; therefore, two-way communication with the significant involvement of growers through weed surveys, questionnaires, and other platforms is necessary for the future of HR weed management plan. Researchers have shown that the early detection or screening of herbicide resistance is possible, in some cases even at a large scale. For example, Kutasy *et al.* (2021) showed the potential of targeted amplicon sequencing (TAS) that uses the next generation sequencing (NGS) approach. They successfully detected two evolved TSR mutations that provided resistance to imazethapyr and linuron in *Ambrosia artemissifolia* L. (common ragweed) out of 16 specific point mutations that are identifiable with this approach. Similarly, Ma *et al.* (2015) demonstrated that an excised leaf assay can be used to detect NTSR due to enhanced herbicide metabolism in waterhemp (*A. tuberculatus*). Likewise, other screening tests such as leaf-disk assay using leaf disks (Wu *et al.* 2021), an agar-based assay using seeds (Perez *et al.* 2021), thermal infrared imagery (Shirzadifar *et al.* 2020a), spectral reflectance indices (Shirzadifar *et al.* 2020b) and Raman spectrometry using leaves (Singh *et al.* 2021) have been shown to screen putative resistance for many herbicides such as glyphosate, dicamba, clethodim, fomesafen and pyroxasulfone in several weed species. Thus, these new approaches, methods, tests, and techniques are available for detecting putative resistance early on, and hence can aid farmers in choosing only the most effective herbicides, reducing the overall use of herbicides and improving weed management. Herbicide resistance is an evolutionary process, and therefore the agricultural community needs to be proactive and keep evolving, adapting and developing new and effective solutions to the challenges posed by HR weeds. In conclusion, the future of herbicide resistance management should involve fewer herbicides and more integrated HR management options.

In the era of modern genetics and omics, many novel technologies hold promising solutions for HR weed management. Targeted genome editing technologies such as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) have the potential to develop non-transgenic crops with resistance to herbicides, which can bypass genetically modified organism (GMO) regulations in some countries such as Canada (Gosavi *et al.* 2022; Jhala *et al.* 2008). RNA interference (RNAi) is promising for restoring herbicide susceptibility; in RNAi, small RNAs (sRNAs) are sprayed on resistant weed populations, inducing gene silencing and ultimately herbicide sensitivity in the weed population (Zabala-Pardo *et al.* 2022). Similarly, gene-driving technology has the potential to restore weed susceptibility to herbicides that they had become resistant against (Perotti *et al.* 2020).

Figure 1. A female Palmer amaranth plant in a food-grade white corn field in southcentral Nebraska, USA with the potential to produce a significant number of seeds

Figure 2. Cereal rye cover crop residue acting as mulch and providing early season weed suppression in corn in eastern Virginia, USA

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OPINION ARTICLE

Weeds can help in biodiversity and soil conservation

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ABSTRACT

The sustainable production systems aim at conservation of both soil and ecological biodiversity. This change in research perspective has changed the view point on weeds, which was focused earlier mainly on eliminating their competition and detrimental effects on crop plants. This opinion article is focused on the positive role of weeds in soil conservation and maintenance of biodiversity. Weeds being a host for rhizobacteria, also act as a source of various nutrients and organic matter which helps in rejuvenating degraded soils and preventing soil erosion. The heavy metals presence detection in the soil and its remediation with weeds helps in sustainable quality production of food. Biodiversity of weeds describes the enormous variety of weeds present in the niche. Maintenance of its biodiversity is crucial as they have enormous potential to serve as genetic source for crop yield and quality improvement and for control of insect pests and diseases in major food crops. Weeds can be utilized for fencing the fields. Allelochemicals present in weeds can be utilized as biological agent for controlling other weeds and thereby minimizing dependency on herbicides for ecofriendly products. The appreciation of the role of weeds in maintaining soil and biodiversity conservation is a key to the sustainable agriculture development.

Keywords: Weeds adaptability strategies, Climate change, Soil remediation, Soil conservation, Weeds usage

Weeds are defined as unwanted and undesirable plants growing out of place. “Are the weeds really unwanted? or man’s greed for food crops makes them unwanted!” is the question that arises. Anything which is growing in nature must have its value as nothing is waste here. Weeds are thriving successfully as they are most adaptive and sustainable plants in nature (Rao and Chandrasena 2022). Why weeds are unwanted, reason being we have not yet explored the usefulness of such plants. The wider knowledge and adaptability of weeds for their beneficial aspects are unknown and need to be explored before blaming them as unwanted plants (Chandrasena 2023).

The currently cultivated crops were earlier opportunistic weeds but their cultivation as food crop after domestication expelled them out of the weed category. The cultivated crops have their weedy ancestors which were grown and domesticated due to promising evolutionary process and selection for potential food crops. *Secale cereale* was earlier a serious weed problem in North America over hundreds of years but in the early 1960s farmers cultivated rye for human consumption and now it is ranked as one of the world’s top 10 cultivated grain crops (Ellstrand *et al.* 2010). *Zea mays*, the cultivated maize was domesticated from *Z. mays* spp. *parviglumis* (Matsuoka *et al.* 2002); *Manihot esculenta* being a rich source of carbohydrate was domesticated from *Manihot esculenta* spp. *flabellifolia* (Allem *et al.* 2001). Even the world’s worst weed *Parthenium argentatum* acts as an alternative source of rubber for the *Hevea brasiliensis* and is known to be useful in several ways (Chandrasena and Rao 2019)

From ecological point of view, weeds are plants which modify the ecosystem of an area through changes in structure of soil while weeds are plants which reduce the productivity of land from the economic perspective; and weeds are non-native and disturb the local attributes from conservative point of view. Nature bestowed us with weed plants which have capability to overpower the natural and anthropogenic calamities. Weeds can uproot the major setbacks faced by society through their various positive aspects which can efficiently be explored for conserving soil and biodiversity.

Role of weeds in soil conservation

Soil is a fundamental component for sustaining life on earth. The soil degradation represents the loss to the natural capital assets and loss to ecosystem services of the nature (Dumanski and Peiretti 2013). Healthy ecosystem provides steady flow of environmental goods and services for steady flow of production system. The overexploitation of the resources results in considerable degradation of these

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natural assets and proving cut in production system. Traditional practices of production system involve ploughing and tilling of land which proves to be highly destructive as 24% of global agricultural land gets degraded due to regular tillage (Bai *et al.* 2008). For conserving soil, new paradigms centered on conserving and improving soil health focused on minimum tillage and conservation tillage aiming to maintenance of permanent soil cover (Cowe *et al.* 2011). Weeds can be used in better way for conserving vast variety of soils all over the world through various means which are analyzed below. This review focused on the positive role of weeds in conservation of soil and maintenance of biodiversity.

Site of rhizobacteria: The rhizosphere is a close interaction among the soil-plant-microorganisms continuum. The microbial biomass of the rhizosphere is determined by the composition of plant efflux which are particular in different plant species (Berg and Smalla 2009).The rhizosphere is enriched with photosynthates leaked from plant roots which are energy rich carbon compounds. The large availability of exudates in the root zone generally facilitates the much higher microbial activity and their biomass in the root zone of weeds. Sturz *et al.* (2001) observed maximum species related to genera *Bacillus* (155.6%) followed by *Arthrobacter* (76.4%), *Stenotrophomonas* (46.8%), *Acinetobacter* (40.9%) and *Pseudomonas* (38.2%) in the rhizosphere. The percentage of microbes present in root zone varied according to particular weed species, for example 19.4% of *Bacillus sphaericus* were observed in roots of *Echinochloa crus-galli*, 12.9% of *Pseudomonas chlororaphis* in roots of *Spergula arvensis*, 17.5% of *Stenotrophomonas maltophilia* in roots of *Solidago canadensis*, 7.5% of *Variovax paradoxus* in roots of *Lolium multiflorum*, 6.3% of *Arthrobacter ilicis* in roots of *Chenopodium album* and 14.5% of *Bacillus sphaericus* in roots of *Elymus repens*.

Rhizobacteria in the weed roots act as plant growth promoting agent through releasing volatile compounds and antibiotics like phenazine (Ryu *et al.* 2003, Chakraborty *et al.* 2009). Rijavec and Lapanje (2016) observed that HCN increases the solubility of phosphorus by metal chelation and sequestration in the rhizosphere. Rhizobacteria also produces siderophores which helps in iron sequestering for plants and delays senescence (Buyer *et al.* 1993). Plant hormones like gibberellins inûuences germination of seed and elongation of stem. Auxins like indole acetic acid (IAA) helps in root development and differentiation of tissues. The hydrolysis of ethylene precursor by 1-amino-cyclopropane1-carboxylate deaminase to lowers the ethylene level in plants, is well-reported mechanism for growth promotion by rhizobacteria (Glick *et al.* 2007, Saleem *et al.* 2007). Plant growth promoting rhizobacteria in the root zone of weeds can be utilized for plant growth and availability of nutrients in deficit soils for sustainable production.

Source of organic matter: Conventional agriculture aims at fulfilling nutrient requirement through fertilizers. However, the long-term nutrient availability is diminishing due to regular decrease in organic matter of soils (Riccaboni *et al.* 2021). Weeds can act as a source of organic matter for soil as these extract nutrient, moisture and light for production of carbohydrate. Sharda and Lakshmi (2014) reported that fresh plants of water hyacinth contain 95.5% moisture on weight basis together with 0.04% nitrogen, 0.06% phosphorous, 0.20% potassium and 3.5% organic matter. Biradar and Patil (2001) prepared vermicompost using weeds viz., *Parthenium hysterophorus*, *Cassia sericea*, *Achyranthus aspera* and *Euphorbia geniculata* which can act as a good source of organic matter. *Solanum melongena* when treated with vermicompost of *Eichhornia* along with 50% recommended dose of fertilizers was found to be superior as compared to vermicompost made of cow-dung. *Lantana camara* can also be used for preparing compost, and when 4t/ha of it was added in soil produces higher number of tillers/hills leading to higher grain yield of rice (Singh and Angiras 2005). Weeds can be used in soils with higher sand content to improve soil organic matter which positively affect absorption of nutrients and retention of water for better root growthin soil.

Source of plant nutrients: Weeds act as a source of nutrients and the recycling of weed biomass enriches the soil. *Chromolaena odorata* is rich in nutrient status mainly through leaves, stems, roots and bulbs. The N, P and K content in leaves (1.92, 0.18, and 1.42%), stem (0.78, 0.12, and 1.98%), roots (1.42, 0.02, and 1.18%) and bulbs (0.48, 0.06, and 0.39%) of *Chromolaena odorata*, a tropical and subtropical weed found mainly in Africa make it a better source of nutrients (Mbalila 2015). *Tithonia* has lower percentage of lignin (6.5%) and polyphenol (1.6%) while considerably higher percentage of nitrogen (3.5%), phosphorus (0.37%) and potassium (4.1%) contents (Jama *et al.* 2000). Higher N fixation from weedy grasses like *Brachiaria humidicola*, *Paspalum notatum* and *Panicum maximum* was observed which derives upto 40% of their N requirement through fixation (Olivares *et al.* 1996). *Leptochloa fusca* in Pakistan has shown high nitrogen fixation activity (Malik *et al.* 1997). Aquatic weeds have gained considerable amount of attention for nutrients contribution [such as N, P and K of water hyacinth (1.86, 0.36, 3.35%), *Potamogeton* spp. (2.51, 0.33, 2.28%), *Pistia stratiotes* (2.1, 0.30, 3.5%), *Hydrilla* spp. (2.7, 0.28, 2.9%), *Ceratophyllum* spp. (3.3, 0.47, 5.9%)] (Roger and Watanable 1984). The use of weeds as a source of nutrient can lessen the dependency on the synthetic fertilizers during period of shortage and lessens the fate of fertilizers.

Indicator and phyto-remediation of heavy metals in soil: Heavy metals [viz. arsenic (As), mercury (Hg), cadmium (Cd), lead (Pb), zinc (Zn), chromium (Cr), copper (Cu) and nickel (Ni)]are naturally occurring materials in soil. Heavy metals are normally present due to either regular climatic cycles or human exercises (He *et al.* 2005, Li *et al.* 2009). In biological systems, soil formation from ultramafic rocks and ore minerals are source of heavy metals (Szyczewski *et al.* 2009). Various anthropogenic sources i.e., vehicular traffic, refining processes and mining exercises contribute to heavy metal contamination (Kabata-Pendias and Mukherjee 2007). Rising urbanization and industrialization have brought about accumulation of heavy metals in ecosystem (Charlesworth *et al.* 2011, Wang *et al.* 2014, Ahmad *et al.* 2016). Since heavy metals are not degradable, these gradually collect in soil, turning out to be possibly hazardous to terrestrial and aquatic biological systems (Tchounwou 2012, Melucci *et al.* 2018). Heavy metals affected the microbial population and plant growth directly through damaging cell structures due to oxidative stress and inhibition of cytoplasmic enzymes (Jadiaand Fulekar 2009). Reduction in root and shoot growth of wheat plant was observed at 5 mg/l concentration of cadmium (Ahmad *et al.* 2012).

Biomonitoring techniques using indicator plants are used to recognize heavy metals in soil and environment (Zereini *et al.* 2007). Mosses and lichens, for instance, are known to be the most sensitive indicator of atmospheric contaminations, consequently they are extensively utilized in metropolitan climate (Jiang *et al.* 2018). Weeds emerged as a new source for indication of heavy metals, *viz. Taraxacum officinale* L. and *Trifolium pratense* L. accumulated higher concentration of Cu which depends linearly with amount of copper present in soil. *Plantago major* L. accumulated small fraction of Mn (5-10%) in its leaves while presence of *Urtica dioica* L. and *Trifolium pratense* L. indicated Pb in the soil (Malizia *et al.* 2012, Galal and Shehata 2015). Indication of heavy metals using weeds appears to be easily accessible method to prevent transfer of heavy metals across several trophic levels of the food chain.

Phyto-remediation of heavy metals can be done through phyto-extraction, phyto-stabilization and phyto-volatilization. Phyto-extraction is the accumulation of heavy metals indifferent plant parts and it can be done by using weeds which are hyper-accumulators [high metal accumulating (10-500 times)] and/or heavy biomass accumulator (high metal mobilizing capacity) (Salt *et al.* 1998). Hyper-accumulator plantshave hyper-tolerance by compartmentalization of heavy metals ions in the cell wall or by excluding metals from plants (Garbisu and Alkorta 2003). Reeves and Baker (2003) have given examples of different weeds which act as heavy metal accumulators viz. *Minuartia verna* (Pb hyper-accumulators), *Aeollanthus subacaulis* (Cu hyper-accumulator), *Thlaspi tatrense* (Zn hyper-accumulators), *Haumania strumrobertii* (Co hyper-accumulator), *Dichapetalum gelonioides* (Ni hyper-accumulators) and *Maytenus bureaviana* (Mn hyper-accumulator).

Phyto-stabilization helps in immobilization of the heavy metals by sorption, precipitation or complexation (Jadia and Fulekar 2009) through their root system. Plants characterized with ability to tolerate soil conditions, dense rooting system, rapid growth to complete coverage can act as phyto-stabilizing agent for heavy metals. Under well manured soil conditions, *Solanum nigrum* reduced Zn percolation through soil by 80% (Marques *et al.* 2008). Phyto-volatilization involves the uptake of pollutant from the soil which get volatilized and transpired into the atmosphere. Genetically engineered plants like *Arabidopsis thaliana* and *Liriodendron tulipifera* with mercuric reductase merA and merB can detoxify organic mercury (methyl-Hg ion) to less toxic elemental Hg, and are used for phyto-volatilization of mercury from soil (Rock *et al.* 2000). In heavily infested soils with heavy metals, weeds can be used to protect the ecosystem with good efficacy being cost effective method which can aid researchers and policymakers for future eco-friendly research.

Rejuvenating saline soils: Basophile weeds like *Prosopis julifera*, *Paspalum vaginatum*, *Sesuvium portulacastrum*, *Cressa arecta*, *Salsola* spp. and *Sporobolus diander* are dominant in saline soils and alkaline soils. Halophyte plants can grow in saline soils and have a mechanism of compartmentation of ions in the vacuoles of cell (Gorham 1995). Such weeds can be allowed to grow in salt-affected soils. These will add organic matter and humus to soils which diverges the earlier barren soils to productive land which can revolutionize the concept of rejuvenating the degraded soils. *Suaeda maritima* reduces the electrical conductivity (EC) from 4.9 to 1.4 ds/m and accumulated 504 kg/ha NaCl in 120 days. Similarly, *Sesuvium portulacastrum, Clerodendron inerme, Heliotropium curassavicum* and *Ipomoea pes-caprae* reduced EC from 4.9 to 2.5, 4.7 to 3.08, 4.8 to 2.6 and 4.8 to 3.56, respectively and removed 473.93, 325.18, 359.5 and 301.46 kg/ha NaCl, respectively in 120 days (Ravindran *et al.* 2007). *Leptochloa fusca* and *Prosopis julifera* decreased soil EC from 2.20 to 0.42 (Singh *et al.* 1989). Globally, soil is salt-affected on 17 million km^2 area which can be reclaimed using weeds. Weeds are efficient extractor of salts from soil because of their small life span, many cohorts per season and germination over variable environments.

Controlling soil erosion: Soil erosion occurs due to different climatic (serious dry spell occasions) and human factors (overgrazing of rangelands) which reduces land use efficiency (Reynolds and Smith 2002). Extensive root system of weed plants prevent soil from water erosion while above-surface growth prevents soil from wind erosion. Weeds intercept raindrops which reduce the impact of water on soil surface.Weeds also maintains the infiltration of water which reduces the crusting of soil surface. Shallow rooted weeds such as *Echinochloa* spp., *Digitaria* spp., *Bromus* spp., *Cynodon dactylon*, *Glechoma hederacea, Stellaria media* prevent soil erosion (Vannoppen *et al.* 2015). Weeds act as mulch on barren soil or sloppy areas or areas with high wind velocity and thus, prevent its erosion.

Role of weeds in biodiversity conservation

Biodiversity is variability among living organisms (terrestrial and aquatic diversity) and ecological complexes (within species, between species and ecosystem) (Penuelas *et al.* 2020). Biodiversity within different species is declining over the past 60 years due to either natural or man-mademalfunctioning in the ecosystem (Tittensor *et al.* 2014, Penuelas *et al.* 2020). Weed biodiversity is an indicator of agronomic and environment sustainability and is essential to buffer the negative impact of weeds on ecosystem and resistance evolution (Storkey and Neve 2018). The presence of more diverse weed community within a niche prevent competition. The continuous suppression of weeds either biologically or chemically have posed a threat to genetic diversity of species forbidding food webs and ecosystem services like pollination (Blaix *et al.* 2018). A diverse weed flora provides wide spectrum of seeds which had positive impact on food web interactions (Harvey *et al.* 2008). Weeds may-provide support for maintenance of biodiversity and ecosystem stability.

Donor of useful genes to crops: The knowledge of genetics, organic chemistry and crop physiology is used in improving varietal traits such as resistance against herbicides and pests (Shuqin and Fang 2018). Weeds act as a plant genetic resource as they are important unit for natural selection and adaptation. Weeds can be used for crop improvement for stress tolerances (viz. salt tolerance, drought tolerance, submergence tolerance, temperature tolerance, heavy metal tolerance, herbicide tolerance, disease and insect resistance). *Diplachne fusca* is perfect example for imparting salt tolerance as these plants comprise of micro-hairs on leaves which secrete salts from the leaf surface to protect it from salts (Céccoli *et al.* 2015).Seeds of *Echinochloa crus-galli* germinate and grow under anaerobic conditions due to its resilience to ethanol and the capacity to utilize key substrates (Céccoli *et al.* 2015). *Cicer reticulatum* have enhanced thermo-tolerance (Hajjar and Hodgkin 2007). Triazine resistant weed biotype of the *Brassica campestris* was found which is used to produce herbicide resistant crops (Beversdorf and Kott 1987). Lr9 gene from *Aegilops umbellulata* and Lr19 and Lr24 from *Agropyron elongatum* were used to produce rust resistant wheat in India (Reddy *et al.* 1996). *Echinochloa crus-galli* has two novel proteins viz. Ec-AMP-D1 and Ec-AMP-D2 which were isolated and used against several fungus (Odintsov *et al.* 2008). The loss of mutation in the main shattering gene of seed such as SH1 in sorghum and its rice orthologs was considered for non-shattering phenotypes. The CRISPR-Cas9/ base editing was suggested to be potentially utilized in the weeds and implemented on rice to cause single nucleotide polymorphism in the regulatory element of qSH1 gene to emulate the shattering loss (Konishi *et al.* 2006; Li *et al.* 2019). Weeds act as reservoir of germplasm that functions as an important source of genes for tolerating biotic and abiotic stresses in crop plants aiming crop improvement in terms of fitness and lesser yield penalty.

Control of insect-pests: Weeds act as reservoirs of beneficial insects and these provide physical shelter, pollen, nectar and water to diverse insects. Wolcott (1928) removed the weeds under tropical climatic conditions and observed increase in crop damage by insect-pests. In a weed-free monocropping system, a large number of sprays were used to control cotton bollworm as compared to weedy system (Hillocks 1998). All these examples favour that weeds act as a host for natural enemies of insect-pests and keep the pest population below economic threshold level (ETL). Weeds on field margins act as conservation area for beneficial insects in Europe (Marshall 1988). In Uganda, *Cissus adenocaulis* was exploited as a trap crop for controlling cotton pest *Taylorilygusv osseleri*. Insecticidal effects of lemon grass oil constituents were observed against *Trichoplusia ni* (Tak *et al*. 2016). Additionally, combination of thymol, linalool and p-cymene were obtained from *Thymus vulgaris* and resulted mixtures have shown synergistic insecticidal activity by targeting the third instar larva of the *Spodoptera littoralis* (Pavela 2014). Weeds being a feeding ground of insect-pests have a positive impact on crop productivity. Beneficial insects may predate on weeds for maintaining their population. The biocontrol methods for sustainable control of weeds can be explored by utilizing this aspect of weeds.

Allelochemicals as biological agents: *Lantana camara* plants repels other plants due to major toxins such as Lantadene A (52%), lantadene B (50%) and salicylic acid (37%) present in it (Singh *et al.* 2012). *Lantana camara* leaf extract contains gentisic, vanillic, salicylic acid, â-resorcylic acid, coumarin, ferulic, caffeic, 6- methyl coumarin and p-hydroxybenzoic acids (Yi *et al.* 2005). Seed germination requires production of gibberellic acid which regulates the synthesis of á-amylase enzyme (starch degrading enzyme). Extract of *Lantana camara* inhibits the production of gibberellins to prevent the synthesis of á-amylase enzyme and inhibit seed germination of certain weeds. *Lantana camara* plants inhibits the germination of *Echinochloa* spp. by 95% (Anaya *et al.* 1997). *Lantana camara* aqueous extract inhibited the growth of *Eichhornia crassipes, Melilotus alba and Lolium multiflorum* (Mishra 2015). *Parthenium hysterophorus* showed inhibition of root length, shoot length, fresh weight, dry weight and leaf area due to leachates from *Lantana camara* (Mishra 2012). These allelochemical properties of weeds can be used as a source of natural weed checking agent under controlled conditions under organic farming system. In a study, the allelopathic effect of *Ficus nitida* was studied against *Corchorus olitorius* and *Echinochloa crus-galli* by mixing leaf powder to soil or by foliar spray. It was reported that with increase in concentration of *F. nitida* extract, bio-herbicidal potential was observed to be increased (El–Wakeel *et al.* 2023).

As fields Fencing: Weeds being hardy, persistent and prolific seed producer can be used for fencing. Live fencing around the agricultural field is done by planting trees or shrubs or bushes. *Lantana camara* can efficiently be used as fence weed along with its beautiful inflorescence which can serve as aesthetic purpose to the landscape. Spinous species of weeds viz. *Euphorbia antiquorum, Euphorbia neriifolia, Euphorbia nivulia, Cereus peruvianus*etc can efficiently be used as fencing (Subrahmanya and Raveendran 2010). However, utmost care should be taken that these weed plants (used as fencing) should be properly monitored and checked for dissemination of seeds/vegetative propagules. The use of weeds for fencing the crop field against biotic (fungi, bacteria, nematode and viruses) and abiotic stresses (unusual temperature, high wind, drought and salinity) can be explored for sustainable crop production.

Nematicidal properties: *Solanum nigrum* and *Datura stramonium* contains various allelochemicals *viz*. phenolic acids, terpenes, alkaloids and flavonoids *etc*. which can efficiently be used to control nematodes (Zhou *et al.* 2012, Sher *et al.* 2015). The plant extract preparation has nematicidal activity which don't have any adverse effect on non-target organism (Oplos *et al.* 2018). Compounds such as 4-quinolone waltherione and waltherione A inhibits egg hatching and have larvicidal activity against *M. incognita* (Jang *et al.* 2015). Leaf extracts of *Andropogon gayanus, Phyllanthus amarus, Euphorbia hirta, Sida acuta* and *Cassia obtusifolia* resulted in 100% control of *Meloidogyne incognita* (Olabiyi *et al.* 2008). Weed with nematocidal properties can be used as cover crop and intercrops in between the main crops.

Other uses: Vegetatively propagated weeds like *Sorghum halepense*, *Cynodon dactylon*, *Saccharum spontaneum* grown along roadsides, railway tracks, waste lands provide fodder, aesthetic and industrial purposes. *Saccharum spontaneum, Saccharum arundinaceum*, *Spartina alternifolia*, *Erianthus arundinaceus*, *Miscanthus sacchariflorus* and *Phragmites australis* contain high quality lingo-cellulose fiber which can be used as raw material for paper making industry (Chandrasena 2014). Large amount of cellulose is present in *Ageratum adenophora* which is used in china for making fiber board (Kim *et al.* 2007). In Asian-Pacific countries, *Eichhornia crassipes* biomass is used as raw material for pulp and paper industry. *Jatropha curcas*, *Arundo donax*, *Thlapsi arvense* are used as raw material for biodiesel as primary product while methane and ethanol as secondary product (Chandrasena 2014). *Saccharum spontaneum* act as repositories of diverse valuable genes for sugarcane (Pandey *et al.* 2015). Various plausible ways to use weeds for sustainable agriculture are depicted in **Figure 1**.

Way forward in attitude toward weeds

Weeds are undesired intruders in the agroecology as they compete for resources like moisture, nutrients, light and space which make them undesirable for the crops. Weeds are phenotypically plastic and genetically labile. Weeds have many harmful effects and conventional agriculture aims at controlling weeds rather than maintaining it. Weeds can be used as organic source, either by directly incorporating these in soil before seed setting or by

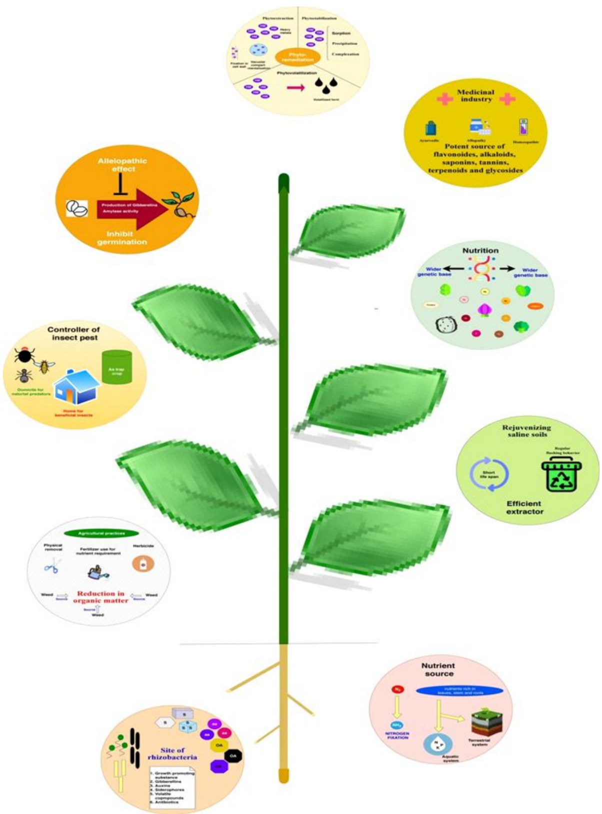

Figure 1. Possible ways of weeds utilization for sustainable agriculture development

preparing compost. However, weeds are not real offender, but are traits of other problems such as overgrazing, monoculture and clean cultivation. Most of publications address the drawback of weeds and advocate for weed control. Much extensive works was carried out in sustainable management of weeds by classical and modern approaches for weed management, whereas very little attentive work has been carried out in the field of weed importance. It is the time to change the mindset of controlling weeds and to recognize the biological aspect of weeds in a way forward. Utilization of different weeds for biodiversity, soil conservation and other positive roles of weeds will help in sustainable agriculture.

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REVIEW ARTICLE

A review on weed management in millets

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ABSTRACT

In recent years, millets have been recognized as nutri-cereals and given much needed impetus for their cultivation by national and international policies. Millets are cultivated mostly under rainfed conditions and under-nourished soils which makes them more susceptible to weed competition losses. Grasses, sedges and broad-leaved including parasitic weed *Striga* infest millet crops. Weeds cause millets yield reduction of 15-97%. It is essential to control weeds during the critical period of crop-weed competition which may be 15-42 days after sowing. Weed management in millets mostly relies on the cultural and mechanical methods due to lack of selective herbicides for usage in these crops, especially the minor millets. Integration of several methods is required to obtain optimum weed management and millet crops yield. Weed competitive crop varieties, reduced spacing, optimum fertilizer dose and placement, mulching with crop residues, inter-cropping, cultural and mechanical methods and use of selective herbicides is the appropriate strategy for weed management in millets. *Striga* management through resistant varieties, crop rotation, catch crops, herbicide use and herbicide resistant varieties may be opted based on the suitability of the methods.

Keywords: Millets, Sorghum, Pearl millet, Finger millet, Kodo millet, Barnyard millet, Foxtail millet, *Striga*, Weed management

INTRODUCTION

Millets are a group of small seeded cereal crops cultivated for grain and fodder purposes. They are considered to be the earliest domesticated crops in human civilization. The earliest domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago (Lu 2009). Mostly, millets are cultivated in parts of tropical and semi-arid regions of the world. These crops are an important source of food and fodder for millions of resource-poor farmers in the world. There are several types of millets, categorized as major, minor and pseudo-millets (**Table 1**). In India, during the past 50-60 years their cultivation and consumption has reduced due to availability of high yielding varieties of rice and wheat and changes in food habit. However, in recent years, owing to their high nutritional values, low glycemic index, awareness to millets as nutri-cereals has increased and they are in high demand again. Millets are climate-resilient crops highly tolerant to drought stress and high temperature, also they need less inputs and management. Therefore, under the changing climate scenario, these crops are more suited to arid and semi-arid regions. India is the leading millet producing country with a share of around 80% of Asia's and 20% of the global production (FAO 2021). Among millets, pearl millet has the highest area of cultivation followed by sorghum and finger millet (**Table 2**). There is ample scope to enhance the area of millet cultivation under different agro-ecological zones based on suitability to climate.

In spite of high yield potential of some of the small/minor millets like finger millet, kodo millet and barnyard millet, the productivity is still quite low, which needs to be increased through development and adoption of better genotypes and improved management practices. Cultivation of millets is beset with many biotic constraints; weeds are the major

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Table 1. Diversity in millets

Scientific name	Common name	Local name
Major millets		
Sorghum bicolor (L.) Moench	Sorghum/Great millet	Jowar
Pennisetum glaucum L.	Pearl millet	Bajra
Minor millets		
Eleusine coracana L. Gaertn.	Finger millet	Ragi, Mandua
Paslpalum scrobiculatum L.	Kodo millet	Kodon
Echinochloa frumentacea L.	Barnyard millet	Sanwa
Panicum sumatrense Roth ex. Roem. and Schult.	Little millet	Kutki
Setaria italica L.	Foxtail millet	Kakun
Panicum miliaceum L.	Proso millet	Chena, Barri
Panicum ramosa L.	Brown-top millet	Korale
Pseudo-millets		
Fagopyrum esculentum L.	Buckwheat	Kuttu
Amaranthus viridis L.	Amaranthus	Chaulai

Table 2. Area, production and productivity of millets in India (2020-21)

Crop	Area (mha)	Production (mt)	Yield (kg/ha)
Pearl millet	7.65	10.86	1420
Sorghum	4.38	4.81	1099
Finger millet	1.16	1.99	1724
Other minor millets	0.44	0.35	781
Total	13.63	18.01	

(Source: https://apeda.gov.in/apedawebsite/index.html)

ones. Therefore, an understanding of the nature of weed problems and their possible management options is very important. In this paper, the recent information on various aspects of weed management in millets has been reviewed.

Weed flora infesting millets

Millets are generally grown in rainy season which favours abundant growth of weeds. All types of weeds, *viz*. grasses, sedges and broad-leaved infest the millet crops during their early phase of growth (**Table 3**). The weed flora infestation, their intensity of competition with the crop varies with the geographic regions, soil and weather conditions and also the field and crop management practices (Stahlman and Wicks 2000; Mashingaidze *et al*. 2012). *Echinochloa colona* (L.) Link. (jungle rice), *Echinochloa crus-galli* (L.) Beauv. (barnyard grass), *Eleusine indica* (L.) Gaertn. (goose grass), *Digitaria sanguinalis* (L.) Scop. (crab grass) and *Sorghum halepense* L. Pers. (johnson grass) among grasses; *Amaranthus palmeri* S. Wats (Palmer amaranth), *A. retroflexus* L. (Redroot pigweed), *Celosia argentea* L. (white cock's comb), *Trianthema portulacastrum* L. (horse weed), *Tribulus terrestris* L. (puncture vine), *Boerhaavia diffusa* L. (hog weed), *Acanthospermum hispidum* DC (Bristly starbur) among broad-leaved; *Cyperus rotundus* L. among sedges, and *Striga asiatica* (L.) Kuntze. and *S. hermonthica* (Del.) Benth. (Witch weed) are the most common weeds of millets worldwide. In sorghum, grasses i.e., *Echinochloa*, *Panicum*, *Digitaria*, and *Sorghum halepense* are considered to be the most common and troublesome weeds (Limon-Ortega *et al.* 1998; Peerzada *et al.* 2017). Carpetweed (*Trianthema portulacastrum*) was also reported to be the dominant (more than 28%) weed in pearl millet crop (Deshveer and Deshveer 2005). Girase *et al.* (2017) recorded grassy weeds like *Cynodon dactylon, Brachiaria eruciformis*; broad-leaved weeds like *Parthenium hysterophorus, Commelina benghalensis, Celosia*

Table 3. Major weeds in millet crops

Crop	Major weeds	References
Sorghum	*Sorghum halepense* (L.) Pers., *Ipomoea purpurea* (L.) Roth., *Amaranthus* spp., *Digitaria sanguinalis* (L.) Scop., *Echinochloa crus-galli* (L.) P. Beauv., *Sida spinosa* (L.), *Urochloa platyphylla* (Nash.), and *Senna obtusifolia* (L.) Irwin and Barne	Smith and Scott 2010
	Echinochloa crus-galli, Cynodon dactylon, Sorghum halepense, Digitaria sanguinalis, Amaranthus viridis, Alternanthera pungens, Digera arvensis, Convolvulus arvensis, Vernonia cinerea, Eclipta alba, Trianthema portulacastrum, Euphorbia hirta, Physalis minima and *Cyperus rotundus*	Verma *et al.* 2018
Pearl millet	*Trianthema portulacastrum, Tribulus terrestris, Cyperus rotundus, Amaranthus viridis, Amaranthus spinosus, Cyperus compressus, Euphorbia* spp., *Echinochloa colona* and *Cynodon dactylon*	Deshveer and Deshveer 2005
	Cynodon dactylon, Echinochloa crus-galli, Brachiaria ramosa, Eluropus villosus, Amaranthus viridis, Digera arvensis, Euphorbia hirta, Boerhaavia diffusa, Acanthospermum hispidum, Commelina benghalensis, Portulaca oleracea and *Cyperus rotundus*	Mathukia *et al.* 2015
	Cynodon dactylon, Brachiaria eruciformis, Parthenium hysterophorus, Commelina benghalensis, Celosia argentea, Panicum isachne, Amaranthus viridis, Euphorbia microphylla, Phyllanthus niruri, Alteranthera triandra and *Cyperus rotundus*	Girase *et al.* 2017
Finger millet	*Cyperus rotundus* L. *Cynodon dactylon* (L.) Pers. *Commelina benghalensis* L. *Ageratum conyzoides* L. *Dactyloctenium aegyptium* (L.) Willd. *Echinochloa colona* (L.) Link, *Digitaria marginata* Stapf, *E. indica. Acanthospermum hispidum* DC. *Spilanthes acmella* (L.) Murray, *Eragrostis pilosa* (L.) *P. Beauv. Parthenium hysterophorus* L. *Amaranthus viridis* L. *Alternanthera sessilis* (L.) R. Br. ex DC. *Celosia argentea* L. *Euphorbia hirta* L. and *Leucas aspera* (Wild.) Link, *Ocimum canum* Sims	Rao 2021
Kodo millet	*Brachiaria reptans, Acrachne racemosa, Dactyloctenium aegyptium, Panicum repens* under grasses, *Cyperus rotundus* under sedge and broad-leaved like *Trianthema portulacastrum, Boerhaavia diffusa, Parthenium hysterophorus, Digera arvensis* and *Tribulus terrestris*	Vinothini and Arthanari 2017
	Cyperus rotundus, Cynodon dactylon, Brachiaria ramosa, Chloris barbata, Dactyloctenium aegyptium, Digitaria marginata, Eleusine indica, Echinochloa colona, Ageratum conyzoides, Alternanthera sessilis, Commelina benghalensis, Cinebra didema, Euphorbia hirta and *Syndrella nodiflora*	Lekhana *et al.* 2021
Little millet	*Echinochloa colona, Enhinochloa crus-gulli, Dactyloctenium aegyptium, Eleusine indica, Setaria glauca, Cynodon dactylon, Cyperus rotundus, Celosia argentea, Commelina benghalensis, Phyllanthus niruri, Solanum nigrum* and *Amaranthus viridis*	Chapke *et al.* 2020
Barnyard millet	*Echinochloa colona, Echinochloa crus-galli, Dactyloctenium aegyptium, Eleusine indica, Setaria glauca, Cynodon dactylon, Phragmites karka, Cyperus rotundus, Sorghum halepanse, Celosia argentea, Commelina benghalensis, Phyllanthus niruri, Solanum nigrum* and *Amaranthus viridis*	Chapke *et al.* 2020
Foxtail millet	*Echinochloa colona, Cynodon dactylon, Echinochloa crus-galli, Eleusine indica, Dactyloctenium aegyptium, Sorghum halepense, Amaranthus viridis, Commelina benghalensis, Celosia argentea, Phyllanthus niruri, Solanum nigrum* and *Cyperus rotundus*	Prabhakar *et al.* 2017

argentea, Panicum isachne, Amaranthus viridis, Euphorbia microphylla, Phyllanthus niruri, Alternanthera triandra; and sedge *Cyperus rotundus* in pearl millet. In the U.S. central Great Plains, Reddy *et al.* (2014) reported Canada thistle [*Cirsium arvense* (L.) Scop.], kochia [*Kochia scoparia* (L.) Schrad.], redroot pigweed (*Amaranthus retroflexus* L.), green foxtail [*Setaria viridis* (L.) Beauv.], and palmer amaranth (*Amaranthus palmeri* S. Watson) as the most common troublesome weeds interfering with millet crops. *Striga* is a major biotic constraint that causes considerable crop damage in millets in the semi-arid tropics. *Striga hermonthica* is a serious weed in the dry savannas of sub-Saharan Africa. Striga infestation in sorghum is reported to be higher in Nigeria than in other West African countries with about 80% of land cropped to sorghum infested by this weed (Mamudu *et al.* 2019).

Losses due to weeds

Weeds successfully compete with the crop, harbour insect pests, and create problems at harvest (Zimdahl 1999, Ottman and Olsen 2009). They compete with crop plants for nutrients, water, sunlight and space, thereby inflict huge loss in soil nutrients and crop yields. The extent of yield loss depends upon the weed flora, time of infestation, soil type, rainfall and management practices followed. In pearl millet, loss in yield of 27.6% was reported from 72 trials at farmer's fields, in sorghum, 23.5–27.4% actual yield losses were observed in the farmers' fields whereas, 35–50% potential yield losses were recorded in weedy condition (Gharde *et al.* 2018). Sharma and Jain (2003) reported up to 40% loss in grain yield due to weed competition in pearl millet. Weeds are a major constraint decreasing the yield and quality of sorghum (Geier *et al.* 2009). In the early development stages, sorghum plants are relatively small, fragile and has slow growth (Silva *et al.* 2014). Competition with weed at this stage is quite critical, and if control measures are not taken in the first few weeks after the emergence of sorghum plants, grain yield can be reduced by around 35-70% (Rodrigues *et al.* 2010). Losses in grain yield from 15 to 97% in sorghum under different climatic conditions were reported by Peerzada *et al.* 2017. In finger millet, loss in yield could be in the range of 5-70% (Prasad *et al.* 1991, Kumara *et al.* 2007, Rao and Chauhan 2015, Mishra *et al.* 2016, Rama Devi *et al.* 2021). In central India, the yield loss due to weeds in finger millet was estimated to be 46.6 to 68.1%, in kodo millet 56.6 to 67.3%, in little millet 59.6% and in barnyard millet it was 63.5% (ICAR-DWR 2021).

Weeds may remove 29.94–51.05, 5.03–11.58 and 48.74–74.34 kg/ ha nitrogen, phosphorus and potassium, respectively from the soil in sorghum crop (Satao and Nalamwar 1993). The nutrient depletion by weeds in pearl millet was up to 61.8 kg N, 5.6 kg P and 57.6 kg K/ha (Ram *et al.* 2004).

Weeds also act as alternate host of pest and diseases of millets. The rust, smut, ergot and downy mildew pathogens of various millets infect weed species like *Cynodon dactylon, Sorghum halepense, Oxalis corniculate, Digitaria marginata, Pennisetum* sp. and *Eragrostis tenuifolia* and help them overwinter (Frederiksen 1984; Marley 1995; Reed *et al.* 2000). Sorghum shoot fly (*Atherigona soccata*) and gall midge (*Stenodiplosis sorghicola*) infest weeds like *Brachiaria distachya, Panicum repens, Setaria intermedia, Cyperus rotundus* and *Sorghum halepense* and survive therein until new crops come (Nwilene *et al.* 1998, Bilbro 2008).

Crop-weed competition

The type of weed, crop varieties, row spacing, placement of fertilizer, soil moisture availability decides the nature of crop-weed competition. Critical period of crop-weed competition defines the maximum period weeds can be tolerated without affecting final crop yields (Zimdahl 1980). Weeds must be removed within this period to reduce the crop losses. This critical period in millets is usually 15-42 days after sowing (**Table 4**). Variations in temperature and carbon dioxide levels are likely to have significant influence on weed biology and crop-weed interactions. Ziska (2001) observed that the vegetative growth, competition and potential yield of sorghum (C_4) could be reduced by co-occurring of common cocklebur (*Xanthium strumarium*), a C_3 weed, as the atmospheric CO_2 increases. Ziska (2003) observed that in a weed-free environment, increased CO_2 significantly increased the leaf weight and leaf area of sorghum but no significant effect on seed yield or total above-ground biomass relative to the ambient CO_2 concentration. An increase in velvet leaf biomass in response to an increasing CO_2, reduced the yield and biomass of sorghum. Watling and Press (1997) studied the effects of CO_2 concentrations (350 and 700 µmol/mol) in sorghum

Table 4. Critical period of crop-weed competition in millets

Crops	Critical periods (days after sowing)	References
Sorghum	28–42	Sundari and Kumar 2002
Pearl millet	15-30	Labarada *et al.* 1994
Finger millet	25–42	Sundraesh *et al.* 1975

with and without *Striga* infestation. They observed that a high CO_2 concentration resulted in taller sorghum plants, and greater biomass, photosynthetic rates, water-use efficiencies and leaf areas; and lower *Striga* biomass/host plant.

Weed management methods

Cultural methods: Cultural practices like tillage, crop rotation, competitive crop varieties, reducing row spacing, increasing seed rate, mulching, timing of fertilizer application and placement techniques, all these helps to reduce the crop-weed competition. The cultural techniques, like reduced row spacing, increase the crop ability to compete for incoming light more efficiently (Grichar *et al.* 2004). Narrow row spacing (<30cm) was found beneficial in reducing weed competition and increasing yield of foxtail and proso millets (Nelson 1977, Agdag 1995). Varietal differences exist for weed competitiveness within a crop. Integration of competitive crop cultivar can be good strategy to suppress weed growth. In sorghum, cultivars 'CSH 16', 'CSV 20' and 'SPV 462' have been identified as weed suppressive (Mishra *et al.* 2014). Intercropping of compatible crops not only helps in suppression of weeds but also gives additional yield. Intercropping of blackgram and greengram in pearl millet significantly reduced the density as well as biomass of weeds and also realized higher net returns, B:C and income equivalent ratio in comparison to sole crop of pearl millet (Mathukia *et al.* 2015). Crop residue mulching in millets is an effective method to control the annual weeds.

Mechanical methods: Mechanical weed management is one of the effective weed management practices followed in cultivation of millet crops. The mechanical weeding involves handheld tools to the most advanced vision-guided hoes (Hussain *et al.* 2018). However, the hand weeding or inter-row cultivation are the most widely practiced methods for millet cultivation. Among the different operations used for cultivating the millet crops, the weeding and inter-cultivation operations are most energy expensive and involve more drudgery (Gowda *et al.* 1999). Usually the inter-cultivation operation performed two to three times at 10 to 15 days interval depending up on the weed pressure and field condition. However, the inter-cultivation operation followed by hand weeding was found to be effective in controlling the weeds (Gowda and Dhananjaya 2000).

Hand hoeing and blade harrowing are the most effectively followed method for weeding in pearl millet. First weeding should be done at 20-25 DAS and should be repeated every two weeks up to 45 DAS for effective weed control (Yadav 2012). Cuerrier *et al.* (2009) used mechanical harrowing to control the weeds in grain pearl millet and forage pearl millet, when weeds are at 3 to 5 leaf stage. The weeding was done by cutting the soil 3 to 4 cm deep using Tine harrow (Hatzenbichler, Austria). The harrow had adjustable flexible tines with working width of 1.5 m. The operational speed was adjusted according to the weed pressure and strength of the tines. In barnyard millet (*Echinochloa frumentacea*) the weeds could be effectively controlled by using a mechanical weeder integrated with hand weeding under rain-fed conditions (Shamina *et al.* 2019). Gowda and Dhananjaya (2000) conducted a comparison study between the improved tools with traditional hoe for weeding in finger millet. Improved blade hoe and improved bent type sweep hoe performed better, controlled the weeds effectively conserved the soil moisture at flowering and grain filling stages; yielded highest grain yield compared to traditional hoe. A blade type engine operated mechanical weeder was developed to perform weeding in finger millet; it could cover 2-4 rows at a time and had very good weeding efficiency. The developed weeder was able to perform weeding operation in crop having a plant height up to 30 cm. The weeding efficiency varied from 85 to 88%, plant damage varied from 2.5 to 3.6%, field capacity varied from 0.11 to 0.14 ha/h and weeding cost in developed weeder varied from Rs. 447.42 to 572 per hectare (Shrinivasa *et al.* 2017).

Herbicide use in millets

Herbicides are an important component of weed management strategy in crops. While proper seedbed preparation and cultivation before planting can help to control early-season weeds, selective pre-emergence soil residual herbicides are often necessary (Vanderlip *et al.* 1998). Due to scarcity of herbicides registered for millets, options for chemical control of weeds in this group of crops are not many (**Table 5**). Herbicides have been most effective in millets when supplemented with one hand weeding. The five best herbicide treatments in terms of weed control and grain sorghum yield were quinclorac, atrazine + dimethenamid-p, S-metolachlor followed by (*fb*) atrazine + dicamba, dimethenamid-p *fb* atrazine, and the standard treatment of S-metolachlor + atrazine *fb* atrazine (Bararpour *et al.* 2019). Pimentel *et al.* (2019) verified that post-emergence application (PoE) of atrazine (2.0 kg/ha) was efficient in the weed control and selective to the sorghum crop, not affecting productivity in Brazil. Oxyfluorfen 0.2 kg/ha *fb* hand weeding at 25 days after seeding (DAS) recorded 92.3 and 95% less population and biomass of *Trianthema portulacastrum* and 86.1 and 91% less population and biomass, respectively, of all other weeds, and thus gave 24.96% more pearl millet yield and highest net return (Deshveer and Deshveer 2005). In pearl millet, pre-emergence application (PE) of atrazine 0.5 kg/ha *fb* hand weeding at 35 DAS and atrazine 0.4 kg/ha PoE at 20 DAS followed by hand weeding at 35 DAS appeared to be the best integrated weed management practice (Girase *et al.* 2017). In kodo millet, isoproturon 500 g/ha PE followed by hand weeding at 40 DAS found to be effective in reducing the density of weed species in irrigated kodo millet (Vinothini and Arthanari 2017). In another study, Lekhana *et al*. (2021) reported that bensulfuron-methyl 0.06 + pretilachlor 0.330 kg/ha at 3 DAS recorded lower total weed density and weed dry biomass with weed control efficiency (59.21%) without any phytotoxic effect on kodo millet and produced higher grain, net returns and BC ratio (2.74). In barnyard millet, bensulfuron-methyl 60 + pretilachlor 495 g/ha (RM) PE on 3 DAS was found effective (Thambi *et al.* 2021).

Integration of nutrient-use efficient and weed suppressive cultivars like 'CSH 16', 'CSV 20' and 'SPV 462' with atrazine at 0.50 kg/ha PE *fb* need-based manual weeding was found necessary to increase the nutrient-use efficiency and productivity of sorghum in semi-arid tropical areas in India (Mishra *et al.* 2014).

Millet breeders in different ecological areas effectively accelerated the breeding process, thereby 30 novel herbicide-resistant millet varieties/hybrid varieties were registered for further breeding programme at the national or local level in China (Darmency *et al.* 2017).

Management of *Striga* in millets

Striga is a root parasite which parasitizes millets like sorghum, pearl millet and finger millet. It is also known as witchweed and can destroy a crop with up to a 100% yield loss (Ejeta 2007). *Striga* spp. parasitism is considered as one of the most devastating agriculture problems across sub-Sharan Africa (SSA) countries. Over 50% of the arable land under cereals in these countries is infested by *Striga* spp. (Gressel *et al.* 2004; Rodenburg *et al.* 2016). Integrated use of weed control and crop management practices could enhance productivity of sorghum and suppress *Striga* (Fasil *et al.* 1997). A treatment consisting of row planting, mineral fertilizer (42 kg N/ha) and 2,4-D herbicide led to 40% increase in cereal yield and appreciable reduction in *Striga* infestation, compared to the control (broadcast planting, no fertilizer and early weeding; farmer's practice).

Table 5. Effective herbicides in millets

Millets	Herbicide	Dose (kg/ha)	Time of application	Weeds controlled	References
Sorghum	Atrazine	0.5–1.0	PE	BL, GR and to some extent *Striga*	Walia *et al.* 2007; Mishra *et al.* 2014
	Pendimethalin	0.75–1.0	PE	GR and BL	-
	2,4-D	0.50–0.75	PoE	BL	-
Pearl millet	Atrazine	0.50	PE	BL, GR and to some extent *Striga*	Banga *et al.* 2000 Girase *et al.* 2017
	Oxyfluorfen	0.20	PE	GR and BL	Deshveer and Deshveer 2005
	2,4-D	0.50–0.75	PoE	BL	-
	Pendimethalin	1.0	PE	GR and BL	Ram *et al.* 2004
Finger millet	Butachlor	0.75	PE	GR and BL	Prasad *et al.* 2010
Finger millet, kodo millet, little millet, barnyard millet (transplanted)	Atrazine	0.50	PE	GR and BL	Dubey and Mishra 2022
	Oxyfluorfen	0.10	PE	GR and BL	
	Pyrazosulfuron	0.02	PE	BL, SG & some GR	
	Metsulfuron	0.004	PoE	BL	
	2, 4-D	0.50	PoE	BL	
Kodo millet	Isoproturon	0.50	PE	GR and BL	Prajapati *et al.* 2007
	Isoproturon	0.50	PE	GR and BL	Vinothini and Arthanari 2017
	Bensulfuron-methyl + pretilachlor	0.06 + 0.330	PE	BL and GR	Lekhana *et al.* 2021
Barnyard millet	Bensulfuron-methyl + pretilachlor	0.06 + 0.495	PE	BL and GR	Thambi *et al.* 2021
Buck wheat	Alachlor	1.00	PE	GR	Rana *et al.* 2003
	Pretilachlor	1.00	PE	GR	
	Oxyfluorfen	0.25	PE	BL and GR	
	Metolachlor	1.00	PE	GR	

BL: broad-leaved weeds; GR: grasses; PE: pre-emergence; PoE: post-emergence

Catch cropping with Sudan grass was found useful to reduce *Striga* infestation in sorghum at Harbu (Parker 1988). It was shown that catch cropping with some varieties of cowpea, groundnut and soybean can cause suicidal germination of *S. hermonthica* (Carsky *et al.* 2000; Schulz *et al.* 2003)

In maize and sorghum, seed treatment with imazapyr showed promise in controlling *Striga* (Dembele *et al.* 2005). 2,4-D PoE effectively controls *Striga*. *Striga* in sorghum could be controlled between 62-92% by the combined application of urea and dicamba, while chlorsulfuron in combination with dicamba achieved 77-100% control of *Striga* (Babiker *et al.* 1996). Rotation of infested land into non-susceptible crops or into fallow is theoretically one of the simplest solutions for parasitic weed control, but it is also one that is neither simple nor acceptable (Parker and Riches 1993).

Wild sorghum accessions are an important reservoir for *Striga* resistance that could be used to expand the genetic basis of cultivated sorghum for resistance to the parasite (Mbuvi *et al.* 2017). Host plant resistance can be a promising method for controlling parasitic weeds. Genetic resistance to *Striga* in sorghum has been reported by Haussmann *et al.* 2004 and Rich *et al.* 2004. The genetic engineering technologies and use of gene-editing and CRISP/Cas9 could help in developing new *Striga* resistant genotypes and exploring further the molecular and genetic mechanisms involved in the resistance to *Striga* (Makaza *et al.* 2023).

Way forward

Millet cultivation is gaining momentum with their projection as the nutri-cereals, particularly in sub-tropical regions. Being climate resilient crops, they appropriately fit into crop diversification under conventional or organic/natural farming systems. Productivity of millets is quite low, which needs to be increased through development and adoption of better genotypes and improved management practices. Weeds offer serious competition for resources thus are the major biotic constraint in millet cultivation. Weed management in millets is a challenging task in the early growth phases. Also, there is lack of pre- and post-emergence selective herbicides, especially in minor millets. In this scenario, an integrated weed management approach comprising weed competitive varieties, agronomic manipulation of cultivation practices to give an edge over weeds, cultural and mechanical interventions along with herbicides would be ideal approach. New AI based weeding tools are also in developmental stage which will helpful in the chemical free farming. Development of herbicide resistant, *Striga* resistant varieties may altogether change the traditional weed management practices. However, the cultivation of herbicide resistant varieties has to be monitored for avoiding development of resistance in weeds.

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RESEARCH ARTICLE

Weed management in dry direct-seeded rice under rainfed ecology of Southern Chhattisgarh

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ABSTRACT

A field study was conducted during rainy (*Kharif*) seasons of 2019, 2020 and 2021 at S.G. College of Agriculture and Research Station, IGKV, Jagdalpur, Chhattisgarh to identify effective and economical weed management measure in dry direct-seeded rice in view of the importance of weeds in successful direct-seeded rice production. Hand weeding twice at 20 and 40 days after seeding (DAS) led to significant reduction of grassy, broad-leaved weeds and sedges and was at par with post-emergence application (PoE) of ethoxysulfuron 18 g/ha. Hand weeding twice at 20 and 40 DAS has significantly increased the tillers/m^2, panicles/m^2, seeds/panicle, 1000 seed weight and grain yield of dry direct-seeded rice. Both bispyribac-Na 25 g/ha PoE and pyrazosulfuron 25 g/ha PoE were as effective as hand weeding twice at 20 and 40 DAS in attaining higher weed control efficiency, enhancing rice growth parameters and yield of dry direct-seeded rice.

Keywords: Dry direct-seeded rice, Ethoxysulfuron, Hand weeding, Herbicides, Pyrazosulfuron, Weed management

INTRODUCTION

Rice is a major cereal in Indian diet and feeds almost 80% population of country. Rice covers 43.8 Mha with production of 116.4 mt, which share 40.86% of total food grain production of India. India has its average productivity of 2.66 t/ha (GoI 2020). Rice occupies 3.60 Mha with productivity ranging 1.2 to 1.6 t/ha under rainfed ecology in Chhattisgarh. Productivity (1.46 t/ha) of Chhattisgarh state is much lower than national yield due to many factors like weeds, timeliness, management of crop (Directorate Agriculture, Chhattisgarh 2020). The southern Chhattisgarh covers 39.06 lakh ha geographical area and 6.40 lakh ha cultivated lands. Among many factors for low rice productivity, the loss due to weeds infestations is of paramount important. Weeds are most serious biological menace in crop production and weeds itself cause 33% of losses due to pests (Verma *et al.* 2015). Irrespective of the method of crop establishment, weeds are a main culprit in rice farming due to their inherent character to compete for growth resources. In general, weeds infest more in direct-seeded rice (DSR) as compared to transplanted rice (Rao *et al.* 2007). Weeds have capacity to grow faster and dominate the crop habitat due to high adaptability and reduce the yield of crop. The dry aerobic rice system is prone to greater infestation of weeds during initial 45 days and weed infestation in DSR results in higher yield loss. Weeds can reduce the grain yield of DSR by 75.8% (Singh *et al.* 2004). Hence, efficient weed management in DSR is main critical issue for attaining optimum rice productivity (Rao *et al.* 2015). Therefore, the present study was undertaken to identify effective and economically sustainable weed management practices in dry direct-seeded rice under rainfed agro-ecology.

MATERIALS AND MTHODS

A field experiment was conducted during rainy (*Kharif*) seasons of 2019, 2020 and 2021at S.G. College of Agriculture and Research Station, IGKV, Jagdalpur, Chhattisgarh. The soil of the experimental site was sandy loam and neutral in pH (6.95) with an EC of 0.35 dS/m. It was low in organic carbon content (0.39%), low in nitrogen (153.93 kg/ha), medium in phosphorus (47.75 kg/ha) and high potassium (302.15 kg/ha). Six herbicidal treatments, *viz*. post-emergence application (PoE) of ethoxysulfuron 18 g/ha, bispyribac-Na 25 g/ha, pyrazosulfuron 25 g/ha, penoxsulam 22.5 g/ha PoE, hand weeding twice at 20 and 40 days after sowing (DAS) and weedy check were arranged in a randomized block design (RBD) with four replications. Each plot size was 5 x 5 m (25 m^2). All the herbicides were applied at 15 DAS using a

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knapsack sprayer with a flat-fan nozzle in stock solution of 500 litres/ha. Rice seeds were sown after optimal tilth by maintaining row spacing of 20 cm. Later, seed sown furrows were covered with soil to ensure proper germination of rice seeds. Recommended dose of fertilizers (80:60:40 kg N:P:K/ha) were applied and 50% nitrogen and total phosphorus and potash were given as basal dose and remaining 50% nitrogen was top dressed at 40 DAS. Other agronomic and plant protection measures during the crop growth were followed as per the recommendation. Quadrat (0.25 m^2) was randomly placed at three places in each of the plot to count weeds prior to uprooting the weeds for biomass measurement. Weed control efficiency of treatments were computed by comparing the control plot. Roots of weeds were separated at root-shoot junction, the foliage of weeds were subjected to oven drying at 65^{o}C for 48 hours and then biomass was recorded. Using biomass, weed control efficiency was computed (Tawaha *et al.* 2002). Grain yield was recorded after harvesting in net plot and converted the yield into t/ha. The data of each year was analyzed separately in OPSTAT for statistical analysis and means were compared using least significant difference (LSD) at p=0.05. The weed data were transformed by square root transformation (“x+0.5) and transformed data were subjected to ANOVA analysis (Gomez and Gomez 1984).

RESULTS AND DISCUSSION

Effect on weeds

Cynodon dactylon L., *Cyperus iria* L., *Echinochloa colona* (L.) Link., *Rotala indica* (Willd.) Koehne, *Spilanthes acmella* (L.) Murray, *Ludwigia perennis* L., *Commelina nudiflora* L., *Ludwigia octovalvis* (Jacq.) P.H. Raven., *Oplismenus burmannii* (Retz.) P. Beauv., *Ammannia baccifera* L., *Brachiaria reptans* (L.) C.A. Gardner and C.E. Hubb., *Sacciolepis indica* (L.) Chase., *and Cyperus difformis L.* were the dominant weeds in the study area.

Hand weeding twice at 20 and 40 DAS caused significant reduction of grasses, broad-leaved weeds (BLWs) and sedges density and biomass as compared to other weed control treatments and was being at par with ethoxysulfuron at 18 g/ha PoE and bispyribac-Na 25 g/ha PoE was equally effective in reduction of density of grasses, BLWs and sedges. The reduction in density of weeds is coupled with efficient suppression of weed flora with hand weeding twice (Singh *et al.* 2007). However, during 2019, bispyribac-Na was not found significantly effective. It was observed that sedges were not controlled effectively with ethoxysulfuron at 18 g/ha PoE during three years of study. The highest weed density and biomass were recorded in weedy check (**Table 1** and **2**). These results are in conformity with the findings of Pradhan *et al.* (2012), Jason *et al* (2007) and Mishra *et al.* (2007).

The higher weed control efficiency was observed with hand weeding twice at 20 and 40 DAS, which was significantly superior over rest of the weed control treatments. Among the herbicidal treatments, application of ethoxysulfuron at 18 g/ha PoE and bispyribac-Na at 25 g/ha PoE were equally effective in attaining higher weed control efficiency during three years of experimentation. Penoxsulam at 25.6 g/ha PoE was more effective than pyrazosulfuron at 25 g/ha PoE in direct-seeded rice and the lowest WCE was recorded under weedy check (**Table 4**) due to remarkably higher weed

Table 1. Effect of weed control treatments on weed density in dry direct-seeded rice

Treatment	Weed density (no./m^2)								
	Grasses			Broad-leaved weeds			Sedges		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
Ethoxysulfuron 18 g/ha PoE	3.58 (12.34)	3.78 (13.82)	4.00 (15.48)	4.46 (19.36)	4.71 (21.68)	4.98 (24.28)	3.05 (8.79)	3.39 (10.99)	3.58 (12.31)
Bispyribac-Na 25 g/ha PoE	4.89 (23.41)	5.48 (26.22)	6.13 (29.37)	7.67 (36.72)	8.59 (41.13)	9.62 (46.06)	3.48 (16.67)	4.35 (20.85)	4.88 (23.35)
Pyrazosulfuron 25 g/ha PoE	6.64 (43.54)	7.43 (48.76)	8.32 (54.62)	10.41 (68.30)	11.66 (76.49)	13.06 (85.67)	4.73 (31.01)	5.91 (38.78)	6.62 (43.43)
Penoxsulam 25.6 g/ha PoE	6.10 (36.75)	6.84 (41.16)	7.66 (46.10)	9.57 (57.65)	10.72 (64.56)	12.01 (72.31)	4.35 (26.17)	5.44 (32.73)	6.09 (36.66)
Hand weeding twice at 20 and 40 DAS	2.72 (6.92)	3.05 (7.75)	3.42 (8.68)	4.27 (10.85)	4.79 (12.16)	5.36 (13.62)	1.94 (4.93)	2.43 (6.16)	2.72 (6.90)
Weedy check	8.24 (67.34)	9.22 (75.42)	10.33 (84.47)	12.92 (105.63)	14.47 (118.31)	16.21 (132.50)	5.87 (47.96)	7.34 (59.97)	8.22 (67.17)
LSD (p=0.05)	0.88	1.08	1.12	2.08	2.56	1.85	1.39	1.43	0.94

*The data in parentheses were transformed with square root transformation $\sqrt{x + 0.5}$; PoE = post-emergence, DAS= days after seeding

Table 2. Effect of weed control treatments on weed biomass in dry direct-seeded rice

Treatment	Weed biomass (g/m^2)								
	Grasses			Broad-leaved weeds			Sedges		
	2019	2020	2021	2019	2020	2021	2019	2020	2021
Ethoxysulfuron 18 g/ha PoE	1.86 (2.96)	1.95 (3.31)	2.05 (3.71)	2.27 (4.64)	2.39 (5.20)	2.51 (5.82)	1.61 (2.11)	1.77 (2.64)	1.86 (2.95)
Bispyribac-Na 25 g/ha PoE	5.46 (5.61)	1.98 (6.29)	2.47 (7.04)	2.77 (8.81)	3.10 (9.86)	1.12 (11.05)	1.40 (4.00)	1.57 (5.00)	1.76 (5.60)
Pyrazosulfuron 25 g/ha PoE	7.41 (10.44)	2.68 (11.69)	3.36 (13.10)	3.76 (16.38)	4.21 (18.34)	1.52 (20.54)	1.91 (7.44)	2.13 (9.30)	2.39 (10.41)
Penoxsulam 25.6 g/ha PoE	6.82 (8.81)	2.47 (9.87)	3.09 (11.05)	3.46 (13.82)	3.87 (15.48)	1.40 (17.34)	1.75 (6.28)	1.96 (7.85)	2.20 (8.79)
Hand weeding twice at 20 and 40 DAS	3.04 (1.66)	1.10 (1.86)	1.38 (2.08)	1.54 (2.60)	1.73 (2.92)	0.63 (3.27)	0.78 (1.18)	0.88 (1.48)	0.98 (1.66)
Weedy check	9.20 (16.15)	3.33 (18.09)	4.17 (20.26)	4.66 (25.33)	5.22 (28.37)	1.89 (31.77)	2.36 (11.50)	2.65 (14.38)	2.97 (16.11)
LSD (p=0.05)	1.87	0.68	1.23	1.35	1.31	0.81	0.68	0.61	0.82

*The data in parentheses were transformed with square root transformation $\sqrt{x+0.5}$; PoE = post-emergence, DAS= days after seeding

Table 3. Effect of weed control treatments on yield attributing characters in dry direct-seeded rice

Treatment	Yield attributing characters											
	Tillers/m^2			Panicles/m^2			Seeds/panicle^2			1000-seed wt. (g)		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Ethoxysulfuron 18 g/ha PoE	260	310	331	249	303	361	238	303	320	24.45	25.51	26.35
Bispyribac-Na 25 g/ha PoE	276	315	334	256	308	364	246	308	333	24.64	25.70	26.56
Pyrazosulfuron 25 g/ha PoE	279	323	342	262	312	373	248	317	343	25.29	26.38	27.26
Penoxsulam 25.6 g/ha PoE	270	311	330	248	302	360	233	302	320	24.42	25.47	26.32
Hand weeding twice at 20 and 40 DAS	290	336	356	273	326	388	256	328	355	26.26	27.39	28.30
Weedy check	262	304	321	246	283	330	221	296	321	23.74	24.77	25.59
LSD (p=0.05)	13.02	22.04	23.33	20.08	18.95	24.56	10.08	20.69	22.39	NS	NS	NS

PoE = post-emergence application, DAS= days after seeding

Table 4. Effect of weed control treatments on grain yield, harvest index, weed control efficiency (WCE) and B:C ratio in dry direct-seeded rice

Treatment	Grain yield (t/ha)			Harvest index (%)			Weed control efficiency (%)			Benefit: Cost		
	2019	2020	2021	2019	2020	2021	2019	2020	2021	2019	2020	2021
Ethoxysulfuron 18 g/ha PoE	3.27	3.86	3.77	50.15	51.81	43.43	80.68	78.33	75.97	2.07	2.22	2.34
Bispyribac-Na 25 g/ha PoE	3.65	3.72	4.08	53.05	47.33	44.44	78.24	81.27	80.73	2.27	2.46	2.57
Pyrazosulfuron 25 g/ha PoE	3.67	4.21	4.34	50.14	50.97	44.51	35.34	38.61	41.02	2.29	2.56	2.68
Penoxsulam 25.6 g/ha PoE	2.97	3.26	3.52	56.04	53.80	49.86	45.43	57.63	49.73	1.77	1.90	2.00
Hand weeding twice at 20 and 40 DAS	4.08	4.86	4.43	50.12	52.26	40.87	85.72	88.02	86.15	2.73	2.93	3.08
Weedy check	1.76	1.94	1.02	47.31	48.87	31.00	-	-	-	0.34	0.36	0.38
LSD (p=0.05)	0.66	0.72	0.78	1.28	1.46	1.70	7.35	8.03	7.53	0.48	0.51	0.54

PoE = post-emergence application, DAS= days after seeding

density and biomass accrued owing to uncontrolled weed growth as reported by Janusch and Tjiirdema (2005), Pathak *et al.* (2020) and Jason *et al.* (2007).

Growth and yield of rice

Hand weeding twice had significantly higher plant height as compared to other weed control treatments during all the three years of experimentation. Pyrazosulfuron at 25 g/ha PoE was comparable to the hand weeding twice in attaining significantly higher plant height (**Table 3**). Tillers/m^2 were significantly higher with hand weeding twice at 20 and 40 DAS and was at par with both bispyribac-Na 25 g/ha PoE and pyrazosulfuron 25 g/ha PoE. Similar trend was observed in panicles m^{-2} and seeds per panicle. No significant difference was noticed in 1000 seed weight under various weed control treatments.

During three years of experimentation, hand weeding twice (20 and 40 DAS) recorded significantly higher rice grain yield (4.08, 4.86 and 4.48 t/ha in 2019, 2020 and 2021, respectively) and was at par bispyribac-Na 25 g/ha PoE and pyrazosulfuron 25 g/ha PoE. The higher rice yield with hand weeding twice might be attributed to effective control of weed flora and improved growth of rice crop along with its yield attributing characters; straw yield also followed same trend in response to weed management treatments (Pradhan *et al.* 2014).

Conclusion

Hand weeding twice at 20 and 40 DAS caused remarkable reduction in weeds density and biomass and was at par with ethoxysulfuron at 18 g/ha PoE and bispyribac-Na 25 g/ha PoE which were equally effective in attaining higher weed control efficiency being enhancing growth parameter and yields of direct-seeded rice.

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RESEARCH ARTICLE

Weed management efficacy of herbicides and allelochemicals in direct-seeded rice

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ABSTRACT

A field experiment was conducted at Zonal Agricultural Research Station, Bangalore to quantify the effect of different herbicides and allelochemicals on weed density, weed biomass, yield and economics of direct-seeded rice. The post-emergence application (PoE) of bispyribac sodium 40 g/ha provided wide spectrum weed control with a weed control efficiency of 94.99% in 2020 and 95.01% in 2021, which was comparable to pre-emergence application (PE) of bensulfuron-methyl + pretilachlor 660 g/ha (93.24% in 2020 and 93.09% in 2021, respectively). The crop growth parameters and grain yield were highest with hand weeding at 20 and 40 days after seeding (DAS) (5.1 t/ha in 2020 and 5.2 t/ha in 2021) and it was at par with bispyribac-sodium 40 g/ha PoE (5.0 t/ha in 2020 and 5.0 t/ha in 2021) and bensulfuron-methyl + pretilachlor 660 g/ha PE (4.8 t/ha in 2020 and 4.9 t/ha in 2021). Among the allelopathic extracts tested, higher rice grain yield was recorded with *Eucalyptus* leaves extract (3.3 t/ha in 2020 and 3.7 t/ha in 2021). The highest B:C of 2.65 and 2.57 in 2020 and 2021, respectively was recorded with bispyribac-sodium 40 g/ha PoE.

Keywords: Allelopathy, Bensulfuron-methyl + pretilachlor, Bispyribac-sodium, Direct-seeded rice, Herbicides, Leaves extracts, Weed management

INTRODUCTION

Rice is grown over an area of 166.57 million hectares, producing 513.67 million tons with productivity of 4.60 t/ha, and occupies top position among all food crops grown worldwide. India is the second largest producer and consumer of rice in the world with a 47 million hectares area, 129.66 million tons total production and a productivity of 4.14 t/ha in 2021–2022 (USDA 2022). Rice accounts for 55% of the nation's cereal production and 43% of the calorie needs of more than two-thirds of the population, making it the most important food source in India (Kaur and Singh 2017).

The transplanting method is the most used rice establishment technique worldwide; however, it has high labour and water requirements (Mahajan and Chauhan 2016). The labor-intensive nature of manual transplanting during the busy season forces farmers to switch to direct-seeded rice (DSR) planting instead (Rao *et al.* 2007, 2017; Choudhary *et al.* 2017). Compared to rice transplanting, direct-seeded rice requires less water and labour. In addition to these DSR also has lower machine usage requirements, reduced methane emission levels (Chauhan *et al.* 2012), improves soil structure, early crop maturation by 7-10 days and facilitates timely sowing of succeeding crop (Roy 2016). However, due to the maintenance of saturated soil conditions at the time of sowing the weeds arises simultaneously as that of crop in direct-seeded rice. Weeds pose a serious threat to DSR by competing for nutrients, moisture, light and space with the crop from the time of emergence and throughout the growing season (Singh and Singh 2010). The extent of yield reduction in DSR ranges from 91.4 to 99 % (Chhokar *et al.* 2014). Hence weed management by herbicides is more crucial.

In recent years, apart from the herbicides use, the aqueous allelochemical extracts from different plant materials are being used as bioherbicides and it is considered to be an effective tool to minimize the reported adverse effects of herbicides (Amali *et al.* 2014). Hence, the present study was conducted to quantify the effect of different herbicides and aqueous allelochemical extracts on the weed dynamics and performance of direct-seeded rice.

MATERIALS AND METHODS

A field experiment was conducted during *Rabi*, 2020 and summer 2021 at Zonal Agricultural Research Station, Gandhi Krishi Vignana Kendra, University of

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Agricultural Sciences, Bengaluru, Karnataka, India (12º 58' N, 77º 33' E). The soil of the experimental site was red sandy loam with 0.41% organic carbon and pH of 6.2. Available N, P and K content in the soil was 261.7, 34.62 and 268.3 kg/ha, respectively. Rice *cv 'MAS 946-1'* (130 days duration) was line sown with a spacing of 30 cm between rows and fertilizer level of 100 kg N, 50 kg P and 50 kg K/ha.

The treatments tested were: pre-emergence application (PE) of bensulfuron-methyl + pretilachlor 660 g/ha, pyrazosulfuron-ethyl 40 g/ha PE, oxadiargyl 100 g/ha PE, post-emergence application (PoE) of bispyribac-sodium 40 g/ha, quizalofop-p-ethyl 37.5 g/ha PoE, cyhalofop-p-butyl 100 g/ha PoE, metamifop 100 g/ha PoE, *Leucas aspera* plant extract, *Eucalyptus* leaves extract, *Hyptis suaveolens* plant extract, hand weeding twice at 20 and 40 days after seeding (DAS) and unweeded control. The herbicides were applied using spray volume of 500 L/ha for pre-emergence (0-3 DAS) and 375 L/ha for post-emergence (15-20 DAS) spray with knapsack sprayer having flood jet nozzle.

For preparing allelochemical extracts, the plant samples during their flowering stage were collected and taken to the laboratory where they were washed thoroughly with tap water to remove the dirt. A 10 g of plant sample was weighed and blended by slowly adding 100 ml of distilled water. The blended solution was first filtered through a double layered muslin cloth and then through Whatman No. 1 filter paper. The obtained 10% (w/v) aqueous allelochemical extract was used for spraying as post-emergence application during 15-20 DAS (Javaid *et al.* 2006).

During sampling time (45 DAS and at harvest), a quadrat of 25 × 25 cm was placed, randomly, at two places in each plot to determine the weed density. The weeds present in one quadrat were removed for estimating weed dry weight (biomass). Weed biomass was recorded after drying the weed samples at 70°C for 48 hours until obtaining a constant weight. Weed control efficiency was calculated based on the formula given by Mani *et al.* (1973).

$$\text{Weed control efficiency} = \frac{X - Y}{X} \times 100$$

Where,

X = Weed biomass in unweeded check plot

Y = Weed biomass in the treated plot

Crop growth parameters like plant height (cm), tillers per m row length, total dry matter accumulation (g/hill) were recorded at the time of harvest. Grain and straw yield (t/ha) were recorded after threshing and sun drying. Weed index was calculated by using the formula given by Gill and Kumar (1969).

$$\text{Weed Index} = \frac{(X-Y)}{X} \times 100$$

Where, X = Yield from hand weeding plot

Y = Yield from treated plot

In addition, the economics of weed management practices were also calculated based on the prevalent market prices of the inputs used.

The data of weed density and biomass were subjected to transformation before analysis and then subjected to Fisher's ANOVA as outlined by Panse and Sukhatme (1954). However, original values are provided in parenthesis for easier comprehension. All the data were analyzed and the results were presented and discussed at a probability level of five per cent.

RESULTS AND DISCUSSION

Effect on weeds

Weed flora of the experimental plots comprised of grasses such as: *Cynodon dactylon, Digitaria sanguinalis, Echinochloa colona, Eleusine indica, Dactyloctenium aegyptium* and *Panicum repens;* broad-leaved weeds: *Alternanthera sessilis, Amaranthus viridis, Borreria hispida, Cassia* sp., *Euphorbia geniculata, Ipomoea alba, Mollugo disticha, Ageratum conyzoides, Portulaca oleracea* and *Phyllanthus niruri* and the sedge: *Cyperus rotundus.*

Bensulfuron-methyl + pretilachlor 660 g/ha PE and bispyribac-sodium 40 g/ha PoE effectively controlled the sedge (**Table 1** and **2**). The lower grass density and biomass during both the years was recorded with metamifop 100 g/ha PoE and was statistically at par with quizalofop-p-ethyl 37.5 g/ha, cyhalofop-p-butyl 100 g/ha and bispyribac-sodium 40 g/ha PoE. Significantly lower broad- leaved weed density and biomass were recorded with bispyribac-sodium 40 g/ha PoE. Among all the herbicidal treatments, bispyribac-sodium 40 g/ha PoE was statistically superior in reducing weed density and biomass followed by bensulfuron-methyl + pretilachlor 660 g/ha PE.

Bispyribac-sodium and bensulfuron-methyl + pretilachlor are broad spectrum herbicides and hence, they reduced the density and biomass of sedges, grasses and broad-leaved weeds which aided in recording lower total weed density and biomass. Between the years, the total weed density and biomass were considerably higher in 2020 than 2021. All the herbicide treatments including allelochemical treatments significantly lowered the weed density and biomass when compared to unweeded control. The results were in conformity with the findings of Chandra *et al.* (2013), Suresh *et al.* (2013) and Prakash *et al.* (2017).

The weed control efficiency (WCE) was largely dependent on weed biomass. The highest weed control efficiency was obtained with hand weeding at 20 and 40 DAS (99.67% in 2020 and 99.66% in 2021) at 45 DAS (**Table 2**). Whereas, among the herbicidal treatments, bispyribac sodium 40 g/ha PoE recoded higher weed control efficiency of 94.99% in 2020 and 95.01% in 2021, followed by bensulfuron-methyl + pretilachlor 660 g/ha PE (93.24% in 2020 and 93.09% in 2021, respectively) confirming findings of Rawat *et al.* (2012) and Teja *et al.* (2015). The herbicides use has resulted in better weed control efficiency compared than with allelochemical plant extracts which might be due to their lesser efficiency, lower residual nature when compared to herbicides.

Effect on the crop

All the crop growth parameters, *viz.* plant height, number of tillers per meter row length, total dry matter accumulation per hill, grain and straw yield were maximum with hand weeding at 20 and 40 DAS followed by bispyribac-sodium 40 g/ha PoE and bensulfuron-methyl + pretilachlor 660 g/ha PE during 2020 and 2021 (**Table 3**). Reduced weed competition and increased availability of growth factors like nutrients, soil moisture, light and space has paved the way for higher crop growth parameters in these treatments which is demonstrated by taller plants and a greater number of tillers, which in turn increased the crop's biomass. The results are in parity with Teja *et al.* (2015) and Prakash *et al.* (2017). Among the allelochemical treatments, application of *Eucalyptus* leaves extract recorded higher grain and straw yield over *Leucas aspera* and *Hyptis suaveolens* plant extracts.

There is an inverse relationship between crop yield and weed index in any crop. The lowest weed index was noticed in bispyribac-sodium 40 g/ha PoE (1.64 and 4.22% in 2020 and 2021, respectively) *fb* bensulfuron-methyl + pretilachlor 660 g/ha PE (5.36 and 5.25% in 2020 and 2021, respectively). The highest weed index was noticed in unweeded control (86.69 and 86.53% in 2020 and 2021, respectively) due to severe yield reduction due to adverse effect of weed competition.

B:C Ratio

The highest B:C was obtained with bispyribac-sodium 40 g/ha PoE (2.65 and 2.57 in 2020 and 2021, respectively) closely followed by bensulfuron-methyl + pretilachlor 660 g/ha PE (2.58 and 2.56 in 2020 and 2021, respectively) due to improved yield and

Table 1. Effect of weed management treatments on sedges, grasses, broad-leaved weeds and total weed density (no./m^2) at 45 days after seeding (DAS) in direct-seeded rice

Treatment	Sedges		Grasses			Broad-leaved weeds		Total weeds
	2020+	2021+	2020#	2021#	2020+	2021+	2020#	2021#
Bensulfuron-methyl + pretilachlor 660 g/ha PE	1.73(2.0)	1.52(1.3)	1.08(10.0)	1.03(8.6)	3.13(8.7)	3.00(8.0)	1.36(20.7)	1.30(17.9)
Pyrazosulfuron ethyl 40 g/ha PE	2.65(6.0)	2.07(3.3)	1.13(11.4)	1.05(9.3)	3.22(9.3)	3.11(8.7)	1.46(26.7)	1.37(21.3)
Oxadiargyl 100 g/ha PE	2.77(6.7)	2.24(4.0)	1.17(12.7)	1.12(11.3)	3.34(10.1)	3.22(9.4)	1.50(29.5)	1.43(24.7)
Bispyribac-sodium 40 g/ha PoE	2.24(4.0)	2.07(3.3)	0.93(6.6)	0.90(6.0)	3.02(8.0)	2.77(6.7)	1.31(18.6)	1.26(16.0)
Quizalofop-p-ethyl 37.5 g/ha PoE	3.70(12.7)	3.61(12.0)	0.90(5.9)	0.83(4.7)	5.23(26.6)	5.26(26.7)	1.67(45.2)	1.66(43.4)
Cyhalofop-p-butyl 100 g/ha PoE	3.70(12.7)	3.42(10.7)	0.94(6.7)	0.82(4.6)	4.70(21.2)	4.65(20.6)	1.63(40.6)	1.58(35.9)
Metamifop 100 g/ha PoE	3.61(12.0)	3.42(10.7)	0.86(5.3)	0.72(3.3)	4.64(20.6)	3.14(21.9)	1.60(37.9)	1.58(35.9)
Leucas aspera plant extract	3.51(11.3)	3.21(9.3)	1.51(30.7)	1.47(27.3)	4.71(21.3)	4.64(20.5)	1.81(63.3)	1.77(57.1)
Eucalyptus leaf extract	3.21(9.3)	2.88(7.3)	1.47(27.3)	1.41(24.0)	4.27(17.3)	4.35(17.9)	1.75(53.9)	1.71(49.2)
Hyptis suaveolens plant extract	3.21(9.3)	3.11(8.7)	1.48(28.0)	1.44(25.3)	4.57(20.0)	4.49(19.2)	1.77(57.3)	1.74(53.2)
Hand weeding twice at 20 and 40 DAS	1.30(0.7)	1.30(0.7)	0.53(1.4)	0.43(0.7)	1.05(0.0)	1.00(0.0)	0.61(2.1)	0.53(1.4)
Unweeded control	3.96(14.7)	3.61(12.0)	1.72(50.0)	1.69(46.7)	6.15(37.2)	6.02(35.3)	2.02(101.9)	1.98(94.0)
LSD (p=0.05)	0.52	0.58	0.16	0.20	0.69	1.43	0.13	0.10

Table 2. Effect of weed management treatments on sedges, grasses, broad-leaved weeds, total weed biomass (g/m^2) and weed control efficiency (WCE) (%) at 45 days after seeding (DAS) and weed index (%) in direct-seeded rice

Treatment	Sedges		Grasses		Broad-leaved weeds		Total weeds		WCE		Weed index	
	2020+	2021+	2020#	2021#	2020+	2021+	2020#	2021#	2020	2021	2020	2021
Bensulfuron-methyl + pretilachlor 660 g/ha PE	1.15(0.3)	1.13(0.3)	0.78(4.0)	0.76(3.8)	0.68(2.8)	0.67(2.6)	0.96(7.2)	0.94(6.7)	93.24	93.09	5.36	5.25
Pyrazosulfuron ethyl 40 g/ha PE	1.24(0.5)	1.22(0.5)	0.85(5.0)	0.82(4.6)	0.77(3.8)	0.74(3.5)	1.06(9.4)	1.03(8.6)	91.15	91.1	8.13	6.96
Oxadiargyl 100 g/ha PE	1.33(0.8)	1.25(0.6)	0.97(7.3)	0.86(5.3)	0.85(5.1)	0.75(3.6)	1.18(13.1)	1.06(9.4)	87.66	90.24	12.56	11.29
Bispyribac-sodium 40 g/ha PoE	1.21(0.5)	1.17(0.4)	0.65(2.4)	0.63(2.2)	0.65(2.4)	0.63(2.2)	0.87(5.3)	0.83(4.8)	94.99	95.01	1.64	4.22
Quizalofop-p-ethyl 37.5 g/ha PoE	4.17(16.4)	3.70(12.7)	0.55(1.5)	0.50(1.2)	1.39(22.6)	1.28(17.1)	1.63(40.6)	1.52(30.9)	61.88	68.05	25.81	25.64
Cyhalofop-p-butyl 100 g/ha PoE	3.62(12.1)	3.47(11.0)	0.56(1.6)	0.53(1.4)	1.30(18.0)	1.25(16.0)	1.53(31.7)	1.48(28.4)	70.21	70.62	24.34	24.98
Metamifop 100 g/ha PoE	3.28(9.8)	3.15(8.9)	0.49(1.1)	0.47(1.0)	1.34(20.1)	1.31(18.4)	1.52(31.0)	1.48(28.3)	70.92	70.77	18.11	17.81
Leucas aspera plant extract	1.53(1.3)	1.50(1.2)	1.40(23.2)	1.36(21.2)	1.31(18.5)	1.20(13.8)	1.65(43.1)	1.58(36.2)	59.55	62.61	59.18	57.52
Eucalyptus leaf extract	1.35(0.8)	1.27(0.6)	1.38(21.8)	1.26(16.2)	1.25(15.9)	1.14(11.7)	1.61(38.5)	1.48(28.5)	63.88	70.51	34.89	29.57
Hyptis suaveolens plant extract	1.43(1.0)	1.33(0.8)	1.38(22.2)	1.26(16.4)	1.26(16.3)	1.24(15.2)	1.62(39.6)	1.54(32.4)	62.84	66.58	48.13	41.73
Hand weeding twice at 20&40 DAS	1.07(0.1)	1.06(0.1)	0.35(0.2)	0.34(0.2)	0.30(0.0)	0.30(0.0)	0.37(0.4)	0.37(0.3)	99.67	99.66	0	0
Unweeded control	4.52(19.4)	4.33(17.7)	1.66(43.2)	1.63(40.5)	1.66(43.9)	1.61(38.6)	2.04(106.5)	1.99(96.8)	0	0	86.69	86.53
LSD (p=0.05)	0.18	0.14	0.28	0.17	0.17	0.13	0.16	0.18	-	-	-	-

Data within the parentheses are original values; Transformed values - # = log (x+2), + = square root of (x+1). PE: pre-emergence application; PoE: post-emergence application; DAS: days after seeding

Table 3. Effect of weed management practices on crop growth parameters at harvest in direct-seeded rice

Treatment	Plant height (cm)		Tillers per meter row length		Total dry matter (g/hill)		Grain yield (t/ha)		Straw yield (t/ha)		B:C	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
Bensulfuron-methyl + pretilachlor 660 g/ha PE	58.00	60.32	176.85	186.69	19.03	20.83	4.8	4.9	6.6	6.8	2.58	2.56
Pyrazosulfuron ethyl 40 g/ha PE	56.74	58.17	174.09	184.48	18.33	20.69	4.7	4.9	6.5	6.7	2.52	2.53
Oxadiargyl 100 g/ha PE	55.83	57.31	170.50	179.91	17.94	18.88	4.4	4.6	6.3	6.7	2.41	2.42
Bispyribac-sodium 40 g/ha PoE	59.60	61.95	179.30	192.91	19.38	21.32	5.0	5.0	6.8	6.9	2.65	2.57
Quizalofop-p-ethyl 37.5 g/ha PoE	51.10	53.67	148.34	161.56	14.32	16.84	3.8	3.9	5.9	5.9	2.05	2.03
Cyhalofop-p-butyl 100 g/ha PoE	53.83	54.27	157.84	168.04	15.01	18.05	3.8	3.9	5.7	6.0	2.18	2.15
Metamifop 100 g/ha PoE	54.37	56.62	161.99	174.20	17.26	18.62	4.1	4.3	6.0	6.0	2.26	2.24
Leucas aspera plant extract	48.62	49.57	131.07	144.15	12.51	13.35	2.1	2.2	4.0	4.2	1.24	1.27
Eucalyptus leaf extract	50.66	52.06	146.37	154.41	14.06	16.31	3.3	3.7	5.2	5.5	1.89	2.01
Hyptis suaveolens plant extract	49.65	51.19	135.61	147.74	13.46	16.47	2.6	3.0	4.2	4.7	1.51	1.67
Hand weeding twice at 20 and 40 DAS	60.97	63.17	185.18	196.00	19.90	21.94	5.1	5.2	6.9	7.0	2.36	2.35
Unweeded control	42.97	44.25	83.53	89.21	6.06	7.53	0.7	0.7	1.5	1.5	0.45	0.46
LSD (p=0.05)	4.19	4.76	10.74	11.36	1.40	2.17	0.4	0.3	0.3	0.4	-	-

PE: pre-emergence application; PoE: post-emergence application; das: days after seeding

reduced cost of weed management with herbicides use. The hand weeding twice at 20 and 40 DAS recoded slightly lower B:C (2.36 in 2020 and 2.35 in 2021) due to increased cost of cultivation. The lowest B:C was recorded in the unweeded control.

Conclusion

Bispyribac-sodium 40 g/ha PoE or bensulfuron-methyl + pretilachlor 660 g/ha PE were found to be best in controlling weeds, recording higher weed control efficiency, rice yield and economic returns in direct-seeded rice.

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RESEARCH ARTICLE

Weed dynamics and productivity of transplanted aromatic rice as influenced by pre- and post-emergence herbicides in lower Gangetic alluvial zone

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ABSTRACT

A field experiment was conducted during *Kharif* seasons of 2018 and 2019 at Instructional Farm, Jaguli Bidhan, Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, with an objective to identify the best weed management practice in transplanted scented rice. The field experiment was laidout in a randomized block design replicated thrice with twelve treatments. It can be concluded that hand weeding at 20 and 40 days after transplanting (DAT) recorded significantly lower total weed density, total weed biomass, higher weed control efficiency and also higher grain yield, straw yield, and harvest index which were statistically at par with pre-emergence application (PE) of pretilachlor 1.5 kg/ha at 2 DAT followed by (*fb*) post-emergence application (PoE) of bispyribac-sodium at 25.0 g/ha at 20 DAT. Thus, it can be used as the better option for managing weeds and achieving higher productivity by the growers of the locally popular scented transplanted Gobindabhog rice variety in the new lower Gangetic alluvial zone of West Bengal.

Keywords: Aromatic rice, Bispyribac-sodium, Herbicides, Pretilachlor, Weed management, Weed control efficiency

INTRODUCTION

Rice (*Oryza sativa* L.) occupies a pivotal place in Indian agriculture as it is the staple food for more than 70% of the population. With the growing demand for rice, both at the global and national level, the required rice production in India by 2030 is estimated to be 138 million tons. Thus, rice production in India, need to grow by 17% from the current level of 118 million tons in 2020 to reach 138 million tons by 2030 (Chakraborty and Priya 2023). In West Bengal, the production of geographical indication (GI) tag Gobindabhog is about 90 thousand tonnes to 1.0 lakh tonnes/ha over 45 thousand hectares area of land with the potential productivity of 3.0 t/ha. Weeds have become an important production constraint in transplanted rice, and failure to control weeds results in lower crop yields with rice yield losses of may up to 40% (Maity and Mukherjee 2008; Pandey and Bhandari 2009; Rao *et al.* 2017). The weed flora emerges in several flushes during the crop growth period and the weed competition during the early growth is more damaging for rice (Rao *et al.* 2007). Because of the morphological similarities, transplanting of *E. crus-galli* with rice seedlings is very common resulting in 48-71% yield losses (Yu and Liu 1986; Rao and Moody 1987, 1988). In West Bengal under the new alluvial zone, the yield loss of rice due to weed was 37.02% and 23.12% in grain and straw, respectively (Mondal *et al.* 2015). However, the effective control of the weeds had increased the grain yield by 85.5% (Mukherjee and Singh 2005). Hand weeding is commonly used as it is very effective but it is not only laborious but also expensive and accounts for about 25% of the total labour force used which amounts to about 900–1200-man hours/ha (Nadeem *et al.* 2008, Nag and Dutt 1979). Thus, proper management of weeds in the crop field, in time, to reduce the crop-weed competition is difficult due to a sharp increase in the wages and unavailability of labour due to industrialization and urbanization in the community. In view of this, chemical weed control is becoming more popular. Several pre-emergence herbicides are available for controlling weeds, and the need for post-emergence herbicide is often realized to combat weeds emerging during later stages of crop growth. Among the post-emergence herbicides, bispyribac-sodium is a systemic herbicide absorbed by roots and leave and inhibits the enzyme acetoacetate synthase in susceptible weed plants (Pathak *et al.* 2011).

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MATERIALS AND METHODS

A field experiment was conducted during *Kharif* seasons of 2018-19 and 2019-20 at Instructional Farm, Jaguli under Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal (22p 93'N latitude, $88^0$53' E longitude, 9.75 m above mean sea level) to identify best weed management practices in transplanted aromatic rice (*Oryza sativa* L.) variety Gobindabhog in lower Gangetic alluvial zone in lower gangetic alluvial zone of West Bengal. Soil at the experimental site (0-15 cm depth) was clayey loam in texture containing 24.5% sand, 37.4% silt and 42.1% clay with 7.21 pH and 0.58% organic carbon (OC) with medium in available N, P and K contents were 187.5, 38.2 and 201.9 kg/ha, respectively. The average annual rainfall is about 1396 mm; of which 70–80% comes from south-west monsoon with its onset in the region during second week of June. The maximum temperature during experimentation ranged between from 30.3°C to 34.2°C and minimum temperature prevailed between 14°C to 23.2°C. The maximum and minimum relative humidity ranged between 93.4 to 97.3% and 52.8 to 82.2%, respectively. The experiment was laid down in randomized block design with three replications and twelve treatments, *viz*. post-emergence application (PoE) of bispyribac-sodium 25.0 g/ha at 20 days after transplanting (DAT), bispyribac-sodium 40.0 g/ha PoE (20DAT), pre-emergence application (PE) of pretilachlor 1.0 kg/ha at 2 DAT, pretilachlor 1.5 kg/ha PE (2 DAT), pretilachlor 1.0 kg/ha PE (2 DAT)followed by (*fb*) bispyribac-sodium 25.0 g/ha PoE (20 DAT), pretilachlor 1.5 kg /ha PE (2 DAT) *fb* bispyribac-sodium 40.0 g/ha PoE (20 DAT), 2, 4-D ethyl ester 0.850 kg/ha PoE (20 DAT), penoxulam22.5 g/ha PoE (20 DAT), butachlor 1.5 kg/ ha PE (2 DAT), hand weeding twice at 20 DAT and 40 DAT, butachlor1.5 kg/ha PE (2 DAT) *fb* hand weeding at 30 DAT and weedy check. The seedlings of rice var. 'Gobindabhog' were transplanted at 20 (row to row) × 20 cm (plant to plant) spacing in the plots of size 5 × 4 m. The experimental field was ploughed twice with disc harrow and tractor-drawn cultivator followed by puddling with rotavator and later levelled uniformly. Twenty-four days old seedlings were transplanted at a spacing of 20 × 20 cm with 2-3 seedlings per hill. The recommended dose of nitrogen, phosphorus and potassium at 40, 20 and 20 kg/ha in the form of urea, single super phosphate and Muriate of Potash, respectively was applied. Nitrogen was applied in three equal splits at transplanting, maximum tillering stage and at panicle initiation. In this experiment, phosphorous was applied as basal dose at the time of transplanting and potassium was applied in two equal splits at transplanting and panicle initiation stage. The water level was maintained initially at two cm depth till the establishment of seedlings. Later on, water level was maintained at 5 ± 2 cm depth up to physiological maturity and then gradually reduced and drained off fifteen days before the harvest of the crop. All the herbicides were applied using 500 litres of water/ha by spraying uniformly in the experimental plots as per treatments with the help of power operated knapsack sprayer. The density of grasses, sedges and broad-leaved weeds was calculated by placing randomly the quadrat ($0.25/m^2$ area) at four places and the density (no./m^2) was estimated. Weed species within the area of quadrat were counted and collected and air dried in hot air oven maintained at 70 to 75ºC temperature for recording weed biomass. The data obtained from the field experiment were subjected to statistical analysis wherever the treatment differences were significant F test and critical differences were worked out at 5% probability level and the values were furnished. Weed index (WI) was calculated based on the grain yield obtained from different treatments using the formula.

$$WI (\%) = \frac{X-Y}{X}$$

Where, WI =Weed index, X = Grain yield from minimum competition plot and

Y = Grain yield from treatment for which weed index has to be worked out

$$\text{Weed control efficiency (\%)} = \frac{(WDM_c - WDM_t)}{WDM_c} \times 100$$

where, WDM_c= Weed biomass in control plot and WDM_t = Weed biomass in the treated plot.

RESULTS AND DISCUSSION

Effect on weeds

The predominant weed flora observed in the experimental site was among grasses: *Echinochloa colona, Echinochloa crus-galli, Cynodon dactylon;* sedges: *Cyperus iria*, *Cyperus difformis*, *Fimbristylis miliacea*, and broad-leaved weeds: *Marsilea quadrifoliata*, *Ludwigia parviflora*, *Ammania baccifera,* and *Alternanthera philoxeroides.* At 30, 60 and 90 DAT, hand weeding twice at 20 and 40 DAT recorded significantly lower weed density and biomass; higher WCE and lower WI than all other the treatments (**Table 1**). The highest weed density and biomass was observed in weedy check (control). Among the herbicide treatments, pretilachlor 1.5 kg/ ha as PE (2DAT) *fb* bispyribac-sodium 25.0 g/ha as PoE (20 DAT) recorded lowest weed density and biomass, higher WCE and lower WI. This might be due to the higher efficacy of pre-emergence herbicide followed by post-mergence herbicide which resulted in lower weed biomass. The results are in conformity with Uma *et al.* (2014), Saha (2006), Sharma *et al.* (2007), Singh (2015), Manjunatha *et al.* (2013). The weed density increased with the advancement of time due to emergence of more flushes of weeds in later stages of crop growth due to weather and agronomic practices (Chauhan and Seth 2013). The minimum weed control efficiency of 64.11% and 54.18% at 60 DAT and 90 DAT, respectively was observed with bispyribac-sodium 25.0 g/ha POE (20 DAT) and the highest weed control efficiency of 86.59% and 74.35% was obtained with hand weeding twice at 20 and 40 DAT, respectively. This might be due to the complete removal of weeds at 20 DAT as it prevents weed regeneration during the period under consideration (Sharma *et al.* 2007).

Effect on crop

At 30, 60 and 90 DAT the best value of plant height, number of tillers, crop dry matter production was recorded with twice hand weeding at 20 and 40 DAT followed by pretilachlor 1.5 kg/ha as PE (2 DAT) *fb* bispyribac-sodium 25.0 g/ha as PoE. The minimum plant, height, number of tillers, crop dry matter production was recorded with weedy check. Among herbicides tested, pretilachlor 1.5 kg/ha PE (2 DAT) *fb* bispyribac-sodium 25.0 g/ha PoE (20 DAT) recorded higher plant height, tillers, crop dry matter production. This might be due to suppression of weed growth by an effective pre-emergence herbicide followed by post-emergence herbicides resulting in better access of resources to growth to rice plants. Pretilachlor 1.5 kg/ha PE (2 DAT) *fb* bispyribac-sodium 25.0 g/ha and hand weeding twice at 20 and 40 DAT recorded highest number of panicles per square metre, panicle length (cm), test weight, grain yield (t/ha), straw yield (t/ha) and harvest index (%). The timely and effective control of weeds with integrated use of pre and post-emergence herbicides resulted in increased yield attributes, which ultimately reflected on grain yield (Deepthi Kiran and Subramanyam 2010). These results are in conformity with Mishra and Singh (2007), Pal and Banerjee (2007), Singh and Paikra (2014) and Uma *et al.* (2014). Minimum yield and yield attributes were recorded with weedy control due to severe weed competition by uncontrolled weed growth (Patra *et*

Table 1. Effect of weed management treatments on weed density, weed biomass, weed control efficiency, weed index (pooled data of 2 years)

Treatment	Total weed density (no./m^2)			Total weed biomass (g/ m^2)			Weed control efficiency (%)			Weed index (%)
	30 DAT	60 DAT	90 DAT	30 DAT	60 DAT	90 DAT	30 DAT	60 DAT	90 DAT	
Bispyribac-sodium 25.0 g/ha PoE (20 DAT)	4.75 (22.0)	7.45 (55.0)	9.66 (92.0)	3.04 (8.7)	3.97 (15.2)	4.74 (21.5)	68.37	64.11	54.18	40.30
Bispyribac-sodium 40.0 g/ha PoE (20 DAT)	3.04 (8.7)	5.31 (27.7)	7.51 (55.0)	2.06 (3.7)	3.22 (9.9)	4.07 (15.7)	86.45	76.79	66.50	16.06
Pretilachlor 1.0 kg/ha PE (2 DAT)	3.20 (9.7)	5.38 (28.4)	7.91 (61.3)	2.18 (4.2)	3.24 (10.0)	4.18 (16.5)	84.61	76.48	64.92	23.33
Pretilachlor 1.5 kg/ha PE (2 DAT)	2.88 (7.7)	5.27 (27.2)	7.31 (52.0)	2.05 (3.7)	3.18 (9.6)	4.02 (15.1)	86.60	77.39	67.72	10.91
Pretilachlor 1.0 kg/ha PE (2 DAT) *fb* bispyribac-sodium 40.0 g/ha PoE (20 DAT)	2.81 (7.4)	5.24 (27.0)	6.91 (46.6)	2.04 (3.6)	3.13 (9.2)	3.89 (14.1)	86.75	78.13	69.89	5.15
Pretilachlor 1.5 kg/ha PE (2 DAT) *fb* bispyribac-sodium 25.0 g/ha PoE (20 DAT)	2.37 (5.1)	4.43 (19.1)	5.97 (34.3)	1.88 (3.0)	2.67 (6.6)	3.69 (12.6)	89.02	84.41	73.09	1.82
2,4-D ethyl ester 0.850 kg/ha PoE (20 DAT)	3.31 (10.4)	5.65 (31.4)	8.51 (71.0)	2.28 (4.7)	3.34 (10.7)	4.33 (17.8)	83.00	74.94	62.18	30.91
Penoxsulam 22.5 g/ha PoE (20 DAT)	3.51 (11.7)	5.98 (35.2)	8.74 (75.0)	2.58 (6.1)	3.42 (11.2)	4.40 (18.4)	77.72	73.67	60.86	37.27
Butachlor 1.5 kg/ha PE (2 DAT)	3.31 (10.4)	5.47 (29.4)	8.00 (62.6)	2.24 (4.5)	3.24 (10.0)	4.25 (17.1)	83.65	76.48	63.62	26.97
Two hand weeding twice at 20 and 40 DAT	2.36 (5.0)	3.95 (15.1)	5.83 (32.6)	1.82 (2.8)	2.49 (5.7)	3.61 (12.0)	89.82	86.59	74.35	-
Butachlor 1.5 kg/ha as PE (2 DAT) *fb* hand weeding at 30 DAT	2.82 (7.4)	5.13 (25.8)	6.49 (40.6)	1.98 (3.4)	2.92 (8.0)	3.80 (13.5)	87.62	81.12	71.30	5.15
Weedy check	8.28 (77.1)	10.92 (130.6)	14.29 (218.9)	4.75 (27.6)	6.02 (42.5)	6.28 (47.7)	-	-	-	42.12
LSD (p=0.05)	0.46	0.52	0.63	0.19	0.31	0.38	-	-	-	-

*Figures in parentheses indicate original values; PE = pre-emergence; PoE = post-emergence; DAT = days after transplanting

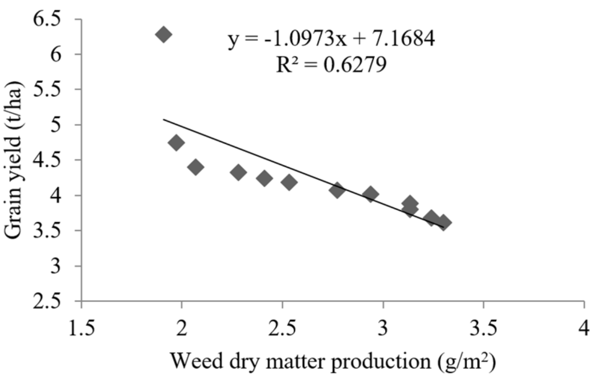
Table 2. Effect of weed management treatments on growth parameters of aromatic rice (pooled data of 2 years)

Treatment	Plant height (cm)			Tillers (no./m^2)			Dry matter production (g/m^2)		
	30 DAT	60 DAT	90 DAT	30 DAT	60 DAT	90 DAT	30 DAT	60 DAT	90 DAT
Bispyribac-sodium 25.0 g/ha PoE (20 DAT)	46.30	69.66	91.01	195.56	237.29	270.68	114.93	223.40	489.40
Bispyribac-sodium 40.0 g/ha PoE (20 DAT)	51.33	72.23	98.21	205.26	247.29	279.42	134.71	289.27	593.00
Pretilachlor 1.0 kg/ha PE (2 DAT)	50.31	71.80	95.90	203.41	245.52	276.51	128.21	281.52	579.51
Pretilachlor 1.5 kg/ha PE (2 DAT)	50.74	72.51	99.43	207.36	249.56	285.17	147.34	310.71	619.24
Pretilachlor 1.0 kg/ha PE (2 DAT) *fb* bispyribac-sodium 40.0 g/ha PoE (20 DAT)	52.21	73.23	102.10	208.46	251.13	289.35	158.43	348.61	660.68
Pretilachlor 1.5 kg/ha PE (2 DAT) *fb* bispyribac-sodium 25.0 g/ha PoE (20 DAT)	58.20	73.49	110.95	213.36	245.40	295.49	173.99	380.41	698.57
2,4-D ethyl ester 0.850 kg/ha PoE (20 DAT)	49.54	72.75	93.79	201.11	243.49	272.51	116.82	229.05	514.74
Penoxsulam 22.5 g/ha PoE (20 DAT)	47.51	69.79	92.34	198.22	240.07	271.67	114.93	228.53	491.94
Butachlor 1.5 kg/ha PE (2 DAT)	50.00	71.21	94.80	202.50	244.31	275.47	115.28	232.29	528.31
Two hand weeding (HW) twice at 20 and 40 DAT	61.23	82.25	121.17	216.71	251.39	302.37	210.65	436.59	773.07
Butachlor 1.5 kg/ha as PE (2 DAT) *fb* HW at 30 DAT	55.01	73.2	106.91	211.18	252.47	290.19	163.43	357.85	646.51
Weedy check	43.50	65.83	87.20	194.50	236.63	268.42	103.17	203.03	455.09
LSD (p=0.05)	2.94	4.45	5.84	0.29	1.29	0.11	10.36	16.60	27.85

Table 3. Effect of weed management treatments on yield and yield attributes of aromatic rice (pooled data of 2 years)

Treatment	No of Panicles/ m^2	Panicle length (cm)	Test weight (g)	Grain yield (t/ha)	Straw yield (t/ha)
Bispyribac-sodium 25.0 g/ha PoE (20 DAT)	281.66	23.77	10.12	1.97	4.10
Bispyribac-sodium 40.0 g/ha PoE (20 DAT)	307.33	25.00	10.60	2.77	5.76
Pretilachlor 1.0 kg/ha PE (2 DAT)	305.00	24.76	10.50	2.53	5.47
Pretilachlor 1.5 kg/ha PE (2 DAT)	313.66	25.26	10.72	2.94	6.05
Pretilachlor1.0kg/ha PE (2 DAT) *fb* bispyribac-sodium 40.0 g/ha PoE (20 DAT)	320.00	25.83	10.83	3.13	6.45
Pretilachlor1.5 kg/ha PE (2 DAT) *fb* bispyribac-sodium 25.0 g/ha PoE (20 DAT)	337.60	26.50	11.26	3.24	6.63
2,4-D ethyl ester 0.850 kg/ha PoE (20 DAT)	297.66	24.33	10.32	2.28	4.79
Penoxsulam 22.5 g/ha PoE (20 DAT)	283.33	24.00	10.24	2.07	4.36
Butachlor 1.5 kg/ha PE (2 DAT)	299.00	24.63	10.36	2.41	5.25
Two hand weeding twice at 20 and 40 DAT	370.00	26.66	11.39	3.30	6.65
Butachlor 1.5 kg/ha as PE (2 DAT) *fb* hand weeding at 30 DAT	328.33	26.23	11.13	3.13	6.41
Weedy check	272.33	23.16	10.08	1.91	4.01
LSD (p=0.05)	33.95	1.72	0.38	0.31	0.37

Figure 1. The linear regression between grain yield and weed dry matter production in transplanted aromatic rice during 2018-19 and 2019-2020



al. 2006). Grain yield with hand weeding twice is appreciably higher due to efficient weed control but it is time-consuming, laborious, presently too costly, and non-availability of labourers at peak agricultural operations. Hence, though grain yield recorded with twice hand weeding was appreciably good due to efficient weed control but it cannot be recommended for large scale. These results are in conformity with Mishra and Singh (2007) and Pal and Banerjee (2007). A significantly negative correlation (R^2=0.627) was observed between grain yield and weed dry matter production (**Figure 1**).

Conclusion

It can be concluded that hand weeding twice at 20 and 40 DAT was statistically at par with pretilachlor 1.5 kg/ha PE (2 DAT) *fb* bispyribac-sodium 25.0 g/ha as PoE (20 DAT) in attaining significantly higher grain yield, straw yield and harvest index by managing weeds effectively. Hence, they are the better options for the growers of the locally popular scented transplanted Gobindabhog variety of rice in the new alluvium lower Gangetic zone of West Bengal.

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RESEARCH ARTICLE

Barnyardgrass (*Echinochloa crus-galli)* seed production and shattering in response to its emergence time and transplanted rice geometry

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ABSTRACT

A field experiments were conducted to study the seed production and shattering pattern of barnyardgrass (BYG) in response to its emergence and transplanted rice geometry. A split-plot design with four replications was used with transplanted rice geometry (M1- 15×15 cm, M2- 25×25 cm) in main-plots and BYG emergence timings [S1- 0 days after transplanting (DAT), S2- 20 DAT, S3- 40 DAT] as sub-plot treatments. The increase in crop spacing by 10 cm in each row and column (M2) increased the BYG seed production by 20% over M1. The wider crop geometry (M2) also recorded significantly higher density (17.2%), dry matter production (39.6%), leaf length (11.6%) and panicle count (24.7%) than M1. With respect to time of emergence, the maximum number of seeds per BYG plant was produced (31987) by S1 (BYG emergence at 0 DAT) while S3 (BYG emergence from 40 DAT) recorded the lowest (5641) number of seeds. The delay in BYG emergence by 40 days leads to 82% reduction in BYG seed production/plant. With respect to seed shattering, the maximum seed (152/panicle) shattering was recorded in crop geometry M1 (15×15 cm) which is 18% higher over M2 (25×25 cm) at 20 days after installation (DAI) of weed seed trap, while at harvest the difference was non-significant. However, seed shattering was significantly more with M2 (25×25 cm) compared to M1 (15×15 cm) and with S1 (BGY emergence from 1st DAT), which was higher by 46% and 50% at 20 DAI and at harvest, respectively, over S3. The seed shattering percentage of BYG was 22 to 26% while around 75% of the seeds produced by BYG remained intact at the time of harvest making BYG a suitable candidate for harvest weed seed control (HWSC). Management techniques need to be developed to control escaped or late emerged BYG in order to prevent its soil weed seedbank enrichment and to ensure sustainable weed management.

Keywords: Barnyardgrass, Crop geometry, *Echinochloa crus-galli,* Seed production, Seed shattering, Time of emergence, Transplanted rice

INTRODUCTION

Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], belonging to the family Poaceae, is a troublesome monocot weed in Asian rice fields and it mimics rice (Jinger *et al.* 2016; Rao *et al.* 2019; Rao 2021) and found to have wider geo-climatic adaptability. The menace of barnyardgrass (BYG) is more under puddled low-land transplanted rice in comparison to non-puddled upland rice during both the rainy and winter seasons (Chauhan and Johnson 2011). Yield loss due to BYG was higher in the wet season compared to the dry season due to its fast growth (Ni *et al.* 2004). The high seed production potential of BYG increases its seedbank in the soil and makes weed control practices more difficult and expensive particularly when it has evolved resistance to herbicides (Mahajan *et al.* 2020). Seven herbicide resistance mechanisms of action were reported in BYG (Heap 2019). Resistance-management programmes are likely to fail if the seedbank renewal of resistant individuals is not entirely arrested (Bagavathiannan *et al.* 2012). Thorough knowledge about biology of BYG is fundamental for designing effective management programmes (Gressel 2011). Seed production and seed shattering of weeds are important determinants of long-term weed population dynamics (Mahajan *et al.* 2020), and weed management programmes that do not aim beyond a single growing season will probably be ineffective (Vijayakumar *et al.* 2022). Weed seeds should be collected before the weed seed rain as it creates the opportunity to prevent their input into the soil weed seedbank. The recent concept of harvest weed seed control (HWSC) aims to prevent the enrichment of

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soil weed seedbank and the efficacy of HWSC depends upon seed retention and seed shattering pattern of the target weed species at crop maturity (Vijayakumar *et al.* 2022). However, the efficacy of these systems is reliant on a high proportion of weed seeds being retained on the plant and collected during harvest.

The reproductive potential of BYG is affected by the time of emergence relative to cotton and rice (Bagavathiannan *et al.* 2012; Chauhan 2013). The BYG emerged 5 and 7 weeks after crop emergence in rice and cotton respectively reported to produce a significant amount of seeds (Bagavathiannan *et al.* 2012). The BYG emerged under wide rows spacing produce greater biomass and more seeds than under narrow rows (Chauhan and Johnson 2010). A greater understanding of specific weed–crop interaction as a function of the time of weed emergence and crop spacing will aid the formulation of effective weed management strategies (Pooja *et al.* 2021a; Ramesh *et al.* 2021). The level of seed shattering in a species is likely influenced by agro-ecological and environmental factors (Schwartz-Lazaro *et al.* 2021). For example, in rice, BYG seed production ranged from 2800 seeds/plant when it emerged with the crop to 100 seeds/plant when it emerged 45 days after rice emergence (Chauhan and Johnson 2010). Understanding of weed biology is critical for devising effective weed management strategies (Gressel 2011) as earlier researchers have proven that BYG seed production is highly variable across crops and environments, yet no such investigations have been carried out in India, where BYG is a major weed in conventional transplanted rice (Rao *et al.* 2021; Saha *et al.* 2021). Such studies will help in finding the suitability of BYG as a candidate weed species for HWSC. Hence, we conducted a two-season field study to evaluate the effect of time of emergence and transplanted rice spacing on seed production and seed retention of BYG at rice crop maturity.

Methodology

A two-season field study was conducted in the winter season of 2020-21 and 2021-22 in the research farm of ICAR-National Rice Research Institute (Latitude: 20.45°, Longitude: 85.94°), Cuttack, Odisha, India. The study area falls in the tropical monsoon climate, with heavy cyclonic rainfall during the monsoon. The average annual rainfall of the study area is 1500 mm, with 80 percent received between June and September. The maximum temperature, minimum temperature, rainfall, and pan evaporation during the crop season were measured in a meteorological weather station located near the experimental site and are presented in **Figure 1**. The soil texture of the experimental site is silty loam (medium texture) and the average organic carbon is 0.55%, soil reaction is neutral (pH 6.7), available N (120.1 mg/kg), available P (6.5 mg/kg), and available K (50.4 mg/kg).

The experiment was laid out in a split-plot design with four replications. Main plot treatments were crop geometry (M1 - 15 × 15 cm, M2 - 25 × 25 cm) and sub-plot treatments were time of BYG emergence [S1 - 0 days after transplanting (DAT); S2 - 20 DAT; S3 - 40 DAT]. The short duration (120-125 days) rice cultivar 'Naveen' was used. The experimental field was puddled twice and levelled before transplanting. The 25-30 days old rice seedling were transplanted (2-3 seedling/hills) as per the treatment geometry. In S1, the BYG was not controlled since transplanting. While in S2 and S3 the plots are kept barnyardgrass free until 20 and 40 DAT. All other weeds in the experimental field during the crop season were removed by manual weeding at regular intervals. All other agronomic management practices like irrigation, fertilizer application (80-40-40 kg NPK per hectare), disease and insect pest management were carried out as per the standard recommendation. The density of BYG in 1 × 1 m quadrat was counted manually and multiplied with gross plot size (8 m × 7 m) to derive the total number of BYG per plot. The panicle lengths and leaf lengths were measured in each plot in five randomly selected plants using a measuring scale and the average is expressed in cm. In each treatment, the number of panicles per BYG was recorded for five randomly selected plants and the average was computed for statistical analysis. Similarly, five BYG was cut at ground level from each plot after flowering and sun-dried for about one week and the dry weight was measured and the average is

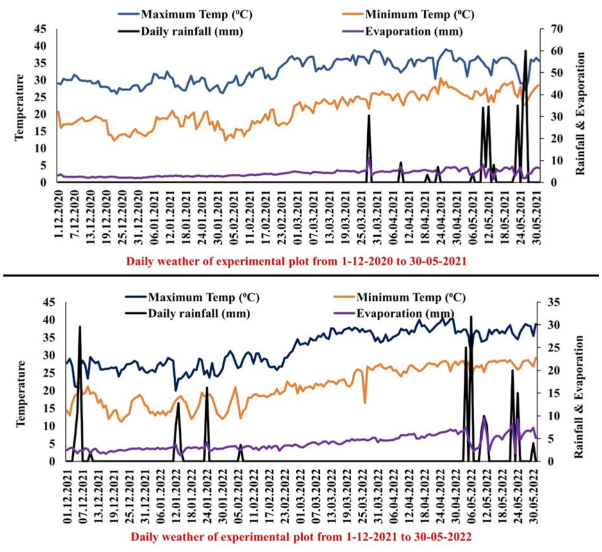

Figure 1. Daily weather of experimental plot during the crop season

expressed in gram (g). Before the installation of the trap, from each plot, the height of five BYG was measured using a 1 m measuring scale and the average is expressed in cm.

In order to study the weed seed production and shattering pattern of BYG, we developed a low-cost weed seed trap using a porous net (galvanized iron wire), plastic nylon tie, polyethylene bag and bamboo stick (**Figure 2**). After the initiation of panicles in BYG, the trap was installed in the field. One trap was installed in each plot. Height of the trap was modified according to the height of BYG by adjusting the length of bamboo stick at the time of installation. The polythene bag was fixed in the bottom of the trap using cello tape and the shattered weed seeds were collected at 20 days after installation (DAI) and at harvest and the shattered seeds were counted manually. Before one day of crop harvest, the BYG panicle inside the trap was harvested to count the un-shattered weed seeds. The total weed seed production per panicle was calculated by summing shattered and un-shattered weed seeds. The shattering percentage of BYG was calculated using the following formula.

$$\text{Shattering percentage} = \frac{\textit{Number of shed seeds collected}}{\textit{Total number of seed produced}} \times 100$$

$$\textit{Total seeds per panicle} = \textit{Shattered seeds @ 20 DAI} + \textit{Shattered seeds @ harvest} + \textit{Unshattered seeds @ harvest}$$

$$\textit{Total seeds per BYG} = \text{Average number of panicle per BYG} \times \text{Average number of seeds per panicle}$$

An exponential function was used to regress the weed count and reproductive traits of BYG (panicle length, panicles/plant, and seeds/plant) relative to the time of emergence (Eqn 1).

$$y = ae^{-bx} \quad ---------- (1)$$

Where, y is the predicted variable (weed count, panicle length, panicles/plant and seeds/plant), a represents the reproductive potential of BYG when it emerges with the crop, e is the exponent, b is a fitted constant and x is the time of weed emergence.

The experimental data were analysed in the Strengthening Statistical computing for National Agricultural Research System (SSCNARS) portal. The F-test was used to decide the significant effects of crop spacing and time of emergence of BYG on seed production and shattering of BYG and the least significant difference (LSD) was used to compare means.

Figure 2. Weed seed trap installed in the experimental field

RESULTS AND DISCUSSION

The number of BYG per plot was found influenced by both crop geometry and its time of emergence. Among the crop geometry, the highest BYG density (1698/plot) was recorded at M2 (25 × 25 cm), and the crop geometry M1 (15 × 15 cm) recorded 15% lower BYG density (1448/plot) compared to M2 (**Table 1**). It shows, a significant decrease in the density of BYG in closer crop spacing compared to wider crop spacing. This might be due to the early closure of the ground surface in M1 as the seedling were transplanted in closer spacing compared to M2 which had wider crop spacing. With respect to BYG emergence, the highest weed density (3274/plot) was recorded in S1 (BGY emergence from 1st DAT) while the lowest density (270/plot) was recorded in S3 (BGY emergence from 40 DAT). The weed density in S3 and S2 plots were lower by 92% and 64% respectively over S1 (**Figure 3**). In S3 the ground surface was covered well by crop plants at 40 DAT as the rice crop produced more dry matter. The complete closure of the crop canopy in turn reduces the germination of BYG and ultimately its density. Whereas, in S1 the ground surface was not covered well as the rice seedling were very young. This shows that the emergence of BYG was reduced with increasing days after transplanting and the higher density of BYG in S1 over S3 is clearly visible at the panicle initiation stage of the rice crop. The dark red coloured panicle of BYG made it easier to distinguish with rice crop.

The height of BYG was not affected significantly by crop geometry whereas the time of emergence of BYG after rice transplanting showed statistical significance (**Table 1**). The significantly highest BYG height (123 cm) was recorded in S1 (BGY emergence from 1st DAT) while the lowest height (107.3 cm) was recorded in S3 (BGY from 40 DAT). The height of BYG was taller than the rice crop in S1 while in S3 it was almost equal to the rice crop. This could be due to the early emergence and competitive advantage of BYG over the rice crop in S1. BYG outgrew rice in height and was able to shade it due to its ability to intercept a greater amount of light with its increased height. BYG seedlings that emerge concurrently with rice seedlings were tall enough to avoid crop shading. Therefore, the shade should occur early in the season to suppress the emergence of BYG in comparison to rice. The tall-growing character of BYG enabled late emerged weed to compete with rice and resulting in significant seed production. The dry matter production, leaf length, leaf number, and panicle number per BYG plant were found to reduce significantly with a delay in its emergence (**Table 1**). Between the crop geometry, the higher weed biomass was recorded in M2 (25 × 25 cm) which was 28% higher than M1 (15 × 15 cm). With respect to the time of emergence of BYG, the highest biomass (4.8 g) was recorded in S1 while S3 recorded the lowest BYG biomass (2.9 g). A similar trend was also found in leaf length and the number of leaves per BYG. The highest leaf length was recorded in M2 (25 × 25 cm) and S1 (BYG emergence from 1st DAT) in the crop geometry and time of emergence treatments, respectively. Crop geometry showed a non-significant effect on the number of leaves per BYG while the time of emergence showed a significant effect. The highest number of leaves per BYG was recorded in S1 (14.25) while S3 recorded the lowest (3.5). The maximum number of panicle/BYG was recorded in S1 (BGY emergence from 1st DAT) followed by S2 (BGY emergence from 20 DAT) and S3 (BGY emergence from 40 DAT). The delay in the emergence of BYG by 20 and 40 days resulted in a 41% and 75% reduction in panicle production per BYG respectively (**Figure 3**). Similarly, the narrow crop spacing M1 (15 × 15 cm) reduced the number of panicle production per BYG by 20% over wider crop spacing M2 (25 × 25 cm). BYG would be anticipated to encounter less resource competition while emerging concurrently with the rice crop than cohorts that arose later, allowing for more effective growth and reproduction. In contrast, it was observed that BYG seedlings would face greater competition from the rice when they emerged after the crop that produced a new and robust root system (Bagavathiannan *et al.* 2012).

The lower density, height, biomass, leaf number, leaf length, panicle number and panicle length of BYG in M1 (15 × 15 cm) and S3 (BYG emergence from 40 DAT) might be due to narrow spacing and delayed emergence, respectively. The narrow crop row spacing helped in suppressing the BYG growth by closing the canopy quickly and increasing shade on BYG as weeds compete with crops for moisture, nutrients, light, and space. Under closer spacing (M1) with delayed emergence after 40 DAT (S3), the competition for growth resources (space, nutrients, water, light) increased and favoured the rice crop rather than BYG (Chauhan and Johnson 2011). When compared to BYG grown in full sunlight, the 75 percent continuous shade reduced *E. crus-galli* height by 22% (Chauhan 2013). However, the extent of competition depends on weed density, weed type and weed species. Weed emergence time and growth habit, influenced the extent of weed-crop competition. Competition for above and below-ground resources can affect the growth and development of weeds, as individuals that emerge during the early crop growth stages have the ability to compete well with crops (Gibson et al. 2002). BYG is a C_4 weed and capable of competing well with C_3 crop rice (Bagavathiannan *et al.* 2012).

The reproductive attributes (number of panicles/plant, panicle length and number of seeds/panicle) of BYG were found to decline for each delay in emergence relative to the crop, but some seed

Table 1. The growth, reproduction and shattering of *Echinochloa crus-galli* (BYG) seed as influenced by transplanted rice geometry and time of emergence of *E. crus-galli*

Treatment	No of BYG/plot	BYG height (cm)	No of leaf/BYG	BYG leaf length (cm)	BYG dry weight (g)	No of panicle/ BYG	Panicle length (cm)	Seed count /panicle) (no.)	Total seed/BYG (no.)	Shattered SC (20 DAI)	Shattered SC @ harvest (no.)	Un-shattered SC (no.)	% shattering
Crop geometry													
M1 - 15 × 15 cm	1448.4^{B}	115.0	6.02	19.9^{B}	3.33^{B}	7.75^{B}	15.3	1935	16021^{B}	152^{A}	352	1431^{B}	26.0^{A}
M2 - 25 × 25 cm	1697.5^{A}	117.6	6.26	22.2^{A}	4.65^{A}	9.67^{A}	15.6	1938	20020^{A}	125^{B}	298	1515^{A}	21.5^{B}
LSD (p=0.05)	112.13	NS	NS	1.34	0.46	1.70	NS	NS	3704	9.80	NS	65.06	3.08
Time of emergence of BYG after rice transplanting													
S1 – BYG germination from 1st DAT	3274.1^{A}	123.3^{A}	6.62^{A}	22.4^{A}	4.79^{A}	14.25^{A}	16.8^{A}	184.9^{A}	31988^{A}	395^{A}	1662^{A}	2242^{A}	25.9
S2 - BYG germination from 20 DAT	1175.1^{B}	118.2^{B}	6.09^{B}	20.9^{AB}	4.28^{B}	8.38^{B}	15.5^{B}	133^{B}	16432^{B}	317^{B}	15078^{B}	1958^{B}	22.9
S3 - BYG germination from 40 DAT	269.6^{C}	107.3^{C}	5.71^{C}	19.8^{B}	2.91^{C}	3.5^{C}	14.1^{C}	98.4^{C}	5641^{C}	263^{B}	1248^{C}	1609^{C}	22.3
LSD (p=0.05)	350.4	3.89	0.30	1.82	0.13	1.08	0.49	17.7	2919	69.77	69.65	102.0	NS
Interaction	NS	NS	NS	NS	NS	NS	S	NS	NS	NS	NS	NS	NS

DAI – Days after installation, SC- Seed count, BYG - Barnyardgrass production was still observed when BYG emerged several days after rice (**Figure 3**). Crop geometry showed a non-significant effect on BYG panicle length while the time of emergence showed a significant effect (**Table 1**). The maximum panicle length (16.8 cm) was recorded in S1 (BGY emergence from 1st DAT) while S3 (BGY from 40 DAT) recorded the lowest (14.1 cm). The early emergence of BYG in S1 increased the panicle length by 11% over S3. The total seed production per panicle of BYG was not influenced by crop geometry while the time of emergence of BYG showed statistical significance. The maximum number of seeds per panicle (2242/panicle) was recorded in S1 (BGY emergence from 1st DAT) while S3 (BGY emergence from 40 DAT) recorded the lowest number (1609/panicle) of it. This might be due to the longer growth period of BYG in S1 compared to S3. Whereas, the shorter growth duration of BYG and higher competition for growth resources in S3 led to a lower number of leaves, dry matter production and height. In S1, BYG takes the advantage of early emergence while in S3 rice crop takes the advantage of early emergence. Due to more number of panicles/BYG and seeds/panicle, the total seed production per BYG was higher again in M2 (25 × 25 cm). The increasing crop spacing by 10 cm in each row and column increased the seed production of BYG by 20%. With respect to time of emergence, the maximum seed production per BYG was recorded in S1 (31987) while S3 recorded the lowest (5641) of it. Seed production per BYG was reduced by 82% due to 40 days delay in emergence. BYG seed production was greater when seedlings emerged with the crop, but some seed production was observed even if seedlings emerged several weeks after crop emergence. The current findings confirm earlier findings that the delayed emergence of BYG lowers seed production relative to the crop (Travlos *et al.* 2011). The total seed production per BYG plant was influenced significantly by the time of emergence of BYG while different crop spacing showed a non-significant effect on it. According to Mitich (1990), BYG can produce up to 1 million seeds/plant under ideal growing conditions, but BYG seed production was highly variable across environments (Bagavathiannan *et al.* 2012).

Both crop geometry and the time of emergence of BYG influenced the seed shattering of BYG. At 20 days after installation (DAI), the maximum seed shattering (152 no./panicle) was recorded in crop geometry 15 × 15 cm (M1) which is 18% higher than M2 (25 × 25 cm). However, at harvest, the crop geometry showed a non-significant effect on BYG seed shattering. Among the sub-plot treatments, the maximum BYG seed shattering was recorded in S1 (BGY emergence from 1st DAT), which is higher by 46% and 50% at 20 DAI and at harvest respectively

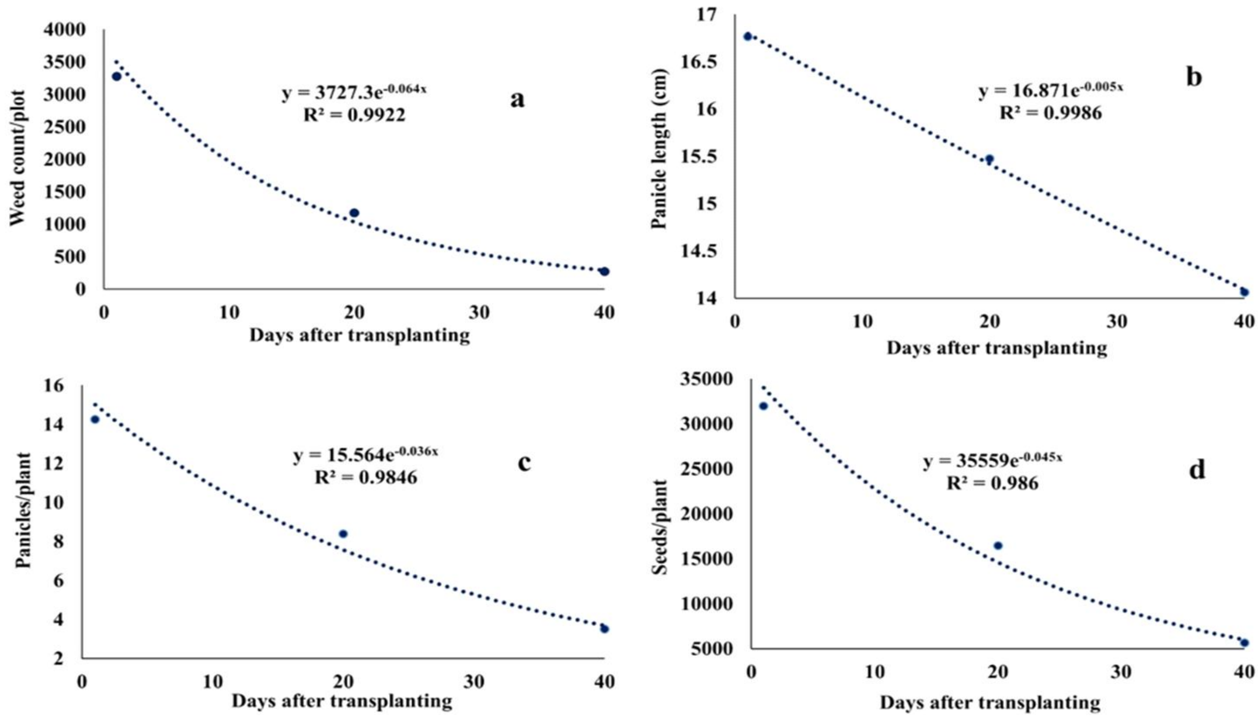

Figure 3. Regression curve for barnyardgrass density (a), panicle length (b), panicles/plant (c) and seeds/plant (d) at different times of emergence in transplanted rice. The data conformed to an exponential relationship ($y=ae^{-bx}$), where a is the initial value that starts the exponential function and b is the fitted constant. The quality of the model fit was expressed using the R^2 value.

over S3. The un-shattered BYG seeds are higher in wider crop geometry i.e. 25 × 25 cm compared to closer crop geometry. The percentage of un-shattered BYG seeds in M2 is 6% higher over M1. The higher BYG seed shattering in M1 might be due to higher competition and early maturity of seeds. With respect to the time of emergence of BYG, the maximum number of un-shattered seeds is recorded in S1 (1662/panicle) while S3 recorded the lowest (1248/panicle). The late emergence and late maturity of BYG in S3, resulted in the lowest number of un-shattered seeds. Although the number of shattered seeds was higher in M1, the percentage of seed shattering was significantly more in M2 (25 × 25 cm) compared to M1 (15 × 15 cm). However, the time of emergence of BYG showed a non-significant effect on shattering percentage though the delayed emergence showed a numerically lower shattering percentage. The seed shattering per BYG was found in the range of 22 to 26%. It reveals that almost 75% of the seed produced by BYG remained intact at the time of harvest. This makes BYG a suitable candidate for HWSC. Removing BYG at the time of harvest by any HWSC method could prevent the enrichment of soil weed seedbank significantly. Shading by the rice canopy is an important mechanism of interference between rice crops and BYG. The growth and reproduction of shaded BYG are significantly hampered by phytochrome-mediated activities as a result of rice crop canopy formation, which normally limits the quantity and quality of light passing through the canopy. Furthermore, it appears that cohorts that emerge earlier than rice seedlings do not experience the effects of shadowing as severely. But for later cohorts of BYG, there would have been fierce competition for both above and below-ground growth resources. The early establishment gives rice crop a competitive advantage over the BYG. *E. crus-galli* seeds are added to the soil seed bank and affect the sustainability of any weed management strategy; thus, practices that reduce weed seed inputs should be viewed as a critical component of a sustainable weed management approach (Chauhan and Johnson 2010). Shade provided by crop interference, on the other hand, should not be viewed as a stand-alone strategy for BYG management in rice. Several best management practices, such as water management, nutrient management, planting time, weed competitive cultivars, and herbicide use, must be combined (Pooja *et al.* 2021b).

Correlation

There was a positive correlation found between BYG biomass and yield attributes [panicle per plant (r = 0.836), panicle length (r = 0.712), seeds per panicle (r = 0.715), total seeds per plant (r = 0.804), revealing that big plants produce more seeds than smaller plants (**Table 2, Figure 3**). Similarly, a positive correlation

Table 2. Pearson correlation coefficients between growth attributes and yield attributes of barnyardgrass

	WD	WH	WDM	WLC	WLL	PP	PL	SPP	TSPP	SWSCH	SWSC20	UWSC	% S
WD	1												
WH	0.769												
	<.0001	1											
WDM	0.710	0.797											
	0.0001	<.0001	1										
WLC	0.767	0.729	0.722										
	<.0001	<.0001	<.0001	1									
WLL	0.527	0.582	0.737	0.395									
	0.0081	0.0029	<.0001	0.0559	1								
PP	0.941	0.858	0.836	0.802	0.642								
	<.0001	<.0001	<.0001	<.0001	0.0007	1							
PL	0.814	0.774	0.712	0.633	0.605	0.869							
	<.0001	<.0001	<.0001	0.0009	0.0017	<.0001	1						
SPP	0.894	0.857	0.715	0.714	0.465	0.925	0.751						
	<.0001	<.0001	<.0001	<.0001	0.0219	<.0001	<.0001	1					
TSPP	0.951	0.852	0.804	0.794	0.617	0.994	0.844	0.944					
	<.0001	<.0001	<.0001	<.0001	0.0013	<.0001	<.0001	<.0001	1				
SWSCH	0.605	0.454	0.268	0.327	0.090	0.569	0.480	0.727	0.601				
	0.0018	0.0259	0.2048	0.1186	0.6772	0.0037	0.0176	<.0001	0.0019	1			
SWSC20	0.826	0.644	0.413	0.636	0.309	0.799	0.713	0.808	0.808	0.624			
	<.0001	0.0007	0.0450	0.0008	0.1420	<.0001	<.0001	<.0001	<.0001	0.0011	1		
UWSC	0.838	0.892	0.818	0.743	0.561	0.905	0.712	0.942	0.916	0.470	0.669		
	<.0001	<.0001	<.0001	<.0001	0.0043	<.0001	<.0001	<.0001	<.0001	0.0204	0.0004	1	
% S	0.344	0.110	-0.100	0.070	-0.136	0.273	0.284	0.403	0.298	0.875	0.560	0.075	
	0.0998	0.6104	0.6404	0.7468	0.5250	0.1962	0.1786	0.0508	0.1575	<.0001	0.0044	0.7281	1

Note: Weed Density, WH - Weed height, WDM - Weed Dry Matter, WLC - Weed Leaf Count, WLL - Weed Leaf Length, PP – Panicles per plant, PL - Panicle Length, SPP - Seeds per panicle, TSPP – Total Seeds per plant, SWSCH – Shattered weed seed count at harvest, SWSC20 - Shattered weed seed count at 20 days after installation, UWSC – Un shattered weed seed count, % S – percentage shattering was also found between weed height and yield attributes [panicle per plant (r = 0.858), panicle length (r = 0.774), seeds per panicle (r = 0.857), total seeds per plant (r = 0.852), revealing that tall plants produce more seeds than short plants. The positive correlation between total seeds per plant and yield attributes [panicles per plant (r = 0.994), panicle length (r = 844), seeds per panicle (0.944)] reveals the total seed production of BYG is highly influenced by yield attributes. However, no correlation was found between BYG leaf length and yield attributes (**Table 2, Figure 3**). Similarly, no correlation was found between shattering percentage and growth (weed density, weed height, weed biomass, weed leaf count, weed leaf length) and yield attributes (panicles per plant, panicle length, seeds per panicle, total seeds per plant) of BYG. The positive correlation between non-shattered weed seed count and growth and yield attributes reveals healthier plants may shatter fewer seeds than weaker plants (**Table 2**). Alternatively, the plant which grows tall, produces more leaves, dry matter, large panicle size and more panicles per plant will retain more of the seeds it produces and shatter only a very less number of seeds.

Conclusion

Characteristics like longer duration of emergence and tall growing nature of BYG enables it competitive with high seed production. BYG seedlings that emerge 40 DAT could produce a significant number of seeds and contribute to the soil seed bank. The majority of the seeds (~75%) produced by BYG are retained in the mother plant at the time of rice crop harvest. This makes BYG a suitable candidate for HWSC. Additionally, the closer crop spacing reduces the density of BYG compared to wider spacing. Thus, crop competitiveness against weeds can be increased by using production strategies like closer row spacing and higher planting density. Cultural approaches that delay the emergence of BYG or approaches that make the associated rice crop more competitive will be useful in integrated management programmes.

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RESEARCH ARTICLE

Enhancing herbicide efficacy with improved spray technology adoption in rice-wheat cropping system

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ABSTRACT

The spraying herbicides with unrecommended spray technology using gun sprayers/knapsack sprayers equipped with single hollow-cone or flat-fan nozzle and lower water volume, has been one of the important factors responsible for the lower efficacy of herbicides in rice-wheat cropping system in Punjab, India. The improved spray technology, involving spraying with tractor operated multi-boom sprayer fitted with flat-fan nozzles, was compared with farmer's practice in rice-wheat system adopting farmers' field in Amritsar County during 2015-16 and 2016-17. In dry-seeded rice, pre-emergence application (PE) of pendimethalin alone and its tank-mix with pyrazosulfuron were used, and in wheat, pendimethalin alone and pre-mix of sulfosulfuron plus metsulfuron-methyl were used for weed management. The major weed flora in dry-seeded rice included: *Dactyloctenium aegyptium, Echinochloa colona, Echinochloa crus-galli, Leptochloa chinensis* and *Digitaria ciliaris* and in wheat, *Phalaris minor* was the dominant weed. The improved spray technology enhanced weed control by 93% in dry-seeded rice and by 95 % in wheat, compared to farmer's practice. The study indicated good scope for enhancing herbicides efficacy by the use of appropriate recommended spray technology

Keywords: Direct-seeded rice, Herbicides efficacy, Rice-wheat cropping system, Spray technology

INTRODUCTION

Rice-wheat cropping system is the most important cereal based cropping system in India. In Indo-Gangetic Plains adoption of rice wheat system is faced with severe competition from several grassy and broad-leaved weeds during crops growth period depending upon the adopted agronomic practices, weed control techniques, soil types and underground water quality. The herbicides use resulted in improved crops yield but the inappropriate use of herbicides is causing herbicide resistance evolution in addition to increasing financial burden on farmers. Due to the use of unrecommended sprayers and spraying methods *i.e.*, gun sprayers equipped with single hollow-cone or flat-fan nozzle and using lower water volume, the adequate volume of herbicides never reaches target weeds resulting in spray loss due to drift of sprayed herbicides (Mohammed *et al.* 2021). This has been one of the important factors responsible for the lower efficacy of herbicides in rice-wheat cropping system in Indian Punjab. The herbicides *viz.* clodinafop, sulfosulfuron and fenoxaprop were recommended to control isoproturon resistant population of *Phalaris minor* which provided effective control of it up to 2007 and improved the productivity of wheat crop. But due to the continuous use of these herbicides resulted to the development of resistance to alternate herbicides too, in *P. minor* (Dhawan *et al.* 2012).

In Punjab, having more than 90 per cent irrigated areas, weed problem is becoming sever due to increased cropping intensity. The yield losses vary from 5% to 100% have been reported in different crops of different areas depending upon the weed density, frequency, type and intensity of competition for growth / yield components (Khaliq *et al.* 2012). The weed management using hoeing, harrowing and cultivation practices has become difficult in Punjab and farmers are opting for herbicides for weed management as proper weed management at the time of seeding or immediately afterwards, crop plants can make the best use of soil and environmental resources leading to enhanced crop productivity. However, the use of unrecommended spray technology, spraying herbicides with gun sprayers/knapsack sprayers equipped with single hollow-cone or flat fan nozzle and using lower water volume, has been one of the important factors responsible for the lower efficacy of herbicides in rice-wheat cropping system in Punjab, India.

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Direct-seeded rice (DSR) in *Kharif* season become very popular among the farmers (Kumar and Ladha 2011; Rao *et al.* 2007; 2017) as it has several advantages such as requirement of 35-57% less water and 67% less labour over transplanting rice and have lesser methane emissions (Chauhan *et al.* 2012 and Singh *et al.* 2016). As the impounding of water is absent in DSR, weeds emerging along with crop compete and severely affect the rice productivity (Rao *et al.* 2007). Manual weeding is considered as the best method to control, but it is not economical. In this situation, herbicides play an important role. It is suggested to use sequential application of pre-emergence herbicides followed by post-emergence herbicides in DSR to effectively manage weeds. However, the efficacy of pre-emergence herbicides can vary with herbicides used and the prevailing climatic conditions (Mahajan and Chauhan 2013). Since, area under DSR is rapidly increasing and weeds are the major constraints, efforts to improve herbicides efficacy under DSR system is essential. Thus, the present study was under taken to identify weed control options, improved spray technologies for enhancing weed control efficacy of herbicides in rice-wheat cropping system to enhance DSR productivity and profitability.

MATERIALS AND METHODS

The present study was carried out by Krishi Vigyan Kendra, Amritsar with collaboration of Department of Agronomy, PAU, Ludhiana. The recommended improved spray technology, spraying with tractor operated multi-boom sprayer fitted with flat-fan nozzles, was compared with farmer's practice (**Table 1**) at farmers' field in Amritsar County in rice-wheat system during 2015-16 and 2016-17. Twenty-five farmers from five different villages were selected in each season in both years. During these two seasons of study, an area of 10 ha was covered with plot size of 0.4 ha. The most popular paddy variety PR121 and wheat variety HD2967 were used in these demonstrations. In dry-direct seeded rice, the standard recommendation of pre-emergence application (PE) of pendimethalin 0.75 kg/ha alone is compared with and its tank-mix with pyrazosulfuron 0.015 kg/ha and farmer's practice (only post-emergence herbicides) (**Tables 2** to **5**). In wheat, treatments *i.e.*, pendimethalin PE and pendimethalin PE followed by (*fb*) post-emergence application (PoE) of pre-mix of sulfosulfuron plus metsulfuron-methyl were compared with farmer's practices for controlling weeds. The major weed flora in dry-direct seeded rice included: *Dactyloctenium aegyptium, Echinochloa colona, Echinochloa crus-galli, Leptochloa chinensis* and *Digitaria ciliaris;* while in wheat, *Phalaris minor* was the dominant weed along with *Chenopodium album, Medicago polymorpha, Melilotus indica* and *Rumex dentatus.*

Before conducting the trial, a survey was conducted to understand the basic problems of weed control with respect to herbicide resistance in rice-wheat cropping system (**Table 1**). 50 farmers were interviewed using a structured questionnaire on different aspects of weed control in DSR and wheat. Later, farmers were selected for conducting demonstrations. Training was imparted to the selected farmers prior to conducting the demonstration. The package of practices used in DSR (**Table 2**) and wheat (**Table 3**) demonstrations and cultural practices currently used by farmers in DSR differed (**Table 2** and **3**). In all the demonstrations, DSR sowing was done with DSR machine and weedicides were sprayed with tractor

Table 1. Herbicides and herbicide spray techniques used, as reported by farmers, in direct-seeded rice and wheat

Parameter	Details	Rice farmers (%) N= 50	Wheat farmers (%) N=50
Herbicides	Only pre-emergence herbicides used	15	12
	Only post-emergence herbicides used	20	75
	Both pre- and post-emergence herbicides used	25	13
	Herbicide use plus hand weeding	40	-
Post- emergence application time	20 days after sowing	51	-
	20-30 days after sowing	40	-
	30-40 days after sowing	09	55
	40-50 days after sowing	-	45
Type of nozzle used	Flood jet/ cone type	61	47
	Flat-fan/cut type	39	63
Volume of spray (l/ha)	225	22	25
	300	34	35
	375	44	40
Type of spray pump	Power operated gun sprayer	73	81
	Power operated knapsack sprayer	27	29

mounted spray pumps fitted with flat fan nozzles. Also, application of recommended dose of fertilizers at right time and in right method as well as need-based plant protection measures were emphasized and comparison has been made with the existing farmers' practice (**Table 2**). The data on weed density were recorded by randomly placing 1 m^2 quadrat at two places per plot at sampling time of 30 days after seeding (DAS) in rice and 50 DAS in wheat. The weed density data was subjected to square root transformation before statistical analysis. The original values were given in parentheses. Weed control efficiency was calculated based on weed dry weight (biomass) recorded using standard procedures. The data were analysed by using standard statistical procedures and comparisons were made at 5% level of significance.

RESULTS AND DISCUSSION

Effect on weeds

In dry-direct seeded rice, pendimethalin and tank mix with pyrazosulfuron-ethyl PE sprayed with the improved spray technology resulted in higher weed control efficiency (71.4 and 73.5% in respective two years) as compared to farmer's practice (40.6 and 40.4%). Same trend was observed in wheat where the sequential spray of pendimethalin PE followed by (*fb*) sulfosulfuron plus metsulfuron-methyl with improved spray technology enhanced weed control efficiency as compared to farmer's practice (**Table 4**) indicating the vast scope for enhancing herbicides efficacy with the use of recommended spray technology. Pendimethalin PE usage with improved technology also achieved higher /equal weed control efficiency in both rice and wheat crop when compared to the farmer's practice of using gun sprayers.

Effect on Crop

All the herbicide applications resulted in significantly higher yield as compared to the non-treated plot. The application of pendimethalin PE alone with tractor mounted spray pump resulted in higher yield than farmer's practice in both rice and wheat crop (**Table 4**) confirming findings of Hundal and Dhillon (2018). The sequential application of pre- and post-emergence herbicide with tractor mounted spray pump resulted in highest yield of both rice and wheat. Thus, with the help of improved, recommended mechanized techniques, farmers realize higher profit with effective herbicides use which may lessen herbicide resistance.

Table 2. Comparison between cultural practices used in direct-seeded rice (DSR) in demonstrations and Farmers practice

Particulars/cultural practice	DSR (Demonstration)	DSR (Farmer's practice)
Farming situation	Irrigated	Irrigated
Soil type	Clay loam	Clay loam
Variety	PR 121	PR121
Time of sowing	10 to 12th, June	20thMay
Methods	DSR drill	Broadcast
Spacing	20 cm line to line	-
Seed treatment	Carbendazim 2g/kg seed	Carbendazim 2g/kg seed
Seed rate	20 kg/ ha	25 kg/ ha
Fertilizer dose	N= 150 kg/ha and 62.5 kg/ha Zinc sulphate heptahydrate (21%). No Phosphorus and Potash was required as per the soil test report	N= 200 kg/ha and 50 kg/ha Zinc sulphate heptahydrate (21%) No Phosphorus and Potash was required as per the soil test report
Fertilizer application time and methods	N fertilizer applied in three equal splits after 2,5 and 9 weeks after sowing and full Zn applied after 5 weeks	Urea applied in three splits *i.e.*, after 2,4, 6 weeks after sowing. Zinc applied 4 weeks after sowing.
Water management	First irrigation was given immediately after sowing and then irrigation given at 10 days interval according to the requirement.	First irrigation was given immediately after sowing and then irrigation given at 4-5 days interval
Weed management Pre-emergence	Tank mix application of pendimethalin 0.75 kg /ha with pyrazosulfuron-ethyl 0.015 kg/ha	Pendimethalin 0.75 kg/ha sprayed as pre-emergence
Weed management Post emergence	Bispyribac 0.025 kg /ha 25 days after sowing	Bispyribac 0.025 kg/ha 35days after seeding (DAS) and one hoeing
Type of spray pump used	Tractor operated multi-boom sprayer fitted with flat fan nozzles	Gun sprayer
Plant protection	Application of cartap hydrochloride 0.32 kg /ha to protect from stem borer at active tillering stage One application of propiconazole 0.075 kg /ha for controlling the sheath blight	Application of cartap hydrochloride 0.32 kg /ha to protect from stem borer at active tillering stage One application of propiconazole 0.075 kg /ha for controlling the sheath blight
Days taken to maturity	Second fortnight of October	Second fortnight of October

Economics

The cost of cultivation under DSR was minimum compared to farmers practice (**Table 5)** in spite of usage of similar inputs. Due to higher weed competition the yield was lesser in farmer's practice. Net returns with pendimethalin and its tank mix with pyrazosulfuron-ethyl PE *fb* bispyribac-sodium PoE were higher due to direct-seeding of rice with seed drill which requires less labour. In this treatment, weeds were controlled effectively with the use of tractor mounted spray pumps. Net return was higher mainly due to lower cost of cultivation and higher return (**Table 5**) due to the spray technology which helped to reduce the cost of cultivation.

Across the locations, all the weed control treatments provided significantly higher returns and B:C over the weedy check. Sequential application of herbicides proved to be best over the sole application of pre-emergence herbicide and farmer's practice. In rice, the pendimethalin and its tank mix with pyrazosulfuron-ethyl PE recorded higher B:C than sole pendimethalin PE alone and farmer's practice confirming findings of Choudhary and Dixit (2018).

In case of wheat crop, pendimethalin PE alone proved better than farmer's practice in terms of net returns and B:C. In general, in rice-wheat cropping system, sequential application of pre- and post-emergence herbicide with tractor mounted spray

Table 3. Comparison between cultural practices used in wheat demonstrations and the wheat farmers fields

Particulars	Wheat demonstration	Wheat farmers fields practice
Farming situation	Irrigated	Irrigated
Soil type	Clay loam	Clay loam
Variety	HD 2967	HD 2967
Time of sowing	10 to 15th November	1-10th Nov
Methods	Drill	Drill
Spacing	20 cm line to line	20 cm line to line
Seed treatment	Tebuconazole 130 ml for 100 kg of seed	Tebuconazole 130 ml for 100 kg of seed
Seed rate	100 kg/ ha	100 kg/ ha
Fertilizer dose	125 kg/ha N and 62.5 kg/ha P and no K required.	125 kg/ha N and 62.5 kg/ha P and no K required.
Fertilizer application time and methods	Full dose of DAP applied at the time of sowing and the urea applied in two splits after 1st and 2nd irrigation	Full dose of DAP applied at the time of sowing and the urea applied in two splits after 1st and 2nd irrigation
Water management	Four irrigations were given as per the need	Four irrigations were given
Herbicide - pre-emergence	Pendimethalin 0.75 kg/ha	No pre-emergence spray
Herbicide - post emergence	Post-emergence spray at 35 DAS of sulfosulfuron plus metsulfuron-methyl 0.03 kg/ha	Tank mix application of clodinafop 0.06 kg/ha and sulfosulfuron 0.024 kg/ha
Type of spray pump used	Tractor operated multi-boom sprayer fitted with flat fan nozzles	Gun sprayer
Plant protection	Application of thiamethoxam 0.0075kg/ha to protect from aphids and jassid at boot stage. One application of propiconazole 0.075 kg/ha for controlling the yellow rust	Application thiamethoxam 0.0075kg/ha to protect from aphids and jassid at boot stage. One application of propiconazole 0.075 kg/ha for controlling the yellow rust
Days taken to maturity	2nd fortnight of April	2nd fortnight of April

Table 4. Comparative efficacy of herbicide treatments in direct-seeded rice and wheat

Treatment	Dose (kg/ha)	Weed density at 30 DAS (no./m^2)		Weed biomass at 30 DAS (g/m^2)		WCE at 30 DAS (%)	
		2016	2017	2016	2017	2016	2017
Direct-seeded rice							
Pendimethalin_ PE	0.75	4.4(19.0)	4.3(18.0)	7.3(53.0)	7.1(49.7)	59.5	58.6
Pendimethalin and tank mix with pyrazosulfuron-ethyl PE *fb* bispyribac-sodium PoE	0.75 + 0.015 +0.025	3.5(11.7)	3.8(13.7)	6.2(37.3)	5.7(31.7)	71.4	73.5
Farmer's practice (pendimethalin PE *fb* bispyribac- sodium PoE)	0.75 + 0.025	6.6(43.0)	6.4(40.0)	8.8(77.6)	8.5(72.0)	40.6	40.4
Weed free	-	1.9(2.7)	1.6(1.7)	2.6(6.0)	1.8(2.3)	95.3	98.1
Weedy	-	8.0(63.3)	7.8(60.6)	11.5(131.7)	11.0(121.3)	00	00
LSD (p=0.05)	-	1.1	1.0	0.8	0.7	7.7	6.59
Wheat							
Pendimethalin PE	0.75	5.5(29.0)	5.3(27.3)	8.7(74.7)	8.4(70.0)	41.5	38.1
Pendimethalin PE *fb* sulfosulfuron plus metsulfuron methyl PoE	0.75 + 0.03	4.6(20.3)	4.5(20.0)	5.7(32.0)	5.5(29.3)	74.9	74.3
Farmer's practice (tank mix clodinafop and sulfosulfuron -PoE)	0.06 + 0.024	6.8(45.0)	6.5(41.3)	8.5(72.3)	7.9(63.0)	43.2	44.1
Weed free	-	2.1(3.7)	1.8(2.33)	3.0(8.3)	2.7(6.3)	93.4	94.4
Weedy	-	8.6(73.7)	8.4(69.7)	11.3(127.7)	10.7(113.6)	00	00
LSD (p=0.05)	-	0.9	1.2	0.6	0.8	8.5	11.8

LSD-least significant difference at the 5% level of significance; DAS-Days after sowing; Figures in parenthesis are original values subjected of square root transformation; PE-Pre-emergence; PoE- Post emergence; *fb*- Followed by; WCE: Weed control efficiency

Table 5. Yield and economic returns of herbicide treatments in rice-wheat cropping system

Treatment	Dose (kg/ha)	Yield (t/ha)		Net returns (x10^3 `/ha)		B:C	
		2016	2017	2016	2017	2016	2017
Direct-seeded rice							
Pendimethalin PE	0.75	6.7	6.8	69.41	737.26	3.2	3.14
Pendimethalin and tank mix with pyrazosulfuron-ethyl PE *fb* bispyribac-sodium	0.75+0.015 +0.025	7.2	7.3	77.14	81.10	3.4	3.33
Farmer's practice - pendimethalin PE *fb* bispyribac-sodium - PoE	0.75 + 0.025	6.5	6.6	64.24	67.73	2.84	2.79
Weed free	-	7.4	7.5	78.78	84.02	3.43	3.38
Weedy	-	4.5	4.4	37.68	37.81	2.25	2.15
LSD (p=0.05)	-	0.6	0.7	-	-	-	-
Wheat							
Pendimethalin PE	0.75	4.7	4.8	63.78	77.09	3.74	4.24
Pendimethalin PE) *fb* sulfosulfuron plus metsulfuron-methyl PoE	0.75 + 0.03	5.1	5.0	70.85	81.35	3.85	4.27
Farmer's practice - tank mix of clodinafop and sulfosulfuron PoE	0.06 + 0.024	4.7	4.6	60.67	72.39	3.26	3.69
Weed free	-	5.4	5.3	75.08	88.85	4.02	4.57
Weedy	-	2.5	2.6	24.26	32.11	2.1	2.46
LSD (p=0.05)	-	0.4	0.6	-	-	-	-

LSD-least significant difference at the 5% level of significance; B:C- Benefit: cost ratio; DAS-Days after sowing; Figures in parenthesis are original values subjected of square root transformation; PE-Pre-emergence; PoE- Post-emergence; *fb*- Followed by

pump proved to be the best option for higher profit and lesser herbicide load.

Conclusions

It may be concluded that improved agronomic technologies with recommended method of herbicide spray helps farmers to attain higher crops productivity and net returns in rice-wheat cropping system.

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RESEARCH ARTICLE

Development and performance evaluation of herbicide applicator-cum-planter to manage weeds in soybean

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ABSTRACT

Manual weeding or herbicide application using manual operated tools/equipment are commonly used by farmers to manage weeds in *Kharif* season and they are laborious and time-consuming. During the rainy season, mechanical weed management is difficult in the early stages of crop growth due to prevailing environment. To address this issue, the ICAR-CIAE, Bhopal, conceived and developed a tractor-operated 6-row pre-emergence herbicide strip-application system used in conjunction with an inclined-plate planter to manage weeds in widely spaced crops. The developed pre-emergence herbicide applicator-cum-planter (PREHAP) was evaluated, during the *Kharif* season, to compare its efficacy using different pre-emergence herbicides with hand weeding and inter cultivation between crop rows for weed management in soybean. The lowest weed density and weed infestation were observed with the broadcast application of pre-emergence herbicide with PREHAP followed by one hand weeding and resulted in highest soybean plant height, number of pods, seed yield, net economic return and B:C. The PREHAP that could spray herbicide in both band and wide area was found to be a good way to apply herbicide while sowing the crop .

Keywords: Herbicide applicator cum planter, Herbicide, Inclined plate planter, Soybean, Weed management

INTRODUCTION

Weed control is extremely crucial to achieve optimal production and productivity of various cultivated crops. Weeds compete with cultivated crops for moisture, nutrients sunlight, and space. It has been reported that if adequate weed control measures are not used, crop yield can be reduced by more than, 50% (Gharde *et al.* 2018). Weed control operations are mainly carried out after the emergence of the crop and weeds. Weed management is done using mechanical, cultural, and chemical approaches. Mechanical weed management comprises just pulling away the weeds by hand or the use of equipment and machines operated by animal or mechanical power sources or their combination. Manual weeding is a highly labour-demanding, drudgery involved, time-consuming, and costly operation (Kumar *et al.* 2019, Kumar *et al*. 2021; Chethan *et al.* 2022). The heavy machines used in mechanical weed control disrupt the soil surface, resulting in soil erosion and loss of nutrients. Weed management with herbicides does not create soil disturbance but may have detrimental impact on the environment. Integrated weed management (IWM) aims to minimise environmental problems, boost economic returns and adoption of non-chemical approaches without reducing yield levels (Swanton and Weise 1991, Rao and Nagamani 2010, Niazmand *et al.* 2008, Talnikar *et al.* 2008). To control the weeds at different stages of the crop's growth, the herbicide can be administered pre-planting, pre-emergence, and post-emergence of the crop. The herbicides are primarily applied either by broadcasting or by banding along the crop rows.

Broadcasting, *i.e.*, spraying of herbicide over an entire agricultural field, is the existing practice of herbicide application in India. The excessive use of herbicides results in environmental problems such as entering the herbicide into underground water resources and deep wells or movement of the herbicide to far places by rainwater or flooding (Kalkhoff *et al*. 2003). Applying herbicide along crop rows, i.e., banded application (Swanton *et al.* 2002, Sankula *et al*. 2001) and mechanical cultivation between the rows, can solve the problem (Malik *et al.* 2006). Herbicide banding consists of spraying herbicide primarily over the crop rows, covering a width of around 200–300 mm. The weeds in the gap between two crop rows could be controlled either manually or mechanically.

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The biggest challenge in carrying out weeding activities is the erratic and continuous rains during the *Kharif* season. Due to climate change, the monsoon pattern has changed drastically. This resulted in persistent heavy rainfall, generating flood like scenarios in some areas and frequent dry periods in other sections of the country. Therefore, a lack of opportunity time makes mechanical as well as chemical weed management problematic in the initial stages of crop growth. In such situations, the application of pre-emergence herbicide along with sowing or planting operations in either band or broadcast mode will provide better control over the weed in the early stages of crop growth. When the pre-emergence herbicide is applied concurrently with the sowing or planting device, both time and money can be saved. In addition, it is evident that banded application of herbicide with mechanical cultivation can minimise herbicide consumption by up to 50% without decreasing crop production. Thus, a pre-emergence herbicide applicator-cum-planter (PREHAP) with a band and broadcast herbicide-spraying ability was developed and the developed machine was evaluated for different weed control treatments.

MATERIALS AND METHODS

Development of herbicide applicator-cum-planter

The tractor-drawn PREHAP (**Figure 1**) is made up of a frame with a cat-II 3-point linkage, a tool bar, one herbicide solution tank, one single action piston pump, one pressure gauge, hose connections, a fertiliser box, six modular seed boxes attached with spray-nozzle assembly, furrow openers, and a ground wheel drive power system to operate the seed and fertiliser metering mechanisms. The solution tank is made of stainless steel with baffles inside the tank to maintain the centre of gravity in the middle line of the frame. An inside-fitting lid is also provided to prevent spillage during operation. A Micronics fitter assembly is fitted inside the tank, and filtered liquid is sent to the intake port of the plunger pump. The overflow pipe returns excess liquid to the top of the tank. Liquid from the bottom of the tank is conveyed to the inlet of the piston pump through a flexible PVC suction hose. After that, the liquid is conveyed from the outlet of the pump to spray nozzles at a desired pressure, as indicated by a pressure gauge, through flexible PVC delivery hoses. For ease of fixing and leak-proof connections, water-tight standard tank nipples of 12.5 and 20 mm are used for overflow and outlet, respectively. A spray nozzle assembly is attached to the seed boxes with the help of mounting clamps. The mounting clamps have provision for adjusting the angle and height of the spray nozzles, which facilitates the system for accurately applying a strip or broadcast of pre-emergence herbicide. The seed boxes have an inclined plate type seed metering mechanism. Seed plates for sowing different seeds can be selected and easily changed in the seed boxes. The plate thickness, number of cells, and size of cells on the seed plate vary according to seed size and desired plant-to-plant spacing. Bold seeds as well as small seeds can be sown with this planter by just changing the suitable metering plate. In addition,

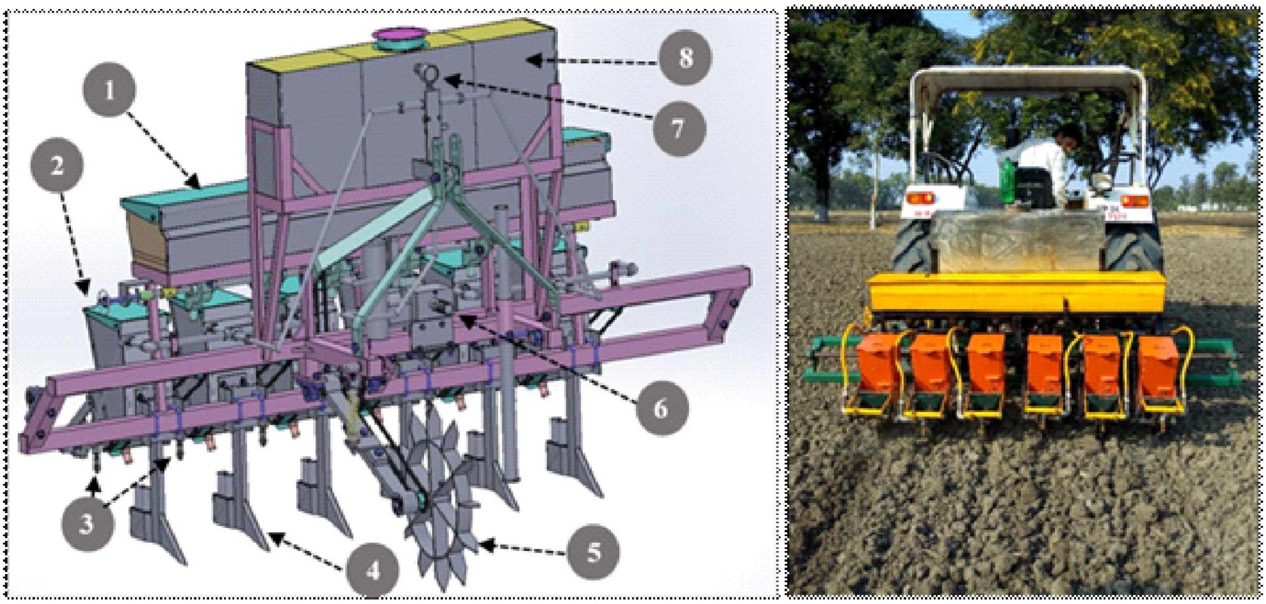

Figure 1. Developed herbicide applicator-cum-planter (1 – Fertilizer box; 2 – Seed box; 3 – Spray nozzle assembly; 4 – Furrow opener; 5 – Ground wheel; 6 – Single-action piston pump; 7 – Pressure gauge; 8 – Herbicide tank)

simultaneous sowing of different intercrops can be possible with the PREHAP. The PREHAP has the benefit that row-to-row spacing between the seed boxes can be easily adjusted. Inverted T-type furrow openers were used for making well-defined groove in the soil for proper placement of the seed. The seed box-furrow opener assemblies are adjustable for sowing seeds at different row-to-row spacings. The fertiliser box, mounted on the main frame, has a fluted roller type metering mechanism for the application of granular fertilizers. All manual adjustments on the PREHAP are made in accordance with ergonomic design principles (Gite *et al.* 2020). The technical details of the PREHAP are given in **Table 1**.

Selection of the spray pump capacity and spray nozzle tip for herbicide application system

For the selection of the spray pump capacity and spray nozzle tip, a few preliminary calculations were made to determine the required spray discharge rate per nozzle tip, total spray discharge rate through all nozzles, and the required spray tank capacity for pre-emergence herbicide application in banded as well as broadcast mode. Generally, the pre-emergence herbicide (pendimethalin) was applied at a rate of 1 kg/ha using 500 L of water (Dixit and Varshney 2009). The required discharge rate per nozzle tip was worked out as 500 mL/min for 450 mm row-row spacing, 200 mm of herbicide band width, and 3 km/h of tractor operating speed. A total discharge rate of 3.0 L/min at pressure 1.0 kg/cm^2 was determined for

Table 1. Technical specifications of the developed herbicide applicator-cum-planter

Particular		Value
Overall dimensions (l×b×h), mm	:	2300 × 1120 × 1010
Size of fertilizer box (l×b×h), mm	:	1600 × 250 × 200
Capacity of fertilizer box, kg	:	150
Machine frame size (l×b×h), mm	:	2510 × 650 × 400
Power source	:	Tractor of 26 kW or higher
No of rows	:	Six
Ground wheel size (diameter), mm	:	540 × 50
Row to row spacing, mm	:	Adjustable from 250 to 450
Seed metering	:	Inclined plates with cells on the periphery made of machined aluminium
Fertilizer metering	:	Casted aluminium fluted rollers.
Furrow openers	:	Inverted T-type
Power train for metering	:	Chain and sprockets and bevel gears
Seed box capacity, kg	:	8 to 10
Number of seed boxes	:	Six
Size of herbicide tank (l×b×h), mm	:	1000 × 200 × 400
Herbicide tank capacity, litres	:	80
Spray pump	:	Single action piston pump of 9 L/min capacity
Spray tip type	:	Flat fan nozzle
Number of spray nozzle tips	:	Six

the whole system for banded mode application of herbicide. Similarly, a discharge rate of 1.125 L/min per nozzle tip and a total discharge rate of 6.75 L/min at pressure 2.0 kg/cm^2 was determined for the whole system for the application of herbicide in broadcast mode. Considering the determined information in the preliminary calculations, a single-action pump having a liquid delivery capacity of 9 L/min was selected. For herbicide applications, flat fan-type spray tips are primarily used (Bindra and Singh 1977). Therefore, the flat fan type of nozzles meeting the desired requirement and commercially available in the market, were selected for the herbicide application during field experiments.

Field experiment

A field experiment was conducted in the *Kharif* 2019 and 2020 for evaluation of the efficacy of the developed PREHAP in *Kharif* soybean crop (variety JS 9560) at ICAR-Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh, India. The experimental farm used in the present study has been under a soybean-wheat cropping system for the last five years, with even topography and a good drainage facility. The study site (Bhopal) is situated at 23.26° N latitude, 77.41° E longitude, and altitude of about 527 m above mean sea level in a humid subtropical climate. The soil of the experimental field was clayey loam in texture with 47-54% clay content, alkaline in nature (pH 7.7), and 0.24 dS/m EC. The field experiments were laid out in a randomized complete block design (RCBD) with three replications and seven treatments of weed control. Each plot size was 100 m^2. The treatments included in the field experiments were: control *i.e.* no herbicide application, no manual/mechanical weeding; intercultivation (hoeing) once between the crop rows; hand weeding once after 30 days after seeding (DAS); banded application of pre-emergence herbicide by PREHAP; broadcast application of pre-emergence herbicide over the entire field by PREHAP; band application of pre-emergence herbicide by PREHAP followed by (*fb*) one manual weeding after 30 DAS; broadcast application of pre-emergence herbicide over the entire field by PREHAP *fb* one manual weeding after 30 DAS.

In the treatments involving no herbicide application, only the planter system of PREHAP was used for seeding of the soybean crop. The developed PREHAP was set at 450 mm of row-to-row spacing between the seed boxes for the soybean crop. The seed metering plates suitable for sowing soybean seeds were mounted in the seed boxes. To operate the

PREHAP, a two-wheel drive tractor (3630 New Holland, CNH Industrial Pvt. Ltd., India) was used as a prime mover for laying down the treatments. During banded and broadcast herbicide application treatments, the pre-emergence application (PE) of herbicide (pendimethalin) at a rate of 1 kg/ha was done using the developed PREHAP, simultaneously with the seeding operation. In banded herbicide application treatments, the pre-emergence herbicide in the band of 200 mm was applied by adjusting the spray nozzle setting. In the case of broadcast herbicide application treatments, spray nozzle tips were adjusted to apply herbicide over the entire field. In order to maintain the weed free experimental plots, the hand weeding was done at 30 DAS using *khurpi*. The nutrients dose of 100 kg/ha of DAP with 18% nitrogen and 46% phosphorous basal recommended for soybean crop in Bhopal region was applied at the time of sowing using PREHAP.

The observations on the weed flora (grasses, broad-leaved and sedges) and weed density were recorded at 60 DAS. The efficacy of the weed management of the different treatments was assessed by weed density in the inter- and intra-row and weed infestation. For the intent of determining the intra-row weed density, segments of crop rows measuring 5 m in length were selected randomly. The weeds emerged in 100 mm of distance on either side along the selected segment of crop row, were measured. Similarly, the 4 m long and 250 mm wide strips between the two subsequent crop rows were randomly selected and measured the inter row weed density. Weed infestation refers to the percentage of weeds in the composite population of weed and crop plants. Weed infestation was calculated using following formula:

$$\text{Weed infestation (\%)} = \frac{\text{(Total number of weeds in unit area)}}{\text{(Total no. weed and crop plants in the same area)}} * 100$$

The data on soybean plant height and the number of pods were also recorded for each treatment prior to the harvesting of the crop. The seed and straw yield data for the different treatments was measured using the standard yield measurement protocol. Weed index for each treatment was determined based on the yield data (Prachand *et al*. 2015). Weed index was computed using the formula given below-

$$\text{Weed index (\%)} = \frac{(X - Y)}{X} * 100$$

Where, X = seed weight (t/ha) in the treatment which has highest yield and Y= seed weight (t/ha) in treatment for which weed index is to be calculated.

The cost incurred for production of soybean for different treatments was estimated. The economic benefit in terms of net return and benefit cost ratio were also determined for each treatment in soybean. The statistical analysis of the recorded data was done using SAS 9.3 software (SAS Institute, Cary, N. C.). The least significant difference (LSD) test was used as post hoc mean separation test ($p<0.05$).

RESULTS AND DISCUSSION

Effect on weeds

The predominant weed flora in the experimental field during both the years of study was: *Brachiaria reptans, Chloris inflata, Dactyloctenium aegyptium, Digitaria lingifora, Eleusine indica* among the grasses, *Acalypha indica, Aerva lanata, Aerva tomentosa, Amaranthus viridis, Chrozophora rottlery, Corchorus olitorius, Euphorbia geniculate* among the broad-leaved weeds and *Cyperus rotundus, Cyperus difformis, Cyperus iria* were among the predominant sedges. Of these, *Cyperus rotundus* was the most dominant weed followed *by Amaranthus viridis* and *Eleusine indica.*

The highest weed density and weed infestation was recorded in untreated control (T1) for both intra- and inter-row of the crop (**Table 2**). The intra-row weed density was higher than the inter-row weed density in one inter cultivation between the crop rows (T2) as mechanical intercultural operations in the intra-row of the crop are difficult. Hand weeding once (T3), banded pendimethalin PE using PREHAP (T4), broadcast pendimethalin PE using PREHAP (T5), banded pendimethalin PE using PREHAP *fb* one hand weeding (T6) and broadcasted pendimethalin PE using PREHAP *fb* one hand weeding (T7) had insignificant effect on the intra-row weed density. The pendimethalin PE using PREHAP controlled broad-leaved weeds and grasses completely but did not control *Cyperus rotundus* (Singh *et al*. 2019). Inter-row weeds were found to be the most abundant in treatments T1 and T4, whereas the inter-row weed densities observed in the treatments T2, T3, T5, T6 and T7 were not significantly different. During both years of field experiments, the treatments T7, T6, T5 and T3 showed good weed control. *Cyperus rotundus* was the most common weed in both the intra-row and inter-row treatments.

The significantly highest weed infestation of 80% was recorded for untreated control (T1), followed by 69% for the banded pre-emergence herbicide application (T4) and 58.6% for the inter cultivation between crop rows (T2) during *Kharif* 2019. Similar results were observed during *Kharif* 2020 with weed infestation of 78.5, 67.5, and 58.1% for the treatments T1, T4, and T2, respectively. The weed control treatments, broadcast pendimethalin PE using PREHAP (T5), banded pendimethalin PE using PREHAP *fb* one hand weeding (T6), and broadcast pendimethalin PE using PREHAP *fb* one hand weeding (T7), had no significant effect on the weed infestation during the field experiments for both years. The lowest weed infestation of 24.2% was observed for the broadcast pendimethalin PE using PREHAP *fb* one hand weeding (T7) during *Kharif* 2019. While during *Kharif* 2020, the lowest weed infestation of 27.9% was observed for broadcasted pendimethalin PE using PREHAP (T5) and might be due to the heavy infestation of the *Cyperus rotundus* weed in other treatment plots. However, the results of weed infestation for the treatments T5, T6, and T7 were found to be similar.

The lowest weed index of 14.3% and 11.9% was observed for the banded pendimethalin PE using PREHAP *fb* one hand weeding (T6) during the *Kharif* of 2019 and 2020, respectively (**Table 2**). The highest weed index of 85.7% in *Kharif* 2019 and 78.4% in *Kharif* 2020 was found in unweeded treatment (T1), followed by the inter cultivation between crop rows (T2) and banded pendimethalin PE using PREHAP (T4). The reason for the highest weed index for the treatments T1, T2 and T4 is the presence of heavy weeds in the intra-row and inter row of the crop during both the *Kharif* seasons. The banded pendimethalin PE using PREHAP and inter-row cultivation of weeds once were not found to be effective measures for controlling weeds. The lower infestation of weeds in the herbicide-applied locations indicated that the herbicide spraying system of the PREHAP performed satisfactorily.

Effect on the crop growth parameters and crop yields

The highest plant height and number of pods per plant was observed with broadcast application of pre-emergence herbicide using PREHAP *fb* one hand weeding (T7) during *Kharif* 2019 and 2020, respectively (**Table 3**). Whereas the lowest plant height of the crop was observed in the unweeded control (T1) during both the crop seasons. However, the plant height and number of pods per plant observed with pendimethalin PE in T5, T6 and T7 was not significantly different. This might be due to lower crop weed competition provided healthy environment during the early stages of the crop's growth. The highest seed yield of 1.40 and 1.34 t/ha was observed for the broadcast application of pendimethalin PE using PREHAP *fb* one hand weeding (T7) during kharif 2019 and 2020, respectively, followed by the banded application of pendimethalin PE using PREHAP *fb* one hand weeding (T6) and broadcast application of pendimethalin PE using PREHAP (T5). However, the seed yield observed in the broadcast application of pendimethalin PE using PREHAP *fb* one hand weeding (T7) and followed by the banded application of pendimethalin PE using PREHAP *fb* one hand weeding (T6) was not significantly different. Similar results were observed in the case of straw yield as in

Table 2. Effect of different weed control treatments on weed parameters in soybean crop at 60 DAS

Treatment	*Kharif* 2019				*Kharif* 2020			
	Weed density (no./m^2)		Weed infestation (%)	Weed index (%)	Weed density (no./m^2)		Weed infestation (%)	Weed index (%)
	Intra-row	Inter-row			Intra-row	Inter-row		
T_1	175^a	271^a	80.0^a	85.7	186^a	296^a	78.5^a	78.4
T_2	142^b	21^c	58.6^c	59.9	134^b	36^d	58.1^c	59.7
T_3	54^c	66^b	51.1^c	39.5	48^c	59^c	48.2^d	39.6
T_4	31^d	254^a	69.0^b	42.9	39^{cd}	218^b	67.5^b	41.8
T_5	24^d	35^c	28.4^d	35.4	27^d	24^d	27.9^f	29.9
T_6	28^d	20^c	27.6^d	14.3	34^d	25^d	33.1^e	11.9
T_7	17^e	23^c	24.2^d	-	31^d	27^d	32.0^{ef}	-
LSD (p=0.05)	14	24	7.8		11	18	4.3	

T_1: control *i.e.* no herbicide application, no manual/mechanical weeding; T_2: intercultivation (hoeing) once between the crop rows; T_3: hand weeding once after 30 days after seeding (DAS); T_4: banded application of pre-emergence herbicide by PREHAP; T_5 : broadcast application of pre-emergence herbicide over the entire field by PREHAP; T_6: band application of pre-emergence herbicide by PREHAP *fb* one manual weeding after 30 DAS; T_7: broadcast application of pre-emergence herbicide over the entire field by PREHAP *fb* one manual weeding after 30 DAS.

the case of seed yield. The lower crop weed competition in the early stages of crop growth resulted in higher soybean seed and straw yield.

Techno-economic feasibility

The broadcast application of pendimethalin using PREHAP with one hand weeding (T7) recorded highest net returns and was followed by the banded application of pendimethalin using PREHAP *fb* one hand weeding (T6) and broadcast application of pendimethalin using PREHAP (T5) (**Table 3**). The treatments without pre-emergence herbicide application fetched lower net returns. The broadcast application of pre-emergence herbicide using PREHAP alone (T5) and *fb* one hand weeding gave the highest B:C and was followed by banded application of pendimethalin using PREHAP (T4) during both the years. The broadcast application of pendimethalin using PREHAP *fb* one hand weeding (T7) proved to be more economical due to better B:C ratio resulted due to better weed control. Due to poor weed control with one inter cultivation between the crop rows (T2) and one hand weeding (T3) resulted in lower B:C ratio and was not found to be cost effective. The results of weed attributes, net returns, and B:C showed that applying a pre-emergence herbicide along with the sowing operation with one-hand weeding results in better weed control and seed yield in a soybean crop. Kushwah and Kushwaha (2001) reported similar results, that pendimethalin PE using PREHAP *fb* one hand weeding resulted in higher weed control efficiency and B:C. Thus, the developed machine PRAHEP can be successfully used for the application of pre-emergence herbicides along with the crop sowing operations.

Conclusion

The designed and developed PREHAP (pre-emergence herbicide applicator-cum-planter) with a band and broadcast herbicide-spraying capability was proven to be useful for applying pre-emergence herbicide along with seeding the soybean. The field capacity and operating cost of the developed system was found to be 0.4 ha/h and ₹ 1650/ha, respectively. It can be concluded that broadcast application of the pre-emergence herbicide pendimethalin 1.0 kg/ha using PREHAP combined with one hand weeding gave optimum weed management in soybean with higher soybean yield and economic return.

Table 3. Effect of different weed control treatments on various crop growth and yield attributing characters, yield and economics of soybean

Treatment	Plant height at 60 DAS (mm)	No. of pods per plant	Seed yield (t/ha)	Straw yield (t/ha)	Cost of cultivation (x10^3 `/ha)	Net return (x10^3 `/ha)	B:C
Kharif 2019							
T$_1$	472^{c}	15.4^{c}	0.21^{d}	0.29^{d}	13.1	0.0013	1.01
T$_2$	528^{b}	22.1^{bc}	0.59^{c}	0.81^{c}	17.1	20.07	2.17
T$_3$	523^{b}	27.3^{b}	0.89^{b}	1.17^{b}	24.6	31.47	2.28
T$_4$	546^{ab}	26.5^{b}	0.84^{b}	1.08^{b}	14.5	38.42	3.65
T$_5$	552^{ab}	33.7^{ab}	0.95^{b}	1.19^{b}	15.6	44.25	3.84
T$_6$	561^{ab}	36.8^{a}	1.26^{a}	1.68^{a}	24.0	55.38	3.31
T$_7$	572^{a}	40.2^{a}	1.40^{a}	1.84^{a}	24.1	68.51	3.84
LSD (p=0.05)	38.4	8.11	0.15	0.22			
Kharif 2020							
T$_1$	481^{c}	18.1^{c}	0.29^{d}	0.41^{c}	13.1	0.5170	1.4
T$_2$	512^{b}	23.4^{bc}	0.54^{c}	0.71^{c}	17.1	16.92	1.99
T$_3$	527^{ab}	25.2^{b}	0.81^{b}	1.10^{b}	24.6	26.43	2.07
T$_4$	534^{ab}	29.0^{b}	0.78^{b}	1.09^{b}	14.5	34.64	3.39
T$_5$	528^{ab}	33.2^{ab}	0.94^{b}	1.26^{b}	15.6	43.62	3.8
T$_6$	536^{ab}	34.0^{ab}	1.18^{a}	1.51^{ab}	24.0	50.34	3.1
T$_7$	548a	36.3^{a}	1.34^{a}	1.74^{a}	24.1	60.32	3.5
LSD (p=0.05)	33.1	6.9	0.18	0.31			

T$_1$: control *i.e.* no herbicide application, no manual/mechanical weeding; T$_2$: intercultivation (hoeing) once between the crop rows; T$_3$: hand weeding once after 30 days after seeding (DAS); T$_4$: banded application of pre-emergence herbicide by PREHAP; T$_5$: broadcast application of pre-emergence herbicide over the entire field by PREHAP; T$_6$: band application of pre-emergence herbicide by PREHAP *fb* one manual weeding after 30 DAS; T$_7$: broadcast application of pre-emergence herbicide over the entire field by PREHAP *fb* one manual weeding after 30 DAS.

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RESEARCH ARTICLE

Complex weed flora managing efficacy of herbicides in soybean and their effect on soil properties, microorganisms and productivity of succeeding mustard

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ABSTRACT

A field experiment was conducted during two consecutive *Kharif* seasons during 2019 and 2020 at Central Research Farm, Bidhan Chandra Krishi Viswavidyalaya, Gayeshpur, West Bengal to study the weed management efficacy of herbicides in soybean and their effect on soil properties, microorganisms, productivity of soybean and succeeding crop. The study comprised of seven treatments which was replicated thrice in a randomized block design. Weed free resulted significantly higher soybean seed yield. Pre-emergence application (PE) of metolachlor 1.25 kg/ha was most effective in controlling different grassy and broad-leaved weeds resulting in higher growth, yield attributes and yield of soybean (1.56 t/ha) and B:C, in comparison with other herbicides. The tested weed management treatments did not significantly affect the soil physicochemical properties and caused no significant impact on succeeding crop (mustard) yield. Soil microflora population increased at the time of harvest of the crop compared to the initial count.

Keywords: Metolachlor, Soil microflora, Soil properties, Soybean, Weed management

INTRODUCTION

Soybean (*Glycine max* (L.) Merill) is the most important oilseed crop next to groundnut which plays the vital role in boosting oilseed production of India (Sangeetha *et al.* 2013). The major limiting factor in soybean production is crop yield loss due to weeds which may range from 31 to 84% (Kachroo *et al.* 2003). First six weeks after sowing is most critical period during which weeds should be managed (Prachand *et al.* 2015). Among the different weed management strategies hand weeding or conventional practice of weed management is very effective but it is costly due to high wages and non-availability of labour during the critical weeding period. Beside this, mechanical weeding disturbs the physical conditions of the soil and may cause mechanical injury to roots and shoots of the plant. Therefore, alternate weed management options particularly use of safer herbicides are being experimented as an alternative to costly hand weeding (Poddar *et al.* 2017). At present several pre-emergence (PE), post-emergence (PoE) or early post-emergence (EPoE) herbicides like pendimethalin, imazethapyr, alachlor, quizalofop-p-ethyl, chlorimuon, fluthiacet-methyl *etc.* are being used for controlling the weeds in soybean crop but their efficacy was found unsatisfactory because of -their inefficacy on many broad-leaved weeds in soybean (Sangeetha *et al*. 2013; Upadhyay *et al*. 2012; Ghosh *et al*. 2017; Singh *et al*. 2013; Andhale and Kathmale 2019). Thus, identification of effective herbicides is necessary for management of complex weed flora in soybean field. Metolachlor 50 EC is a new formulation whose efficacy needs to be tested. Thus, the present study was conducted with it at different doses and compared it with other marketed herbicides to quantify their efficacy against complex weed flora in soybean and yield along with its impact on soil properties, behavior of soil microorganism and the yield of succeeding mustard crop.

MATERIALS AND METHODS

This experiment was carried out at the Central Research Farm, Bidhan Chandra Krishi Viswavidyalaya, Gayeshpur, Nadia, West Bengal, India (22°97´ N latitude and 88°43' E longitude with the 9.75 m above MSL) during two consecutive *Kharif* seasons of 2019 and 2020. The land was medium in slope having deep tube well facility for irrigation. The soil of the experimental site was sandy

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loam in texture having 53.42% sand, 21.84% silt and 24.74% clay with a pH of 6.85 and bulk density of 1.33 g/cc. It contained 0.674% organic C, 123.46 kg available N/ha, 23.2 kg available P/ha and 131.31 kg available K/ha. The climate of the study site was sub-tropical humid. There were seven treatments, *viz*. metolachlor 750 g/ha; metolachlor 1.0 kg/ha; metolachlor 1.25 kg/ha; pendimethalin 1.0 kg/ha; alachlor 2.50 kg/ha; weedy check and weed free. A randomized block design with three replication was used. The pre-emergence application (PE) of herbicides was done at two days after sowing (DAS). Herbicides were applied using a spray volume 400 l/ha by knapsack sprayer fitted with flat fan deflector nozzle under moist soil. Soybean variety 'Bragg' was sown at 45 × 5 cm spacing on 5 × 4 m (20 m^2) area at the end of June in each of the experimental year. The recommended dose of fertilizers, *i.e.* 20 kg N, 40 kg P and 40 kg K/ha was applied before sowing in the seed row zone. Nitrogen, P and K were applied through urea, SSP and MOP, respectively. Different categories of individual weeds (grass, sedge and broad-leaved) were counted separately from each plot. Weed density (no.) and biomass (g)/m^2 in different plots were estimated using quadrat of 0.5 × 0.5 m placed randomly at three places in each plot at 15, 30 and 45 days after herbicide application (DAA). Different categories-wise weed/m^2 were calculated. After counting, the weed samples were uprooted washed in tap water and these weeds were sundried for two days and then kept in an oven at 70 °C for 48 h for recording weed biomass. Weed control efficiency (WCE), weed persistence index (WPI), herbicide efficiency index (HEI), weed index (WI) and weed management index (WMI) were calculated using the following equations (Kundu *et al.* 2021):

$$\mathrm{WCE} = \frac{\mathrm{WDMc} - \mathrm{WDMt}}{\mathrm{WDMc}}$$

Where, WDMc is the dry matter of weed (g/m^2) in control plot; WDMt is the weed dry matter (g/m^2) in treated plot.

$$\mathrm{WPI} = \frac{\mathrm{WDMt}}{\mathrm{WDMc}} \times \frac{\mathrm{WDc}}{\mathrm{WDt}}$$

Where, WDc is weed density in control plot; WCt= Weed density in treated plot.

$$\mathrm{HEI} = \frac{\mathrm{Yt} - \mathrm{Yc}}{\mathrm{Yt}} \times \frac{\mathrm{WDMc}}{\mathrm{WDMt}}$$

Where, Yt is crop yield from the treated plot; Yc is crop yield from the control plot; WDMc is the weed dry matter weight (g/m^2) in control plot; WDMt is the weed dry matter weight (g/m^2) in treated plot.

$$\mathrm{WI} = \frac{\mathrm{Yf} - \mathrm{Yt}}{\mathrm{Yf}} \times 100$$

Where,Yf is weed-free plot yield; Yt is treated plot yield.

$$\mathrm{WMI} = \frac{\text{Per cent yield over control}}{\text{Per cent control of weeds}}$$

The crop harvested from the net plot area was dried, threshed and pods were weighed to obtain the seed yield per plot wise. These observations were then used to get the seed yield in kg/ha at 14% moisture content.

The harvest index (HI) was calculated by using the formula (Kundu *et al.* 2021).

$$\mathrm{HI}\ (\%) = \frac{\text{Seed yield}}{\text{Total biological yield}} \times 100$$

The physico-chemical properties of experimental soil: texture, bulk density (BD), water holding capacity (WHC), pH, electrical conductivity (EC), organic carbon, available nitrogen, available phosphorus and available potassium content were estimated by combined glass electrode pH meter method, Walkley and Black's rapid titration method, modified macro Kjeldahl method, Olsen's method and flame photometer method, respectively (Jackson 1967).

Soil samples were taken at a depth of 0–15 cm from the space in between the rows at different dates, *viz.* initial (pretreatment), 1 DAA, 7 DAA, 15 DAA, 30 DAA and at harvest for microbial analysis by serial dilution technique and pour plate method (Pramer and Schmidt 1965). The counts were taken at 3rd day of incubation.

Residual toxicity of tested herbicides applied in soybean on succeeding mustard was done assessed by calculating mustard (cv. Vinoy) on the same plot without disturbing the previous field lay-out. Recommended agronomic practices were adopted in all plots for growing mustard crop. Germination % along with the plant population of mustard crop was recorded at 30 days after sowing (DAS). Mustard yield was recorded by harvesting the mustard.

Mean values of two years research data on crops and weeds were jointly analyzed by analysis of variance method (Gomez and Gomez 1984). As the error mean squares of the individual experiments were homogenous, combined analysis over the years were done through unweighted analysis. The values wherever necessary were transformed into square root values (Panse and Sukhatme 1978).

RESULTS AND DISCUSSION

Effect on weeds

The major weeds in the experimental field were: *Dactyloctenium aegyptium, Digitaria sanguinalis, Echinochloa colona and Eleusine indica* among grassy weeds, *Cyperus difformis* the sedge and *Digera arvensis, Euphorbia hirta, Phyllanthus niruri, Scoparia dulcis and Physalis minima* among broad-leaved weeds. Among the different categories of weeds, *Cyperus difformis* was more dominant among the all monocot and dicot weeds followed by *Eleusine indica*. The relative density of grassy weeds was 42.60 and 39.30% at 15 DAA and at 30 DAA, respectively which was more predominant than broad-leaved weeds (29.52% at 15 DAA and 31.50% at 30 DAA) and sedges (27.87% at 15 DAA and 29.20% at 30 DAA) in the weed check plot of the experimental field (**Figure 1**). Similar observations in soybean field were made earlier by Meena *et al.* (2022).

The dominant weed flora in the experimental site was in the order of grass>broad-leaved weeds>sedges at all date of observation. The lowest density and biomass of different categories of weed was recorded in weed free whereas highest in weedy check irrespective of time of observation (**Table 1**). In general weed population increased with the advancement of crop growth. Among the different herbicide treatments, higher dose of metolachlor 1.25 kg/ha resulted in significantly lower weed density and biomass, higher weed control efficiency than pendimethalin or alachlor along with its lower doses. Pendimethalin 1.25 kg/ha efficacy was statistically at par with alachlor 2.50 kg/ha in reducing density of different categories of weeds, irrespective of time of observation though at 15 DAA grassy weed density was significantly different among these two treatments. Higher doses of herbicides helped in reducing weed density and biomass conforming the findings of Singh *et al.* (2013)

In general, sedges were controlled less effectively than grasses and BLW. Pendimethalin and alachlor caused WCE similar to metolachlor 1.0 kg/ha. WPI also followed the similar trend as like WCE and the descending order of WPI during 15 DAA for all categories of weeds was metolachlor 1.25 kg/ha >alachlor 2.50 kg/ha >pendimethalin 1.0 kg/ha > metolachlor 1.0 kg/ha > metolachlor 750 g/ha (**Table 2**).

Metolachlor 1.25 kg/ha recorded comparatively higher HEI (1.12) which was followed by metolachlor 1.0 kg/ha (0.98) and alachlor 2.50 kg/ha (0.97) (**Figure 2)**. There was greater variation in WMI among the different treatments, among which metolachlor 1.0 kg/ha was the best with lowest WMI value (0.27 and was followed by lower dose of 1.0 kg/ha (WMI of 0.31) of same herbicide. Weed index was maximum in weedy check (45.7) and minimum with metolachlor 1.25 kg/ha (18.6). The other herbicidal treatments like pendimethalin or alachlor recorded numerically similar values as metolachlor 1.0 kg/ha. Variations in different weed indices due to different weed management approaches through various herbicides were also previously described by Poddar *et al.* (2017) and Kundu *et al.* (2021).

Table 1. Effect of different treatments on different categories weeds density (pooled data of two years)

Treatment	Weed density (no./m^2)									Weeds biomass (g/m^2)								
	Grassy weeds			Sedges			Broad-leaved weeds			Grassy weeds			Sedges			Broad-leaved weeds		
	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA
Metolachlor 0.75 kg/ha	64.46 (8.06)	82.98 (9.14)	103.98 (10.22)	51.55 (7.21)	64.91 (8.09)	82.67 (9.12)	45.22 (6.76)	58.36 (7.67)	70.65 (8.44)	7.56	11.20	18.60	6.46	8.89	14.68	2.02	6.34	16.01
Metolachlor 1.00 kg/ha	50.05 (7.11)	66.49 (8.18)	80.44 (9.00)	45.09 (6.75)	55.32 (7.47)	68.01 (8.28)	33.82 (5.86)	41.06 (6.45)	55.72 (7.50)	5.62	9.63	17.42	5.97	8.06	13.25	1.87	5.88	14.89
Metolachlor 1.25 kg/ha	33.91 (5.87)	55.44 (7.48)	69.93 (8.39)	36.65 (6.10)	49.79 (7.09)	56.62 (7.56)	26.50 (5.20)	35.79 (6.02)	45.85 (6.81)	4.89	8.59	16.56	5.60	7.61	13.21	1.63	5.52	13.78
Pendimethalin 1.00 kg/ha	42.91 (6.59)	58.85 (7.70)	79.37 (8.94)	40.84 (6.43)	51.58 (7.22)	62.60 (7.94)	31.40 (5.65)	39.55 (6.33)	53.05 (7.32)	5.46	9.54	17.14	6.01	7.91	13.38	1.80	5.81	14.26
Alachlor 2.50 kg/ha	37.66 (6.18)	58.08 (7.65)	74.73 (8.67)	39.52 (6.33)	50.60 (7.15)	60.76 (7.83)	31.51 (5.66)	38.53 (6.25)	52.33 (7.27)	5.23	9.22	17.00	5.93	7.85	13.34	1.77	5.82	14.45
Weedy check	93.73 (9.71)	107.50 (10.39)	125.03 (11.20)	61.32 (7.86)	79.88 (8.97)	106.03 (10.32)	64.95 (8.09)	86.16 (9.31)	103.84 (10.21)	16.17	21.65	31.87	9.55	12.44	19.59	5.27	14.56	31.92
Weed free	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00 (0.71)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LSD (p=0.05)	2.41	2.90	4.38	4.15	3.80	4.73	1.55	2.19	2.74	0.27	0.19	0.63	0.44	0.23	0.57	0.09	0.26	0.72

#Data are subjected to square root transformation ($\sqrt{x+0.5}$); values in the parentheses are transformed value

Effect on crop growth, yield and economics

The growth and yield parameters like crop dry matter accumulation, pods/plant, seeds/pod and seed yield were significantly higher in weed free check whereas the lowest values were observed in weedy check (**Table 3**). Among the different herbicide treatments, metolachlor 1.25 kg/ha was the next best in terms of crop dry matter accumulation (527.36 g/ m^2) which was 43.9% higher than weedy check treatment. There was a net gain of 12.5 to 59.6% more dry matter in soybean due to different weed management treatments. Weed management helps in creating a less completion environment to the crop plant which helped them to utilize more natural resources efficiently and thus produced more dry matter than weedy check (Poddar *et al.* 2017; Kundu *et al.* 2021). Number of pods/plant and seeds/pod also followed the similar trends. Variation in yield attributes due to different weed management in soybean was also reported previously by Singh *et al.* (2014) and Andhale and Kathmale (2019).

There was a significant variation in seed yield of soybean due to different weed management treatments (**Table 3**). Different weed management treatments resulted in 33.8 to 61.9% higher seed yield of soybean when compared with weedy check. The weed free recorded significantly highest seed yield (1.68 t/ha) which was followed by metolachlor 1.25 kg/ha (1.56 t/ha) > metolachlor 1.0 kg/ha (1.54 t/ha) > alachlor 2.50 kg/ha (1.52 t/ha) in the order of decreasing seed yield of soybean. However, all the herbicide applied treatments showed statistically at par result in terms of seed yield except metolachlor 750 g/ha. The weed free environment in the weed free check helped the crop to grow more vigorously reslting in greater yield attributes which ultimately resulted in higher seed yield (Poddar *et al.* 2014; Kundu *et al.* 2021). Lowest seed yield was recorded in weedy check plot (1.04 t/ha). Stover yield also followed the similar trend like seed yield of soybean. Harvest index did not differ significantly amongst the various weed management approaches.

Table 2. Effect of different treatments on weed control efficiency and weed persistency index of different categories of weeds

Treatment	Weed control efficiency (%)									Weed persistency index (WPI)								
	Grassy weeds			Sedges			Broad-leaved weeds			Grassy weeds			Sedges			Broad-leaved weeds		
	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA	15 DAA	30 DAA	45 DAA
Metolachlor 0.75 kg/ha	53.23	32.27	61.72	48.29	28.53	56.42	41.65	24.93	49.84	0.68	0.67	0.70	0.80	0.88	0.96	0.55	0.64	0.74
Metolachlor 1.00 kg/ha	65.22	37.43	64.57	55.50	35.22	59.58	45.37	32.37	53.33	0.65	0.72	0.85	0.85	0.94	1.05	0.68	0.85	0.87
Metolachlor 1.25 kg/ha	69.74	41.24	69.07	60.33	38.82	62.04	48.02	32.58	56.77	0.84	0.77	0.93	0.98	0.98	1.26	0.76	0.91	0.98
Pendimethalin 1.00 kg/ha	66.21	36.95	65.91	55.95	36.39	60.07	46.21	31.69	55.29	0.74	0.80	0.85	0.94	0.98	1.16	0.71	0.87	0.87
Alachlor 2.50 kg/ha	67.68	37.81	66.50	57.44	36.91	60.00	46.67	31.84	54.69	0.80	0.79	0.89	0.96	1.00	1.19	0.69	0.89	0.90
Weedy check	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Weed free	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	-	-	-	-	-	-	-	-	-

Table 3. Effect of different treatments on seed yield of soybean (pooled data of two years)

Treatment	Crop dry matter (g/m^2)	Pods/ plant	Seeds/ pod	Seed yield (t/ha)	Stover yield (t/ha)	Harvest index (%)	B:C
Metolachlor 0.75 kg/ha	412.33	14.6	1.89	1.39	2.13	39.45	1.34
Metolachlor 1.00 kg/ha	439.54	15.3	2.00	1.54	2.31	39.93	1.92
Metolachlor 1.25 kg/ha	527.36	16.7	2.33	1.56	2.37	39.64	2.03
Pendimethalin 1.00 kg/ha	472.51	15.4	2.00	1.51	2.33	39.29	1.77
Alachlor 2.50 kg/ha	489.85	15.7	2.11	1.52	2.30	39.72	1.80
Weedy check	366.42	13.2	1.67	1.04	1.62	39.14	1.12
Weed free	584.76	17.5	2.33	1.68	2.55	39.74	1.79
LSD (p=0.05)	12.71	0.41	0.05	0.054	0.012	NS	-

Table 4. Physical and chemical properties of the experimental field soil at harvest (pooled data of two years)

Treatment	BD (g/cc)	WHC (%)	Sand (%)	Silt (%)	Clay (%)	pH	EC (dS/m)	Organic carbon (%)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
Metolachlor 0.75 kg/ha	1.343	45.29	55.31	23.55	21.14	6.82	0.164	0.674	123.42	23.43	132.96
Metolachlor 1.00 kg/ha	1.334	45.38	55.18	23.06	21.76	6.85	0.165	0.665	124.15	23.54	131.89
Metolachlor 1.25 kg/ha	1.341	45.35	55.43	23.11	21.46	6.79	0.165	0.673	123.88	24.14	132.82
Pendimethalin 1.00 kg/ha	1.340	45.37	55.42	23.25	21.33	6.80	0.166	0.677	124.52	23.86	131.44
Alachlor 2.50 kg/ha	1.332	45.30	54.72	23.2	22.08	6.82	0.165	0.665	124.38	23.71	131.09
Weedy check	1.330	45.38	55.23	23.36	21.41	6.76	0.166	0.677	124.49	23.62	132.11
Weed free	1.335	45.36	55.32	23.16	21.52	6.79	0.165	0.674	123.23	23.45	131.06
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

The lowest B:C (1.12) was with weedy check while metolachlor 1.25 kg/ha recorded highest value (2.03) followed by its lower doses of 1.0 kg/ha (1.92). Weed free check ranked fourth in terms of B:C (1.79) due to higher cultivation cost associated with higher for labour wages.

Effect on soil physico-chemical properties

Different physical properties of soil like sand, silt and clay contents; bulk density, water holding capacity along with various chemical properties like pH, electrical conductivity (EC), organic carbon (%), total nitrogen content, available phosphorus (P) and potash (K) contents of the harvested soil of the experimental field were estimated (**Tables 4)**. There were no significant variation indifferent physical and chemical properties of the soil due to herbicide treatments and is the conformity of the finding of Bera and Ghosh (2013).

Effect on soil microorganism

Different soil microorganism like total bacteria, actinomycetes and fungi population counting was done at initial or before spraying of herbicides and 1 DAA, 7 DAA, 15 DAA, 30 DAA and at harvest (**Table 5)**. Total bacteria, fungi and actinomycetes population did not differ significantly among the treatments before spraying or in initial soil sample. Weedy check treatment did not show much variation in counting different microorganism at different dates of observation. After application of herbicides all the microorganism population gradually decreased with maximum reduction at 30 DAA. Later reverse trend occurred with the increase in the counting at harvesting which was higher than that of initial. The decrease in the bacterial population was due to competitive influence and the toxic effect of chemicals in soil. Herbicidal treatments plots recorded 22.6 to 28.8% higher population of bacteria, 12.3 to 19.1% higher population of fungi and 7.8 to 12.8% higher population of actinomycetes than the weedy check at the time of harvesting of soybean crop. Microorganisms have the ability of degradation of herbicides and utilize them as a source of biogenic elements for their own physiological processes and they multiply rapidly (Bera and Ghosh 2013; Pal *et al.* 2013).

Effect on succeeding crop

After harvesting of soybean crop the succeeding crop mustard was sown in the plot without disturbing the layout of the experiment. There was no significant impact of different herbicidal treatments on germination %, population/m^2 and seed yield of mustard (**Table 6**). Lack of adverse effects of

Table 5. Influence of herbicides on soil microorganisms population (pooled data of two years)

Treatment	Total bacteria (CFU x 10^6/g of soil) Initial	Herbicide application					Fungi (CFU x 10^4/g of soil) Initial	Herbicide application					Actinomycetes (CFU x 10^5/g of soil) Initial	Herbicide application				
		1 DAA	7 DAA	15 DAA	30 DAA	At Harvest		1 DAA	7 DAA	15 DAA	30 DAA	At Harvest		1 DAA	7 DAA	15 DAA	30 DAA	At Harvest
Metolachlor 0.75 kg/ha	40.11	28.47	25.67	23.11	21.11	60.33	25.11	16.11	15.33	14.67	12.11	33.67	80.67	56.67	52.67	47.33	44.67	92.33
Metolachlor 1.00 kg/ha	40.33	27.33	24.33	22.67	20.33	61.33	24.33	16.33	15.67	14.67	12.67	34.33	79.00	55.33	52.00	46.00	42.33	96.67
Metolachlor 1.25 kg/ha	39.67	26.67	23.33	21.00	20.11	62.67	25.33	16.11	15.33	14.33	12.33	35.33	78.67	53.00	48.00	44.67	41.67	96.33
Pendimethalin 1.00 kg/ha	40.17	26.11	25.33	21.67	22.33	59.67	25.00	16.67	15.00	14.11	12.00	34.67	79.33	56.67	49.67	48.00	44.67	95.00
Alachlor 2.50 kg/ha	40.33	26.67	25.11	22.33	21.67	60.00	24.67	16.33	15.67	14.67	12.33	33.33	78.33	55.67	51.33	47.67	43.33	96.33
Weedy check	39.67	44.33	43.67	44.33	45.33	48.67	24.33	25.33	25.00	26.00	27.67	29.67	78.67	80.00	80.67	81.67	84.00	85.67
Weed free	40.33	43.67	44.33	45.11	46.67	49.33	24.67	25.67	25.33	26.67	27.33	30.33	79.33	80.33	81.00	82.33	84.67	87.33
LSD (p=0.05)	NS	1.62	1.12	1.54	1.86	1.44	NS	1.16	1.12	1.42	1.36	1.92	NS	1.66	2.38	2.72	1.86	2.42

Table 6. Effect of different weed management on germination %, population and seed yield of succeeding crop (mustard)

Treatment	Germination %	Population /m^2 (30 DAS)	Seed yield (t/ha)
Metolachlor 0.75 kg/ha	79.8	19.28	1.53
Metolachlor 1.00 kg/ha	78.9	19.85	1.54
Metolachlor 1.25 kg/ha	78.3	19.80	1.55
Pendimethalin 1.00 kg/ha	79.8	19.52	1.51
Alachlor 2.50 kg/ha	78.4	19.58	1.54
Weedy check	79.6	19.98	1.50
Weed free	80.3	19.95	1.60
LSD (p=0.05)	NS	NS	NS

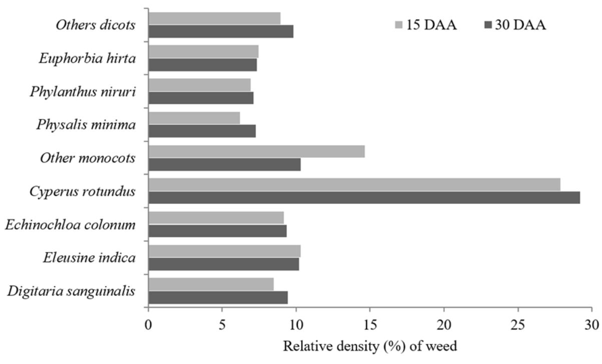
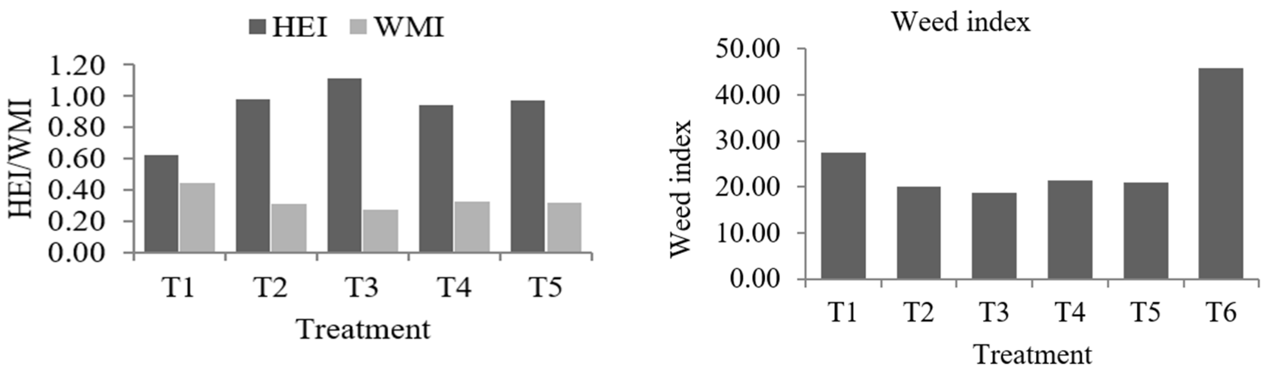


Figure 1. Relative weed density of different categories of weeds in weedy check plot at 15 days after application (DAA) and 30 DAA in soybean field



Where, T_1: metolachlor 750 g/ha, T_2: metolachlor 1.0 kg/ha, T_3: metolachlor 1.25 kg/ha, T_4: pendimethalin 1.0 kg/ha, T_5: alachlor 2.50 kg/ha; T_6: weedy check

Figure 2. Effect of weed management treatments on herbicide efficiency index (HEI), weed index (WI) and weed management index (WMI)

different herbicides on succeeding crops on seed yield were reported earlier also by Poddar *et al.* (2014).

Conclusion

It may be concluded that metolachlor 1.25 kg/ha as PE was very effective in managing different categories of weeds and also produced higher seed yield and maximum profit in soybean without hampering soil physico-chemical properties and activity of soil microorganism. The next best treatment was metolachlor 1.0 kg/ha.

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RESEARCH ARTICLE

Effect of non-chemical weed management practices on growth and yield of tomato

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ABSTRACT

A field experiment was conducted to study the effect of non-chemical weed management practices on weeds, growth and yield of organic tomato (*Solanum lycopersicum* L.). It was conducted at Western block, Horticultural College and Research Institute, Periyakulam during *Kharif* season of the years 2021 and 2022. The experiment was carried out in randomized block design with eight treatments and three replications. Tomato variety PKM 1 was raised at a spacing of 60 x 45 cm. Treatments include: tamarind leaf mulch at 4 t/ha; mango leaf mulch at 4 t/ha; paddy straw mulch at 5 t/ha; black polythene mulch (50 micron); live mulch with multi varietal grains (Navathaniyam) at 50 kg/ha; mechanical weeding twice at 15 and 30 days after transplanting (DAT); hand weeding twice at 15 and 30 DAT and unweeded control. Among different non-chemical weed management treatments, hand weeding twice at 15 and 30 DAT and black polythene mulch recorded significantly lowest grass, sedge and broad-leaved weed density and total biomass and higher weed control efficiency. Tomato plant growth parameters, *viz.* plant height and number of branches were higher with hand weeding twice at 15 and 30 DAT and black polythene mulch. Hand weeding twice at 15 and 30 DAT recorded significantly higher tomato fruit yield and higher net returns (₹ 3,87,000) and B: C (2.87) and was followed by black polythene mulch which recorded higher net returns of ₹ 3,00,500 and B: C of 2.25.

Keywords: Black polythene mulch, Economics, Mechanical weeding, Mango leaf mulch, Non-chemical weed management, Tomato, Weed control efficiency

INTRODUCTION

Tomato is one of the most important vegetable crops with special nutritive value. There are different varieties of tomato, *viz.* round, oval, cherry, but all have the same nutritional characteristics, being an important source of K, P, Mg, Fe which are necessary for the normal activity of nerves and muscles. Tomato is the third source of vitamin C in human diet and the fourth for vitamin A (Rao 2000). It is one of the most versatile vegetables with wide usage in culinary tradition. Tomato is the world's largest vegetable crop after potato and sweet potato and it tops in the list of canned vegetables.

The increasing need for vegetables to meet dietary requirements of increasing human populations in the tropics necessitates the effective weed control to attain optimum yields. Any single method of weed control cannot adequately control weeds in any crop. Changes in environmental factors, land use systems and shifts in weed flora and population density coupled with cost of alternative weed control methods necessitates the combinations of methods that will give farmers the best returns on their investment (Gare and Raundal 2015). Number of factors have amplified the importance of non-chemical weed control techniques. Some of the methods are environmental concerns arising by overuse of herbicides, rising demands for organic food and an evolution of herbicide resistance in weeds. Therefore, in order to control weed growth and obtain maximum yield in tomato, various non chemical weed control treatments such as black polythene mulch, tamarind leaf mulch, mango leaf mulch paddy straw mulch, live mulch with multi varietal grains, mechanical weeding and hand weeding were evaluated in tomato to manage weeds and improve organically grown tomato yield.

MATERIALS AND METHODS

A field experiment was conducted during *Kharif* seasons of 2021 and 2022 at Western block, Horticultural College and Research Institute, Periyakulam, Tamil Nadu located at 100.13' N, 770.59' E and at an altitude of 289 m above MSL with average rainfall of 791.1 mm. The soil was sandy loam having pH 7.3, organic carbon (0.28%), medium in available nitrogen (285 kg/ha), low in available P (10.1 kg/ha) and medium in available potash (212 kg/ha). A randomized block design with three replications was used. The experiments consisted of eight treatments, *viz*. tamarind leaf mulch 4 t/ha; mango leaf mulch 4t/ha; paddy straw mulch 5 t/ha; black polythene mulch (50 micron); live mulch with multi varietal grains (Navathaniyam) 50 kg/ha; mechanical weeding twice

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at 15 and 30 days after transplanting (DAT); hand weeding twice at 15 and 30 DAT and unweeded control. Tomato variety PKM 1 was used in this experiment. The seedlings were transplanted at a spacing of 60 x 45 cm. Organic package of practices was followed for the crop as per the crop production guide. Irrigation was given through drip system depending up on the demand of the crop for both the years. Tamarind leaf mulch 4 t/ha, mango leaf mulch 4 t/ha, paddy straw mulch 5 t/ha was applied immediately after transplanting. Black polythene mulch (50-micron thickness) was used for this study. Tomato seedlings were transplanted immediately after laying black polythene mulch sheets. Multi Varietal Grains were sown immediately after the transplanting of tomato seedlings in the respective treatment plots. Mechanical weeding was done using star type weeder. Hand weeding was done at 15 DAT and 30 DAT in the respective treatments. Data on weed density and biomass were recorded at 15, 30, 45 and 60 DAT with the help of 0.25 m^2 quadrat placed randomly in each plot. After identifying the weed species, weeds were grouped into monocotyledons and dicotyledons, separately. Weed density was estimated on the basis of the total number of an individual weed species/m^2. On the basis of weed data, weed control efficiency was computed using the following formula:

$$\text{Weed control efficiency (\%)} = \frac{\text{Weed biomass in control plot - Weed biomass in treated plots}}{\text{Weed biomass in control plot}} \times 100$$

Observations on growth, yield attributes and yield of tomato were recorded during both the years of the study and the data were statistically analyzed and subjected to pooled analysis for interpretation. Economics were calculated based on the prevailing market price of organic tomato and labor wages/man day. The data recorded on various parameters during the course of investigations and the summed-up data were statistically analyzed following the analysis of variance for Randomized Block Design as suggested by Gomez and Gomez (1984).

RESULTS AND DISCUSSION

The weed flora observed in the experimental fields during this study consisted of grasses, sedges and broad-leaved weeds (BLW). *Cynodon dactylon*, *Chloris barbata* and *Dactyloctenium aegyptium* in grasses, *Cyperus rotundus* among sedges, *Amaranthus viridis*, *Boerhavia diffusa*, *Eclipta alba*, *Cleome viscosa*, *Euphorbia hirta*, *Trianthema portulacastrum*, *Sida acuta*, *Phyllanthus niruri* and *Parthenium hysterophorus* among broad-leaved weeds. The predominant weeds were sedges followed by broad-leaved weeds and grasses. *Cyperus rotundus*, *Trianthema portulacastrum* and *Cynodon dactylon* were the dominant sedge, broad-leaved weed and grass, respectively. Among different weeds species identified in the experimental fields, sedges contributed 42.15%, whereas BLW and grasses contribution was 33.48% and 24.37%, respectively during *Kharif* 2021. Similar trend of weed species was observed in the experimental field during *Kharif* 2022 with 46.26% of sedges, 31.97% of BLW and 21.77% of grassy weeds.

Effect on weeds

Among different non-chemical weed management practices, hand weeding twice at 15 and 30 DAT recorded significantly lowest grass, sedge and broad-leaved weed density at 15 DAT. However, it was on par with the black polythene mulch treatment (**Table 1**). This was followed by tamarind leaf mulch 4 t/ha and mango leaf mulch 4 t/ha, live mulch with multi varietal grains (Navathaniyam) 50 kg/ha, paddy straw mulch 5 t/ha and mechanical weeding at 15 and 30 DAT. This might be due to organic mulch reduces the weed seed germination and growth of weed through the less light penetration into the soil. Similar findings were reported by Challa and Bavindra (1999) and Muhammad *et al.* (2017). Tomato mulched with the tamarind leaves had significantly greater root spreads, accounting a greater depth and also plant height was significantly higher when mulched with tamarind leaves. The highest weed density was observed in unweeded control.

Hand weeding twice at 15 and 30 DAT recorded significantly the lowest weed density and biomass at 15 DAT and it was on a par with the black polythene mulch. This was followed by tamarind leaf mulch 4 t/ha (**Table 1**). Similar trend observation was noticed at 45 and 60 DAT.

Better control of weeds resulted in lower weed biomass and higher weed control efficiency (**Table 1**) in hand weeding and black polythene mulching treatments as the black polythene mulch did not allow the weeds to grow as reported earlier by Monks *et al.* (1997). Lesser weed biomass may be due to lesser weed germination and weed infestation by restricting the penetration of solar radiation under black polythene mulch resulted in higher weed control efficiency (Muhammad *et al.* 2017). Highest weed biomass was recorded in unweeded control at all stages of observation due to higher total weed density as reported earlier in tomato (Bakht *et al.* 2014; Arun *et al.* 2021).

Effect on growth, yield parameters and fruit yield of tomato

Significantly higher plant height, no. of branches and higher fruit yield per plant and fruit yield a was

Table 1. Effect of non-chemical weed management treatments on total weed density, weed biomass and weed control efficiency in tomato (pooled data of 2021 and 2022)

Treatment	Weed density (no./m^2)				Weed biomass (g/m^2)				Weed control efficiency (%)			
	15 DAT	30 DAT	45 DAT	60 DAT	15 DAT	30 DAT	45 DAT	60 DAT	15 DAT	30 DAT	45 DAT	60 DAT
Tamarind leaves mulch 4 t/ha	6.0(36)	7.6(57)	8.8(76)	10.4(108)	4.6(21)	4.9(24)	5.3(28)	5.7(32)	53.4	66.9	79.5	82.2
Mango leaves mulch 4 t/ha	5.7(33)	7.4(54)	8.6(73)	10.2(104)	4.2(17)	4.5(20)	4.9(24)	5.4(29)	58.0	70.9	83.0	85.5
Paddy straw mulch 5 t/ha	6.0(35)	7.5(56)	8.7(75)	10.4(107)	4.5(20)	4.8(23)	5.2(26)	5.6(31)	54.7	68.0	80.5	83.1
Black Polythene mulch (50 micron)	1.4(1.5)	4.8(23)	6.5(42)	8.3(68)	2.8(7)	3.1(9)	3.7(13)	4.3(18)	70.5	82.3	93.0	95.0
Live mulch with multi varietal grains (Navathaniyam) 50 kg/ha	11.0(120)	11.9(141)	12.7(160)	13.9(192)	7.7(58)	7.8(61)	8.1(65)	8.4(70)	6.2	26.3	44.0	48.4
Mechanical weeding at 15 and 30 DAT	5.3(28)	7.1(50)	8.3(68)	10.1(101)	4.1(17)	4.5(20)	4.9(23)	5.4(28)	58.4	71.3	83.3	85.8
Hand weeding twice on 15 and 30 DAT	1.4(1.5)	4.8(23)	6.5(42)	8.6(74)	2.6(6)	3.1(9)	3.4(11)	4.3(18)	71.3	82.8	94.9	95.1
Unweeded control	13.3(178)	14.2(201)	16.4(268)	17.0(289)	8.9(79)	9.6(92)	10.3(106)	10.6(111)	-	-	-	-
LSD (p=0.05)	0.62	0.82	0.95	0.12	0.49	0.6	0.63	0.66				

Data in parentheses are original values. Others are $\sqrt{x+0.5}$ transformed values.; DAT = days after transplanting

Table 2. Effect of non-chemical weed management treatments on yield parameters, yield and economics of tomato (pooled data of 2021 and 2022)

Treatment	Plant height (cm)	Branches (no./ plant)	Fruits (no./ plant)	Fruit yield (kg/ plant)	Yield/ Plot (kg)	Fruit yield (t/ha)	Cost of cultivation (x10^5 `/ha)	Gross returns (x10^5 `/ha)	Net returns (x10^5 `/ha)	B:C
Tamarind leaves mulch 4 t/ha	88.7	26.9	14.9	0.653	2337	18.3	1.23	3.66	2.43	1.98
Mango leaves mulch 4 t/ha	90.5	30.0	17.3	0.666	2386	18.7	1.23	3.74	2.51	2.04
Paddy straw mulch 5 t/ha	89.8	26.6	16.7	0.663	2376	18.6	1.23	3.72	2.49	2.02
Black Polythene mulch (50 micron)	92.2	30.1	18.8	0.712	2551	21.7	1.34	4.34	3.01	2.25
Live mulch with multi varietal grains (Navathaniyam) 50 kg/ha	87.1	25.3	14.4	0.639	2289	18.1	1.23	3.62	2.39	1.94
Mechanical weeding at 15 and 30 DAT	91.5	28.8	17.7	0.680	2435	19.1	1.25	3.82	2.57	2.06
Hand weeding twice on 15 and 30 DAT	96.5	32.7	28.8	0.805	2736	26.1	1.35	5.22	3.87	2.87
Unweeded control	65.6	16.7	7.3	0.595	2143	6.2	1.13	1.24	0.11	0.10
LSD (p=0.05)	4.29	2.21	2.45	0.30	261	2.76	--	-	-	-

recorded with hand weeding twice at 15 and 30 DAT followed application of black polythene mulch and mechanical weeding at 15 and 30 DAT followed by the treatments with organic mulches (**Table 2**). Unweeded control recorded lowest plant height due to higher weed density and heavy competition for critical inputs, *viz*. water and nutrients. Similar findings were reported by Arun *et al.* (2021).

Economics

The treatment of hand weeding twice at 15 and 30 DAT recorded significantly higher fruit yield; higher net returns (₹ 387000/-) and B:C (2.87) (**Table 2**). This was followed by black polythene mulch which recorded significantly higher fruit yield per ha with higher net returns of ₹ 300500 and B:C of 2.25 (**Table 3**). Cost of cultivation was found to be more with the black polythene mulch than rest of the treatments. But the better control of weeds was observed with black polythene mulch and there by higher fruit yield and premium market price of organic tomato resulted in increased economic returns as observed earlier by Reddy (2015).

It could be concluded that using black polythene mulch for organic tomato cultivation will reduce thpe weed growth, increase the growth parameters of tomato with an increase of tomato yield, economically.

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RESEARCH ARTICLE

Integrated weed management to manage complex weed flora in turmeric

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ABSTRACT

A field experiment was carried out during two consecutive *Kharif-Rabi* seasond of 2019-20 and 2020-21 at AICRP Weed Management Farm, B. A. College of Agriculture, Anand Agricultural University, Anand to evaluate the effect of pre-emergence application (PE) (next day after planting) of atrazine 750 g/ha, metribuzin 500 g/ha, pendimethalin 750 g/ha and atrazine 500 g/ha + pendimethalin 500 g/ha (tank-mix) followed by (*fb*) rice straw mulch 5 t/ha (one day after application of PE) *fb* hand weeding (HW) at 75 days after planting (DAP) and interculturing (IC) *fb* HW at 20, 40 and 60 DAP and earthing up at 75 DAP on weed control, rhizome yield and economics of turmeric on loamy sand soil. Atrazine 500 g/ha + pendimethalin 500 g/ha (tank-mix) PE *fb* rice straw mulch 5 t/ha (0-3 DAP) *fb* HW at 75 DAP provided effective control of weeds with higher weed control efficiency and higher rhizome yield with better economic returns. The next best treatment was metribuzin 750 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP during both the years.

Keywords: Atrazine, Economics, Integrated weed management, Metribuzin, Mulching, Pendimethalin, Turmeric

INTRODUCTION

Turmeric (*Curcuma longa* L.) is widely used as a spice, cosmetic and natural medicine in many countries. Turmeric is a rhizomatous herbaceous perennial plant of the ginger family (Priyadarsini 2014). Curcumin is being recognized and used worldwide in many different forms for multiple potential health benefits (Gupta *et al*. 2013). Turmeric is the second most important spice crops after chilli and India accounts for 78% in world production and 60% in world export share (Angles *et al*. 2011). India is the largest turmeric producer, consumer and exporter of this crop where it is cultivated on an area of 253.35 thousand hectare with total production of 976.97 thousand tons (Anonymous 2019). The major turmeric producing states in India are Andhra Pradesh, Orissa, Tamil Nadu, Assam, Gujarat and Maharashtra (Patel *et al*. 2012). Being a long duration crop with delayed emergence, slow initial growth and planted in wider space permit more sunlight to reach the soil provides congenial condition for rapid weed growth during initial stage which leads to enormous damage to the crop in terms of quality and quantity. It is essential to the crop free of weeds during 70 to 160 days after planting for higher yield of turmeric (Hossain *et al*. 2008). Farmers rely on manual weeding for the control of weeds but with increase in labour cost and scarcity of labour, manual weed control has become difficult and also damage to the rhizome during mechanical weeding. Thus, adoption of herbicides for weed control is the best alternative to manual weeding. Due to long duration of the crop, use of pre-emergence herbicides alone does not provide the season-long weed control. Hence, the integration of other alternatives to manage the weeds during growing period is needed. Use of mulch after pre-emergence application of herbicide is another approach adopted by the farmers as it helps in conserving soil moisture and modifies soil temperature for benefit of crop, besides controlling weeds. However, inadequate research work was carried out on use of herbicides in integration with mulch. Hence, a study was carried out to assess the efficacy of integrated weed management for the management of complex weed flora in turmeric.

MATERIALS AND METHODS

The experiment was carried out during two consecutive *Kharif-Rabi* season of the year 2019-20 and 2020-21 on loamy sand soil of AICRP Weed Management Farm, B.A. College of Agriculture, Anand Agricultural University, Anand. The soil of the experimental field was low in available nitrogen and medium in available phosphorous and high in potassium. Six different weed management treatments tested consisted of: pre-emergence application (PE) of atrazine 750 g/ha followed by (*fb*) rice straw mulch 5 t/ha at 0-3 days after planting (DAP) *fb* hand weeding (HW) at 75 DAP; metribuzin 500 g/ha PE *fb* rice straw mulch 5 t/ha (0-3 DAP) *fb* HW at 75 DAP; pendimethalin 750 g/ha PE *fb* rice

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straw mulch 5 t/ha (0-3 DAP) *fb* HW at 75 DAP; atrazine 500 g/ha + pendimethalin 500 g/ha (tank-mix) PE *fb* rice straw mulch 5 t/ha (0-3 DAP) *fb* HW at 75 DAP; inter cultivation (IC) *fb* HW at 20, 40 and 60 DAP and earthing-up at 75 DAP and weedy check were laid out in the randomized block design with four replications. Turmeric cv. GNT 2 was planted on 07 June 2019 and 29 May 2020 keeping the distance of 45 cm x 20 cm by using 2500 kg/ha rhizomes. The crop was harvested on 7 March 2020 and 19 February 2021. The crop was fertilized with recommended rate of fertilizer (100-50-50 NPK kg/ha) applied using urea, single super phosphate and muriate of potash, respectively during both the years of experimentation. The recommended package of practices was adopted to raise the crop. Weed management practices were adopted as per the treatment wherein, mulching treatment was imposed after application of pre-emergence herbicides. Weed biomass of monocot, dicot and sedges were recorded from randomly selected four spots in net plot by using 0.25 m^2 iron quadrat by destructive sampling method. Weed control efficiency (WCE) was calculated using standard formula as suggested by Maity and Mukherjee (2011). Other observations were also recorded from net plot area following standard procedures.

RESULTS AND DISCUSSION

Effect on weeds

Monocot weeds dominated (76.5%) the experimental period. Major weeds observed in the experimental field were: *Eleusine indica* (32.0%), *Dactyloctenium aegyptium* (17.4%), *Digitaria sanguinalis* (12.5%) and *Eragrostis major* (5.7%) amongst monocot weeds and *Trianthema monogyna* (8.1%), *Oldenlandia umbellata* (4.9%), *Boerhavia erecta* (3.2%) and *Phyllanthus niruri* (3.0%) amongst dicot weeds (**Table 1**).

All the weed management treatments resulted in significant reduction in dry biomass of monocot, dicot and total weeds as compared to weedy check during both the years of experimentation at harvest (**Table 1**). Dry biomass of monocot (8.71 and 5.94 g/m^2) and total (10.1 and 8.86 g/m^2) weeds was observed significantly lower with atrazine 500 g/ha + pendimethalin 500 g/ha (tank-mix) PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP as compared to weedy check during both the years, respectively. The lower dry biomass might be due to effective control of germinating weeds by tank-mix herbicide application while mulches restricted the penetration of solar radiation to soil surface, hampering the germination and emergence of weeds thereby reduced the dry biomass of weeds (Choudhary *et al.* 2020 and Rana *et al.* 2017) in turmeric. However, metribuzin 500 g/ha PE *fb* rice straw mulch 5 t/ha (0-3 DAP) *fb* HW at 75 DAP provided excellent control of dicot weeds (5.02 and 6.75 g/m^2) during both the years, confirming findings of Jadhav and Pawar (2014). Hand weeding thrice and earthing up at 75 DAS provided maximum weed control efficiency of 75.37 and 70.79% during both the years, due to repeated removal of weeds resulting in the lowest weed growth during critical crop weed competition period and highest weed control efficiency, amongst all the treatments tested. Among integrated treatments, atrazine 500 g /ha + pendimethalin 500 g/ha (tank-mix) PE *fb* rice straw mulch 5 t/ha (0-3 DAP) *fb* HW at 75 DAP or metribuzin 70% WP 500 g ha *fb* rice straw mulch 5 t/ha (0-3 DAP) *fb* HW at 75 DAP recorded maximum weed control efficiency due to reduction in density of weeds which lead to reduced the dry biomass of weeds and thereby higher weed

Table 1. Weed biomass at harvest and weed control efficiency as influenced due to different weed management treatments

Treatment	Weed biomass (g/m^2) Monocot 2019-20	Monocot 2020-21	Dicot 2019-20	Dicot 2020-21	Total 2019-20	Total 2020-21	WCE (%) 2019-20	WCE (%) 2020-21
Atrazine 750 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	10.6 (111)	8.14 (66.5)	5.52 (29.8)	7.63 (57.9)	11.9 (141)	11.2 (124)	65.61	53.21
Metribuzin 500 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	9.03 (81.2)	6.13 (37.2)	5.02 (24.6)	6.75 (45.0)	10.3 (106)	9.08 (82.2)	74.15	68.98
Pendimethalin 750 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	9.66 (92.9)	8.01 (64.9)	6.07 (37.2)	8.16 (66.0)	11.4 (130)	11.5 (131)	68.29	50.57
Atrazine 500 g/ha + pendimethalin 500 g/ha (tank- mix) PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	8.71 (75.2)	5.94 (35.2)	5.13 (25.9)	6.53 (42.2)	10.1 (101)	8.86 (77.4)	75.37	70.79
Intercultivation (IC) *fb* HW at 20, 40 and 60 DAP and earthing-up at 75 DAP	11.7 (138)	8.00 (63.5)	6.02 (36.4)	6.12 (36.6)	13.2 (174)	10.0 (100)	57.56	62.26
Weedy check	15.9 (254)	11.2 (125)	12.5 (156)	11.7 (139)	20.2 (410)	16.3 (265)	-	-
LSD (p=0.05)	2.37	2.19	1.88	2.54	2.03	2.22	-	-

Note: Data subjected to $(\sqrt{x+1})$ transformation. Figures in parentheses are means of original values. *PE = pre-emergence application; DAP = days after planting; *fb* = followed by, HW = hand weeding, DAP=days after planting

Table 2. Rhizome yield and economics of turmeric as influenced by weed management treatments

Treatment	Rhizome yield (t/ha)		WI (%)		Gross returns (x10^3 `/ha)		Net returns (x10^3 `/ha)		B:C	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
Atrazine 750 g /ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	19.4	13.6	19.83	35.24	291.0	204.0	112.5	25.5	1.63	1.14
Metribuzin 500 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	23.7	20.6	2.07	1.90	355.5	309.0	175.6	129.1	1.98	1.72
Pendimethalin 750 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	19.6	14.8	19.01	29.52	294.0	222.0	115.4	43.4	1.65	1.24
Atrazine 500 g/ha + pendimethalin 500 g/ha (tank- mix) PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP	24.2	21.0	-	-	363.0	315.0	184.1	136.1	2.03	1.76
Intercultivation (IC) *fb* HW at 20, 40 and 60 DAP and earthing-up at 75 DAP	20.7	17.3	14.46	17.62	310.5	259.5	130.4	79.4	1.72	1.44
Weedy check	5.00	3.70	79.34	82.38	75.0	55.5	-78.9	-98.4	0.49	0.36
LSD (p=0.05)	3.67	4.71								

*PE = pre-emergence application; DAP = days after planting; *fb* = followed by, HW = hand weeding, DAP=days after planting

control efficiency. Beneficial effect of reducing the dry biomass of weeds due to integration of herbicides and mulches was also observed by Dhillon and Bhullar (2014) in turmeric.

Effect on crop

None of applied herbicide showed phytotoxic effect on turmeric at all the growth stages. All the treatments were significantly superior than weedy check in increasing rhizome yield. Atrazine 500 g/ha + pendimethalin 500 g/ha (tank-mix) *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP recorded significantly higher rhizome yield and it was at par with metribuzin 750 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP during both the years of experimentation. The higher yield might be owing to control of complex weed flora due to integration of herbicide, mulching and hand weeding which provides congenial weed free environment to the crop resulted in significantly higher rhizome yield over other treatments. Thus, the integration of herbicides with mulching and hand weeding provided an effective weed management in a long duration crop like turmeric than sole dependence on any single method as reported by Rana *et al.* (2017) and Kumar *et al.* (2014). Among all the treatments, weedy check recorded significantly the lowest rhizome yield during both the years. Yield reduction due to weeds was minimum with metribuzin 500 g/ha PE *fb* rice straw mulch 5 t/ha *fb* hand weeding at 75 DAS while maximum yield reduction was observed under weedy check as observed by Patel *et al.* (2022); Roy and Dharminder (2015) and Rana *et al.* (2017).

Economics

Economics of various weed management treatments indicated that atrazine 500 g/ha + pendimethalin 500 g/ha (tank-mix) PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP recorded higher gross returns, net returns and benefit cost ratio which was followed by application of metribuzin 750 g /ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP during both the years of experimentation. Jadhav and Pawar (2014) also noticed higher net returns and B:C with integration of herbicide with mulching and hand weeding in turmeric.

It can be concluded that atrazine 500 g/ha + pendimethalin 500 g/ha (tank-mix) PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP or metribuzin 750 g/ha PE *fb* rice straw mulch 5 t/ha *fb* HW at 75 DAP provides effective control of weeds, increases rhizome yield as well as benefit cost ratio in turmeric.

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RESEARCH ARTICLE

Integrated approach to manage the complex weed flora in garlic

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ABSTRACT

A field experiment was conducted during *Rabi* seasons (2014-15 and 2015-16) at AICRP-Weed Management, GBPUA&T, Pantnagar, to evaluate the effect of integration of different herbicides and mulching on weeds, yield and economics of garlic. The experiment involved the integration of two mulch treatments in the main plot (with and without rice straw mulch) and four weed management treatments replicated thrice in a split-plot design. The weed density and biomass, weed control efficiency, plant growth parameters and garlic bulb yield varied significantly amongst tested weed management treatments. During both the years, grassy and non-grassy weed density was significantly reduced with rice straw mulch 5 t/ha integration with different herbicides compared to without mulch. The pre-emergence application (PE) of oxyflurofen 0.223 kg/ha recorded lowest density and biomass of all the weeds. The rice straw mulch 5 t/ha resulted in significantly the highest garlic yield (2.95 and 4.25 t/ha); net returns (₹ 1,75850 and 2,80250/ha and B:C (2.9 and 4.7), during both the years, respectively. Among herbicides, oxyflurofen 0.223 kg/ha PE recorded the highest net returns (₹ 1,31700 and 2,04100/ha) and B:C (2.4 and 3.7) during both the year, respectively.

Keywords: Garlic, Herbicides, Integrated weed management, oxyfluorfen, Mulchng

INTRODUCTION

Garlic (*Allium sativum* L.) is cultivated commercially throughout the tropical and subtropical region of the world. It is one of the oldest cultivated spices and is next to onion in production. Although India stands second in area and production of garlic but its productivity (5.69 t/ha) is strikingly far below China and Egypt (National Horticulture Board advanced Estimates for 2015). India produced 2,916,970 tonnes of garlic from 362,950 hectares cultivated area with 8,037 kg/hectare yield during 2019-20 (Spices Board India, Ministry of Commerce and Industry, Government of India). Garlic grows best in well drained fertile soils that are high in organic matter. Incorporating compost or well-rotted manure into heavy soils will result in the soil being friable and suitable for production. Like onion, garlic is sensitive to highly acidic, alkali and saline soils and water logging conditions (Khade *et al.* 2017). It requires cooler weather during the early stages of growth and dry atmosphere with moderately high temperature for maturation.

Garlic is highly vulnerable to weed infestation, due to its slow emergence. Weed infestation is the major factor responsible for reduction in bulb yield upto 30-60% (Lawande *et al.* 2009). Garlic is a closely planted crop with very small canopy, non-branching habit, sparse foliage and shallow root system with requirement for frequent irrigation and high fertilizer application, which aid to weed species occurrence with variation and abundance which hamper the growth and yield of crop (Sahoo *et al.* 2018). A single hand weeding is not sufficient to control weeds in garlic due to its longer crop duration. These factors necessitate the reliance on herbicides for an effective and timely control of weeds in garlic (Kumar *et al.* 2013). Often, due to shortage of labour, high wages and unexpected rains, hand weeding and mechanical operations are either delayed or not implemented at all. The herbicidal weed management in garlic becomes much more important under such situations (Sampat *et al.* 2014, Chaudhary *et al.* 2019) as herbicides are most practical, effective and economical method to control weed and increasing bulb yield of garlic crop (Siddhu *et al.* 2018). However, continuous and intensive use of herbicide over a period of time leads to development of resistant biotypes within the weed community (Shibayama 2001). To overcome these

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problems, there is need to reduce the reliance on synthetic herbicides and shift to low-input sustainable means of weed management, which are eco-friendly (Farooq *et al.* 2011). In this respect, mulching is an agricultural and horticultural technique, not only increase bulb yield but also improve some quality indices such that ash percent, TSS and vitamin C in garlic bulb and create congenial condition for crop growth by regulating soil moisture and temperature, reducing salinity and controlling the weeds (Slam *et al.* 2007; Najafabadia *et al.* 2012). Among organic mulching materials, straw makes good mulch as straw suppresses weeds conserves moisture and retain in soil for longer period (Close 2017; Slam *et al.* 2007).

Thus, this study was conducted to quantify the efficacy of new herbicides and paddy straw mulch used either alone or in combination at different times to manage weeds and improve garlic yield.

MATERIALS AND METHODS

A field experiment was conducted during *Rabi* seasons of 2014-15 and 2015-16, at Norman E. Borlaugh Crop Research Centre, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand. The experimental site was situated at 29^0N latitude, 27.3^0E longitude and at an altitude of 243.8 MSL in subtropical climatic condition of Himalaya foot hill of Uttarakhand. The soil of the experiment was loamy, medium in organic carbon (0.67%), available nitrogen (210 kg/ha), phosphorus (17.5 kg/ha) and potassium (181.2 kg/ha) with a pH value of 7.5. During the growing period, the temperature ranged 11.6-25.0 ^{0}C and total rainfall was 206.9 mm in *Rabi* season of 2014-15 and the temperature range was 12.7-28.3 ^{0}C and the total rainfall 33.2 mm in *Rabi* season of 2015-16.

Garlic variety white "*Nashik*" was planted on Nov. 8^{th} and Oct. 26^{th}, during *Rabi* season of 2014-15 and 2015-16, respectively. The experiment was laid out in split-plot design with three replications. There were eight treatments consisting of two mulch treatments in main plots (with and without rice straw mulch) and four weed control treatments in sub-plot *viz*. recommended herbicides (pre-emergence application (PE) of pendimethalin 1.0 kg/ha, oxyfluorfen 0.223 kg/ha), hand weeding twice at 25 and 45 days after seeding (DAS) and unweeded (control). Pre-emergence application of herbicides was done on Nov. 10^{th}, 2014 and Oct. 28^{th}, 2015 by using knap-sac sprayer fitted with boom along with flat-fan nozzle and the crop was harvested on April 15^{th} 2014 and 20^{th} 2015 during *Rabi* season of 2014-15 and 2015-16, respectively.

Density and biomass of dominated weed species was recorded at 75 DAS. For recording both, density and biomass of the weeds a quadrat of 0.25 m^2 was placed randomly at two places in each of the plots and weeds were counted and biomass was estimated using standard procedure. The data are presented on per m^2 basis. The relative weed density and weed control efficiency was calculated according to the method given by Moinuddin *et al.* (2018). The yield and yield attributes were recorded at harvest and converted to per hectare.

Relative weed density (%)

The relative weed density in weedy check plots was estimated at 75 DAS during both the years (**Table 1**) by following formula:

$$\text{Relative weed density (\%)} = \frac{\text{Total number of individual weed species}}{\text{Total number of all weed species}} \text{ x100}$$

RESULTS AND DISCUSSION

Effect on weeds

The dominant weed species in the experimental plot were. *Phalaris minor*, *Avena ludoviciana*, *Polypogon monspeliensis* among grasses, *Medicago denticulata*, *Melilotus alba*, *Coronopus didymus*, *Polygonum plebeium*, *Chenopodium album*, *Anagallis arvensis*, *Rumex acetosella*, *Fumaria parviflora* among BLWs and *Cyperus rotundus* as sedge. The *Coronopus didymus* and *Phalaris minor* had the highest relative density during both the years, respectively (**Table 1**).

Table 1. Relative density of weeds at 75 days after seeding in weedy plot

Weed Species	Relative weed density (%)	
	2014-15	2015-16
Grasses		
Phalaris minor	18.6	56.2
Avena ludoviciana	3.0	1.4
Polypogon monspeliensis	14.7	6.0
Broad-leaved weeds		
Medicago denticulata	6.6	4.6
Melilotus alba	6.3	2.6
Coronopus didymus	25.6	10.8
Polygonum plebeium	12.5	7.7
Chenopodium album	3.4	5.2
Anagallis arvensis	1.7	1.2
Rumex acetosella	2.0	0.9
Fumaria parviflora	1.3	1.3
Sedge		
Cyperus rotundus	4.4	2.1

Among grasses, the lowest density of *P. minor*, *A. ludoviciana* and *P. monspeliensis* was recorded with straw mulch 5 t/ha during *Rabi* 2014-15 at 75 DAS. However, during 2015-16, the density of *P. minor* and *P. monspeliensis* was not significantly affected due to mulch treatments. *P. monspeliensis* was completely controlled with pendimethalin 1.0.kg/ha PE during both the *Rabi* seasons. The lowest density of *P. minor* and *A. ludoviciana* was recorded with pendimethalin 1.0 kg/ha PE during *Rabi* 2014-15 and with oxyfluorfen 0.223 kg/ha PE during *Rabi* 2015-16 and both treatments were found at par to each other with respect to reducing the density of grasses **(Table 2)**.

Among the broad-leaved weeds, the density of *F. parviflora* and *R. acetosella* during *Rabi* 2014-15 and of *M. denticulata*, *M. alba*, *C. didymus* and *C. album* during *Rabi* 2015-16 was not significantly influenced with mulching. However, the lowest weed density of *M. denticulata*, *M. alba*, *C. didymus*, *P. plebeium*, *F. parviflora*, *R. acetosella*, *C. album* and *A. arvensis* was recorded with straw mulch 5 t/ha during both the *Rabi* seasons. Among sub plot treatments, pendimethalin 1.0 kg/ha PE and oxyfluorfen at 0.223 kg/ha PE had completely controlled *P. plebeium*, *C. album*, *A. arvensis* and *R. acetosella* during both the seasons. The lowest density of *M. denticulata* and *C. didymus* was recorded with oxyfluorfen 0.223 kg/ha PE and of *M. alba* with pendimethalin 1.0 kg/ha PE during both the seasons **(Table 3)**.

The density of sedge; *C. rotundus* was not significantly influenced by straw mulch 5 t/ha during *Rabi* 2014-15 but it recorded the lowest density with straw mulch 5 t/ha during *Rabi* 2015-16. Among the herbicidal treatments the lowest density of *C. rotundus* was recorded with oxyfluorfen 0.223 kg/ha PE during both the seasons **(Table 4)**. Effective control of all the weeds with mulching indicates the weed suppression effectiveness of rice straw (Chaudhary *et al.* 2019). Mulch controls the weeds by smothering seedlings, prevent day light which

Table 2. Effect of treatments on weed density of grasses at 75 DAS

Treatment	Weed density (no./m^2)					
	P. minor		*A. ludoviciana*		*P. monspeliensis*	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Mulching						
Without straw mulch	4.1 (21.3)	6.5(69.7)	3.0(9.7)	2.3(5.2)	3.1(20.7)	2.4(9.6)
Rice straw mulch (5 t/ha)	2.9(14.0)	4.6(51.8)	2.2(4.5)	1.7(2.2)	1.8(3.0)	1.9(3.3)
LSD (p=0.05)	0.4	NS	0.2	0.67	0.7	NS
Weed management						
Pendimethalin 1.0 kg/ha	2.4(6.0)	3.2(10.3)	3.4 (10.7)	2.4(5.0)	1.0(0.0)	1.0(0.0)
Oxyfluorfen 0.223 kg/ha	2.8(8.0)	3.3(14.7)	3.1(8.7)	2.3(4.3)	1.2(0.7)	1.2(0.6)
Manual weeding (25 and 45 DAS)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.6(2.0)	1.6(2.0)
Weedy check	7.6(56.7)	14.8(218.0)	3.1(9.0)	2.5(5.3)	6.0(44.7)	4.7(23.3)
LSD (p=0.05)	0.4	0.59	0.3	0.35	0.5	0.61

*DAS: Days after sowing; NS: Non-significant; Values in parentheses were original and transformed to $(\sqrt{x+1})$ for analysis

Table 3. Effect of treatments on weed density of broad-leaved weeds at 75 DAS

Treatment	Weed density (no./m^2)															
	M. denticulata		*M. alba*		*C. didymus*		*P. plebeium*		*C. album*		*A. arvensis*		*R. acetosella*		*F. parviflora*	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Mulching																
Without straw mulch	5.0 (25.0)	3.8 (16.0)	3.9 (16.7)	6.5 (64.6)	6.3 (44.3)	4.8 (24.6)	3.3 (19.7)	2.7 (12.5)	1.8 (4.3)	2.1 (7.3)	1.5 (2.0)	1.4 (1.7)	1.6 (2.3)	1.4 (1.3)	1.3 (1.0)	1.5 (1.7)
Rice Straw mulch (5 t/ha)	2.7 (7.3)	2.2 (5.0)	3.1 (9.7)	2.6 (11.3)	4.5 (25.7)	3.2 (11.3)	1.9(4.0)	2.2 (5.5)	1.3 (0.8)	1.6 (2.7)	1.2 (0.7)	1.2 (0.7)	1.5 (1.3)	1.0 (0.0)	1.4 (1.3)	1.6 (2.0)
LSD (P=0.05)	0.7	NS	0.7	NS	1.4	NS	0.4	0.35	0.2	NS	0.2	0.26	NS	0.22	NS	0.18
Weed management																
Pendimethalin 1.0 kg/ha	4.8 (24.0)	3.7 (13.7)	2.4 (4.7)	2.0 (3.7)	4.2 (18.7)	3.5 (12.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)
Oxyfluorfen 0.223 kg/ha	3.1 (12.0)	2.9 (10.3)	5.1 (26.0)	5.6 (46.3)	2.9 (10.0)	2.6 (7.3)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.2 (0.7)	1.8 (2.3)
Hand weeding (25 and 45 DAS)	3.0 (8.7)	1.0 (0.0)	1.9 (2.7)	1.0 (0.0)	5.8 (33.3)	3.4 (10.7)	3.2 (9.3)	2.6 (6.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.0 (0.0)	1.5 (1.3)	1.1 (0.3)	1.0 (0.0)	1.0 (0.0)
Weedy check	4.5 (20.0)	4.3 (18.0)	4.4 (19.3)	9.6 (100.2)	8.8 (78.0)	6.5 (42.0)	5.4 (38.0)	5.4 (30.0)	3.2 (10.3)	4.5 (20.0)	2.5 (5.3)	2.3 (4.7)	2.6 (6.0)	2.1 (3.7)	2.2 (4.0)	2.4 (5.0)
LSD(p=0.05)	0.5	0.28	0.5	1.3	0.7	0.51	0.2	0.34	0.8	0.25	0.1	0.16	0.2	0.22	0.2	0.13

*DAS: Days after sowing; NS: Non-significant; Values in parentheses were original and transformed to $(\sqrt{x+1})$ for analysis

Table 4. Effect of treatments on density of sedges at 75 DAS

Treatment	Weed density (no./m^2)	
	2014-15	2015-16
	C. rotundus	
Mulching		
Without straw mulch	3.7(17.3)	3.3(12.3)
Rice Straw mulch (5 t/ha)	3.6(13.0)	2.3(4.8)
LSD (p=0.05)	NS	0.6
Weed management		
Pendimethalin 1.0 kg/ha	6.0(36.0)	4.2(18.3)
Oxyfluorfen 0.223 kg/ha	3.1(8.7)	3.0(8.0)
Hand weeding (25 and 45 DAS)	1.8(2.7)	1.0(0.0)
Weedy check	3.7(13.3)	3.0(8.0)
LSD(p=0.05)	0.5	0.31

*DAS: Days after sowing; NS: Non-significant; Values in parentheses were original and transformed to $(\sqrt{x+1})$ for analysis

helps faster germination from reaching weed seeds and prevents airborne seeds from taking hold on the soil surface (Amoroso *et al*. 2009). Better control of weeds with oxyfluorfen and pendimethalin in garlic was reported earlier (Shashidhar *et al*. 2013).

Weed biomass and weed control efficiency

The straw mulch 5 t/ha could not significantly reduce the grassy weed biomass during *Rabi* 2014-15 and of BLW's during *Rabi* 2015-16. However, the sedges biomass was significantly reduced by mulching (5 t/ha) during both the years. Sub plot treatments had significant effect on grasses and non-grasses weeds. Among herbicidal treatments, oxyfluorfen 0.223 kg/ha PE caused lowest biomass of all weed categories during both the seasons except of broad-leaved weeds during *Rabi* 2015-16 whereas pendimethalin 1.0 kg/ha PE recorded lowest weed biomass at 75 DAS **(Table 5).** The dry biomass of total weeds was recorded significantly lower under straw mulch 5.0 t/ha spread after planting as mulch smothered weed seedlings, prevented day light from reaching weed seeds and prevented airborne seeds from taking hold on the soil surface. Further, significantly the lowest density and biomass of total weeds was recorded with hand weeding at 25 and 45 DAS due to removal of weeds manually at 25 and 45 DAS. Further, oxyfluorfen 0.223 kg/ha PE proved superior over pendimethalin 1.0 kg/ha PE with respect to reducing density and biomass of weeds at 75 DAS confirming findings of Sampat *et al.* (2014) and Malik *et al*. (2017). The highest weed density and biomass was observed under weedy check due to absence of weed control practices.

The straw mulch 5 t/ha did not reduce the total biomass significantly at 75 DAS during both the seasons. However, oxyfluorfen 0.223 kg/ha PE recorded the lowest total weed biomass. The highest weed control efficiency was recorded with straw

Table 6. Effect of treatments on total weed biomass and weed control efficiency (%) at 75 DAS

Treatment	Total weed biomass (g/m^2)		Weed control efficiency (%)	
	2014-15	2015-16	2014-15	2015-16
Mulching				
Without straw mulch	13.4 (205.8)	13.1 (229.5)	24.7	40.2
Rice straw mulch (5 t/ha)	12.0 (160.5)	10.5 (146.4)	32.6	52.1
LSD (p=0.05)	NS	NS	-	-
Weed management				
Pendimethalin 1.0 kg/ha	15.2 (230.7)	11.5 (134.3)	14.6	47.5
Oxyfluorfen 0.223 kg/ha	11.8 (148.3)	10.7 (125.4)	34.5	51.1
Hand weeding (twice)	5.9 (35.1)	3.1 (9.6)	66.9	85.8
Weedy check	17.8 (318.5)	21.9 (482.6)	-	-
LSD (p=0.05)	1.0	0.9		-

*DAS: Days after sowing; NS: Non-significant; Values in parentheses were original and transformed to $(\sqrt{x+1})$ for analysis

Table 5. Effect of treatments on weed biomass of grasses, broad-leaved weeds (BLW's) and sedges at 75 DAS

Treatment	Grasses weed biomass (g/m^2)		BLWs weed biomass (g/m^2)		Sedges weed biomass(g/m^2)	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Mulching						
Without straw mulch	10.3(136.4)	10.8(165.0)	7.3(57.7)	7.0(57.8)	3.5(11.7)	2.6(6.6)
Rice straw mulch (5 t/ha)	9.8(120.5)	9.3(120.0)	5.7(13.0)	4.3(24.1)	2.7(6.6)	1.8(2.4)
LSD (p=0.05)	NS	0.78	0.7	NS	0.3	0.49
Weed management						
Pendimethalin 1.0 kg/ha	12.8(164.9)	10.0(100.0)	6.9(50.4)	4.8(25.4)	4.0(15.4)	3.0(8.5)
Oxyfluorfen 0.223 kg/ha	9.9(100.3)	8.6(76.1)	6.3(44.3)	5.8(45.6)	2.2(3.7)	2.1(3.7)
Hand weeding (twice)	1.7(2.6)	1.7(2.5)	4.9(25.5)	2.7(7.1)	2.7(6.9)	1.0(0.0)
Weedy check	15.7(245.8)	19.8(391.2)	7.9(62.3)	9.2(85.6)	3.3(10.4)	2.5(5.8)
LSD (p=0.05)	1.0	0.73	0.6	0.75	0.3	0.22

*DAS: Days after sowing; NS: Non-significant; Values in parentheses were original and transformed to $(\sqrt{x+1})$ for analysis

Table 7. Effect of treatments on yield and yield attributing characters of garlic

Treatment	Bulb/m^2		Bulb diameter (cm)		No. of cloves/bulb		Bulb weight(g)		Bulb yield (t/ha)	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Mulching										
Without straw mulch	11.9	14.7	6.9	7.8	11.5	15.0	8.8	9.6	1.25	1.78
Rice Straw mulch (5 t/ha)	19.5	30.7	8.4	8.6	13.5	18.4	13.4	12.4	2.95	4.25
LSD (p=0.05)	7.3	8.8	0.2	1.1	NS	2.3	0.6	NS	0.79	1.21
Weed management										
Pendimethalin 1.0 kg/ha	15.7	24.0	8.3	8.2	13.1	16.6	12.7	11.5	2.26	3.07
Oxyfluorfen 0.223 kg/ha	16.6	24.2	8.8	8.9	13.7	18.9	12.8	12.1	2.33	3.23
Hand weeding (25 and 45 DAS)	27.7	39.3	8.6	9.6	12.9	20.6	13.4	14.1	3.65	5.55
Weedy check	2.9	3.3	4.9	6.1	10.5	10.7	5.5	6.2	0.17	0.21
LSD (p=0.05)	3.1	3.9	0.7	0.8	NS	3.0	1.2	0.7	0.29	0.59

*DAS: Days after sowing; NS: Non-significant

Table 8. Economics of garlic crop as influenced by mulching and weed management practices

Treatment	Cost of cultivation (x10^3 `/ha)		Gross returns (x10^3 `/ha)		Net returns (x10^3 `/ha)		B:C	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Mulching								
Without straw mulch	53.75	53.75	100.00	142.20	46.25	89.55	0.9	1.7
Rice Straw mulch (5 t/ha)	60.15	60.15	236.00	340.40	175.85	280.25	2.9	4.7
Weed management								
Pendimethalin 1.0 kg/ha	55.40	55.40	180.80	246.00	125.40	190.60	2.3	3.4
Oxyfluorfen 0.223 kg/ha	54.70	54.70	186.40	258.80	131.70	204.10	2.4	3.7
Hand weeding (25 and 45 DAS)	61.75	61.75	292.00	444.00	230.25	382.25	3.7	6.2
Weedy check	52.65	52.65	13.60	16.56	-39.05	-37.35	0.7	0.7

DAS: Days after sowing; Pendimethalin: ₹ 500/lit; Oxyfluorfen: ₹ 3000/lit; Straw- ₹ 150/quintal; one hand weeding: ₹ 4000/ha; Garlic- ₹ 8000/quintal

mulch (5 t/ha) and oxyfluorfen 0.223 kg/ha PE and hand weeding twice during both years at 75 DAS **(Table 6)**. The lowest WCE was recorded in weedy check as reported by Rahman *et al.* (2012) in garlic and Hussain *et al.* (2008) in onion.

Effect on garlic yield and yield attributes

The highest number of bulb (19.5/m^2 and 30.7/m^2) and diameter of bulb (8.4 and 8.6 cm) were recorded with rice straw mulch 5 t/ha during both the seasons. Among herbicidal treatments oxyfluorfen 0.233 kg/ha PE recorded highest yield attributing characters which was comparable to pendimethalin 1.0 kg/ha PE.

Similarly, significantly higher bulb yield of 2.95 t/ha and 4.25 t/ha was achieved with straw mulch material (5 t/ha) during both the seasons. The positive response of mulching on increased bulb yield of garlic was also reported by Mia *et al.* (1996) and Rahman *et al.* (2005). Among herbicide treatments, the highest yield (2.33 t/ha and 3.23 t/ha) was recorded with application oxyfluorfen 0.233 kg/ha PE which was at par with pendimethalin 1.0 kg/ha PE during *Rabi* 2014-15 and 2015-16, respectively **(Table 7)** due to effective reduction of the density and biomass of monocot (grasses), dicot (broad-leaved) and total weeds which resulted in better availability of nutrient for better growth and development of plant and thereby bulb yield. Further, better management of weeds is turn to increased plant height and produced more assimilates synthesized, translocated and accumulated in plants organs which positively reflected on bulb yield.

Economics

The highest net returns (₹/ha 175850 and 280250) and B:C (2.9 and 4.7) was achieved with straw mulch application (5 t/ha). Oxyfluorfen 0.233 kg/ha PE recorded the highest net returns (₹ /ha 131700 and 204100) and B:C (2.4 and 3.7) during both the seasons, respectively **(Table 8)** due to remarkable increase in gross returns due to higher crop yield (bulb yield) with comparatively low cost of cultivation of garlic in this treatment. Higher B:C with herbicide use was also reported by Kumar *et al.* (2013) in garlic. In hand weeding plots the cost of cultivation increased remarkably due to higher cost involved in manual weeding operations. Moreover, weedy check (control) recorded significantly lesser B:C due to lower bulb yield as recorded by Prakash *et al.* (2000) and Vermani *et al.* (2001).

Conclusion

It is concluded that the use of straw mulch 5 t/ha and oxyfluorfen at 0.223 kg/ha as pre-emergence herbicide may be recommended for effective weed management and to achieve higher garlic bulb yield.

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RESEARCH ARTICLE

Integrated weed management in mesta (*Hibiscus sabdariffa*)

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ABSTRACT

A Field experiment was conducted during *Kharif* 2018, 2019 and 2020 to evaluate chemical, mechanical, cultural practices and their integration for weed management in mesta (*Hibiscus sabdariffa* L.) under AINP on Jute and Allied Fibres, ARS, Amadalavalasa, Andhra Pradesh. The experiment consisted ten treatments with three replications. The pooled analysis indicated high WCE at 15 days after emergence (DAE) (91%) and 35 DAE (98%), fibre yield (2.08 t/ha), net returns (₹ 40131/ha), B:C (2.44) with pre-emergence application (PE) of pretilachlor 900 g/ha within 48 hrs of sowing with sufficient rain or irrigation followed by (*fb*) hand weeding (HW) at 15 days after emergence (DAE). However, the post-emergence application (PoE) of quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha at 15 DAE *fb* hand weeding at 30 DAE recorded higher WCE at 35 DAE (99.9%), and 45 DAE (84%), weed management index (5.16), herbicide efficiency index (330.3), integrated weed management index (4.66) and on par fibre yield (1.79 t/ha), net returns (₹ 33181/ha) and B:C (2.24) with that of pretilachlor 50 EC 900 g/ha + HW at 15 DAE. Thus, farmers may use pretilachlor 900 g/ha within 48 hrs of sowing with sufficient rain or irrigation *fb* HW at 15 DAE or quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE + HW at 30 DAE for effective and economic weed management and obtaining higher mesta fibre yield .

Keywords: Fibre yield, Herbicides, Integrated weed management, Mesta, Nail weeder, Weed indices

INTRODUCTION

Mesta is an important natural and commercial fibre crop next to cotton and jute. India accounts for 46.3% of area and 50.6% of the estimated raw jute (jute and mesta) production of the world. Majority of the manufactured jute goods consumed in India is for packaging agricultural products and for other jute diversified products, *viz*. geotextile, composite, textile, paper and pulp, handicrafts, biofuel, pharmaceutical, nutraceutical benefits. Raw jute is an eco-friendly and safe packaging material as it is biodegradable, natural, annual renewable source. As per the current provisions of the Jute Packaging Material Act, 1987, 100% of food grains and 20% of sugar are to be mandatorily packed in jute bags and there is high demand for jute bags (sacking).

Raw jute occupied an area of 6.63 lakh ha in India during the year 2020-21, with a production of 95.6 lakh bales and yield of 2595 kg/ha and mesta occupies 6.1% and 4.3% of total raw jute area and production, respectively. In India, West Bengal occupies first place in area (78%), production (80%) and yield (2815 kg/ha) of jute and mesta (2406 kg/ha), while Bihar is leading both in area (32.2%) and production (40.6%) of mesta (DE&S, 2022a). The two cultivated species of mesta grown in India for fibre purpose are Roselle (*Hibiscus sabdariffa*) and Kenaf (*Hibiscus cannabinus*). Mesta (Roselle) is largely grown as rainfed crop during *Kharif* season in West Bengal, Bihar, Odisha, Andhra Pradesh, Assam, Meghalaya, Chhattisgarh, Nagaland and Tripura. In Andhra Pradesh, jute and Mesta are mainly grown in Vizianagaram, Srikakulam, Guntur and Prakasam districts. Mesta occupied an area of 1000 ha in Andhra Pradesh with a production 10440 bales and yield of 1880 kg/ha during the year 2020-21 (DE&S, 2022b).

Under rainfed situation, weed infestation is identified as the important production constraint in mesta cultivation. Fibre yield reduction up to 40 to 70% was reported under unweeded situation (Ghorai *et al*. 2013). Weeds compete with mesta for soil moisture, nutrients and light as its growth is slow during initial crop growth period. Critical period of crop-weed competition in jute is during 21 to 45 days after sowing (Kumar *et al.* 2015). Grassy weeds are predominant in jute and mesta fields followed by sedges and broad-leaved weeds (Bhattacharya 2012, Raju and Mitra 2020). Manual weeding twice in the

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early stages of crop growth has been a common weed management practice in mesta. Conventional manual weeding is more expensive due to high manual labour requirement and involves 30-40% of total cultivation cost (Islam 2014). Mechanical weeding and inter cultivation are difficult as the many of the farmers follow broadcasting instead of line sowing. Application of herbicides can create weed free environment in the initial stages of crop growth and increase fibre yield. Combined application of two or more herbicides is being practised for effective and economic management of weeds in fibre crops. Use of broad-spectrum herbicides checks variety of weeds that are not controlled by single application. Keeping this in view, experiment was conducted to evaluate pre, post emergence herbicides, mechanical, cultural practices and their integration for cost effective weed management with increased fibre yield in mesta.

MATERIALS AND METHODS

Field experiments were conducted for three consecutive years during *Kharif* 2018, 2019 and 2020 under rainfed condition at All India Network Project on Jute and Allied Fibres, Agricultural Research Station (ANGRAU), Amadalavalasa in North Coastal zone of Andhra Pradesh. The experimental site is situated at 18.4°N latitude, 83.89°E longitude and altitude of 35 m MSL. Soil type of the experimental site is sandy loam having acidic pH (5.2), normal EC (0.02 dS/m), low in organic carbon (0.25%), available nitrogen (226 kg/ha), available phosphorus (20.6 kg/ha) and available potassium is medium (205 kg/ha).

The present experiment consisted of ten treatments with a plot size of 5.4 x 4.6 m, replicated thrice in a randomized complete block design. Weed management treatments included pre-emergence application (PE) of pretilachlor 900 g/ha within 48 hrs of sowing with sufficient rain or irrigation followed by (*fb*) hand weeding (HW) at 15 days after emergence (DAE), post-emergence application (PoE) of quizalofop-ethyl 38 g/ha at 15 DAE *fb* HW 30 DAE, quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE, quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW 30 DAE, propaquizafop 90 g/ha PoE at 15 DAE *fb* HW 30 DAE, pendimethalin 525 g/ha PE within 48 hours after sowing with sufficient rain or irrigation *fb* one HW 15 DAE, nail weeder at 5 DAE *fb* quizalofop-ethyl 60 g/ha PoE at 25 DAE, unweeded check, HW twice/mechanical weeding (nail weeder) at 15-20 DAE and 35-40 DAE and weed free check.

Mesta variety '*AMV 5*' at a seed rate of 12.5 kg/ha was sown with a spacing of 30 x 10 cm by hand dibbling. Mesta crop was sown on 14.07.2018, 12.07.2019 and 12.05.2020 and harvested at 50% flowering on 20.11.2018, 19.11.2019 and 05.11.2020, respectively. Mesta was sown utilizing the rainfall received during 2018, 2019 and with pre sowing irrigation during *Kharif* 2020. Rainfall received during Mesta crop growing period was 956 mm, 953 mm and 953 mm and 676 mm in 2018, 2019 and 2020, respectively. Fertilizers at the rate of 60:13:25 kg NPK/ha were applied to all the treatments uniformly. Nitrogen was applied in three equal splits as basal, top dressing at 30 and 45 days after sowing. Battery operated knapsack sprayer fitted with flat fan nozzle was used for herbicide application. Weed flora was recorded in unweeded plot and weed samples were collected, in all treatments at 15, 35 and 45 days after emergence of crop, by randomly placing two quadrats of 50 x 50 cm. The weed samples were first dried in shade followed by oven drying at 70 °C for 12 hours and recorded weed biomass (g/m^2). Plant height, basal diameter and fibre yield of mesta were recorded at the time of harvesting. Weed indices, *viz.* weed control efficiency (WCE), weed index (WI), weed management index (WMI), herbicide efficiency index (HEI) and integrated weed management index (IWMI) were calculated following methodology of Devasenapathy *et al.* (2008). Sucking pest incidence was observed in all the years and controlled by spraying of dimethoate and profenophos 2 ml/l of water. Incidence of foot and stem rot disease was low to moderate during 2018, moderate in 2019 and was controlled by drenching with Metalaxyl 8% + Mancozeb 64% 3 g/l of water, while it was high during 2020. The crop was harvested at 50% flowering, followed by retting in stagnated water in retting tank. Fibre was extracted manually, washed in fresh water, well dried before recording of fibre weight. Economics of the various weed management practises was calculated considering the cost of all cultivation practices, herbicides used and MSP for mesta during respective years.

Data recorded on weed biomass was subjected to square root transformation ($\sqrt{x+0.5}$) before statistical analysis. The replicated data pertaining to transformed weed biomass, plant height, basal diameter and fibre yield of all the three years was statistically analysed as per the procedure suggested by Gomez and Gomez (1984) for combined analysis of randomized complete block design over years and treatment means were compared at LSD p=0.05.

RESULTS AND DISCUSSION

Weed flora

The weed flora in the experimental field comprised of *Echinochloa colona, Echinochloa crus-galli, Digitaria sanguinalis, Cyanotis axillaris, Cynodon dactylon, Panicum repens, Chloris barbata, Cyperus rotundus, Celosia argentea, Eclipta alba, Euphorbia hirta, Commelina benghalensis, Cleome viscosa* and *Vernonia cineraria.*

Weed biomass

Weed biomass was significantly affected by various weed management treatments across three years of study. The combined analysis over years indicated significant reduction in weed biomass in all weed management treatments over unweeded check. The weed biomass recorded at 15,35 and 45 DAE **(Table 1)** was significantly higher during 2020 compared to 2019 and 2018. Among the various weed management treatments, weed free check recorded significantly lower weed biomass as it was maintained without weeds throughout the crop growing period. The pretilachlor 900 g/ha PE and pendimethalin 525 g/ha PE recorded significantly lower weed biomass at 15 DAE as compared to other treatments and both were on par with weed free check. The interaction effect of various weed management treatments over years was significant; weed free check, pretilachlor 900 g/ha and pendimethalin 525 g/ha were on par and recorded significantly lower weed biomass followed by running of nail weeder at 5 DAE during the year 2018 and 2019. Pretilachlor being the pre-emergence to early post-emergence broad spectrum herbicide effectively controlled the annual grasses, sedges and broad-leaved weeds in the initial stages (Raju and Mitra 2020, Dutta and Kheroar 2020).

Post-emergence herbicides and hand weeding imposed at 15 or 30 DAE resulted in significant decrease in weed biomass at 35 DAE in all the weed management treatments. Unweeded check recorded significantly higher weed biomass and all other treatments were on par with each other. Among, herbicide treatments, lower weed biomass was recorded with quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE + HW at 30 DAE followed by propaquizafop 90 g/ha at 15 DAE *fb* HW at 30 DAE and quizalofop-ethyl 38 g/ha at 15 DAE *fb* HW at 30 DAE. The interaction effect was also significant over years; weed free check, quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE, propaquizafop 90 g/ha at 15 DAE *fb* HW at 30 DAE were on par and recorded significantly lower weed biomass during all the three years of experimentation, while pretilachlor and pendimethalin were on par during two out of three studied years.

At 45 DAE, next to weed free check, quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha at 15 DAE *fb* HW at 30 DAE recorded significantly lower weed biomass and was on par with other treatments except quizalofop-ethyl 38 g/ha at 15 DAE *fb* HW at 30 DAE, nail weeder at 5 DAE *fb* quizalofop-ethyl 60 g/ha at 25 DAE and unweeded check. The interaction effect was also significant and quizalofop-ethyl 5 EC 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE, quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE recorded significantly lower weed biomass and both were on par with weed free check. Dutta and Kheroar 2020 also reported lowest weed biomass with quizalofop-ethyl + ethoxysulfuron *fb* manual weeding in jute. Singh *et al.* 2015 recorded 23-53% lower weed biomass with quizalofop-ethyl *fb* hand weeding than pretilachlor *fb* hand weeding during critical crop weed competition period. Kumar *et al.* 2015 reported ethoxysulfuron as a broad-spectrum herbicide for control of grass, sedge and broad-leaved weeds in jute. Pooled analysis has clearly indicated that pretilachlor PE and pendimethalin PE controlled weed flora of mesta upto 15 DAE, whereas quizalofop-ethyl 5 EC 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE was most effective in controlling weeds at 35 and 45 DAE.

Weed indices

Highest WCE was observed in weed free check at 15, 35 and 45 DAE in all the three years of study, whereas unweeded check recorded lowest weed control efficiency (**Table 1**). At 15 DAE, pooled analysis indicated that pendimethalin 525 g/ha PE recorded WCE of 94 while pretilachlor 900 g/ha recorded (91%). Mechanical weeding with nail weeder at 5 DAE controlled 64% of the weeds upto 15 DAE. All weed management practices recorded WCE of 97.3 to 99.9% at 35 DAE. Application of post-emergence herbicides at 15 DAE followed by hand weeding at 15 or 30 DAE as per the treatments resulted in higher WCE. Quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE recorded higher WCE of 83.9% among all weed management practices at 45 DAE followed by pendimethalin 525 g/ha *fb* HW at 15 DAE (81.6%), quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE (80.1%), propaquizafop 90 g/ha PoE at 15 DAE *fb* HW at 30 DAE (77.7%) and pretilachlor 900 g/ha PE *fb* HW at 15 DAE (73.7%). Next to weed free check, pretilachlor 900 g/ha PE *fb* HW at 15 DAE recorded lower weed index of 23% followed by hand weeding twice at 15-20 and 35-40 DAE (27.6%) and quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE (31.5%). Raju and Mitra (2020) also reported higher WCE in mesta with pretilachlor 900 g/ha PE *fb* HW at 15 DAE.

Quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ ha PoE at 15 DAE *fb* HW at 30 DAE recorded higher WMI (5.16), HEI (330.31) and IWMI (4.66) compared to all other treatments **(Table 1)**. This was followed by propaquizafop 90 g/ha PoE at 15 DAE *fb* HW at 30 DAE, which recorded WMI, HEI, IWMI values of 3.98, 254.5 and 3.48, respectively. A weed management treatment can be considered as ideal, if it records higher values of weed indices like WCE, WMI, HEI and IWMI and lower value of weed index (Awan *et al.* 2015).

Yield attributes and fibre yield

Integrated weed management practices have shown significant effect on plant height, basal diameter and fibre yield of Mesta. Pooled analysis of three years of experimentation (**Table 2**) indicated that, significantly taller plants (332 cm, 24.2 mm) with higher basal diameter were recorded in weed free treatment. Pretilachlor 900 g/ha *fb* HW at 15 DAE (282 cm, 19.9 mm), quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE (287 cm, 18.7 mm), propaquizafop 90 g/ha PoE at 15 DAE *fb* HW at 30 DAE (281 cm, 18.9 mm), quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE (271 cm. 17.4 mm), recorded on par plant height and basal diameter as that of hand weeding twice at 15-20 and 35-40 DAE (298 cm, 18.2 mm). The interaction of weed management practices over years was also found to be significant. Taller plants with higher basal diameter were noticed in weed free check followed by pretilachlor 900 g/ha PE *fb* HW at 15 DAE, quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE and propaquizafop 90 g/ha PoE at 15 DAE *fb* HW at 30 DAE.

Fibre yield of mesta was significantly higher and on par during 2018 and 2019 compared to 2020. Highest fibre yield was recorded in weed free check (2.64 t/ha), which was significantly higher than rest of the treatments. Pretilachlor 900 g/ha *fb* HW at 15 DAE (2.08 t/ha), quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE (1.79 t/ha), quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE (1.75 t/ha), propaquizafop 90 g/ha at 15 DAE *fb* HW at 30 DAE

Table 1. Weed biomass and other weed indices as influenced by integrated weed management (pooled data of 2018-2020)

Treatment	Weed biomass (g/m^2)			Weed control efficiency (%)			WMI			HEI			IWMI			WI (%)
	15 DAE	35 DAE	45 DAE	15 DAE	35 DAE	45 DAE	15 DAE	35 DAE	45 DAE	15 DAE	35 DAE	45 DAE	15 DAE	35 DAE	45 DAE	
Pretilachlor 900 g/ha (PE) *fb* HW 15 DAE	1.91 (6.0)	1.47 (2.8)	6.25 (50.3)	91.0	98.2	73.7	1.5	1.4	1.8	1.9	10.4	10.2	1.0	0.9	1.3	23.0
Quizalofop-ethyl 38 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	5.63 (31.5)	0.91 (0.4)	7.24 (58.5)	32.2	99.5	65.5	8.4	0.6	0.8	1.0	311.4	1.8	7.9	0.1	0.3	48.7
Quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha (PoE) at 15 DAE	5.27 (27.8)	1.32 (1.2)	5.30 (46.2)	38.9	98.3	80.1	5.3	1.1	1.3	1.8	65.9	37.0	4.8	0.6	0.8	33.6
Quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	5.35 (29.6)	0.74 (0.04)	4.69 (37.5)	33.6	99.9	83.9	13.1	1.1	1.3	2.4	958.3	30.3	12.6	0.6	0.8	31.6
Propaquizafop 90 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	5.63 (31.5)	0.76 (0.07)	5.68 (49.0)	33.6	99.9	77.7	9.6	1.1	1.3	1.5	748.3	13.7	9.1	0.6	0.7	34.8
Pendimethalin 525 g/ha (PE) *fb* HW 15 DAE	1.67 (4.1)	1.67 (4.1)	5.02 (42.2)	93.8	97.3	81.6	0.3	0.3	0.3	1.6	3.9	3.6	-0.2	-0.3	-0.2	58.8
Nail weeder at 5 DAE *fb* quizalofop-ethyl 60 g/ha (PoE) at 25 DAE	4.25 (20.3)	0.97 (0.5)	7.99 (68.3)	64.4	99.2	57.0	1.1	0.7	1.3	3.4	199.1	1.9	0.6	0.3	0.8	43.7
Unweeded check	7.10 (50.6)	9.37 (92.5)	12.14 (155.4)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.3
HW twice/nail weeder at 15-20 DAE and 35-40 DAE	6.46 (41.8)	1.34 (1.3)	7.10 (57.5)	17.1	98.3	66.7	10.8	1.3	1.8	1.5	74.2	4.6	10.3	0.8	1.3	27.9
Weed free check	0.71 (0.0)	0.71 (0.0)	0.71 (0.0)	100	100	100	2.1	2.1	2.1	-	-	-	1.6	1.6	1.6	0.0
LSD (p=0.05) for Year	0.14	0.06	0.21													
LSD (p=0.05) for Treatment	2.17	1.73	2.85													
LSD (p=0.05) for Year x Treatment	0.43	0.19	0.65													

* Data is subjected to ($\sqrt{x + 0.5}$) before statistical analysis and figures in parenthesis were original values; PE – pre-emergence application within 48 hours of sowing with sufficient rain or irrigation; PoE – post-emergence application, *fb* = followed by; DAE - Days after emergence; HW – Hand weeding; WMI – Weed Management Index; HEI- Herbicide Efficiency Index; IWMI – Integrated Weed Management Index; WI – Weed Index

(1.7 t/ha) recorded on par yields with handing twice at 15-20 DAE and 35-40 DAE (1.89 t/ha). Fibre yield of mesta was significantly lower in pendimethalin 525 g/ha *fb* HW 30 DAE (1.04 t/ha) applied plots and lowest fibre yield was recorded in unweeded check (0.85 t/ha). The increase in mesta fibre yield with pretilachlor 900 g/ha PE *fb* HW at 15 DAE, quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE might be due to the less weed infestation during the critical period of crop weed competition, which lead to increase in the plant height, basal diameter and fibre yield of mesta. Dutta and Kheroar (2020) also observed 33% and 136% increase in fibre yield of jute with application of pretilachlor 900 g/ha PE *fb* HW at 35 DAE and quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE *fb* HW 35 DAS, respectively over unweeded plots. Similarly, Raju and Mitra (2020) reported taller plants with higher basal diameter and fibre yield with pre-emergence application of pretilachlor 900 g/ha + HW at 15 DAE. Kumar *et al.* 2015, Dutta and Kheroar (2020) also reported ethoxysulfuron as a broad-spectrum herbicide, which effectively controlled grasses, sedges, broad leaf weeds in jute when applied alone in combination.

Fibre yield obtained across all the treatments during the year 2020 was comparatively lower than 2018 and 2019. This is mainly due to the lower rainfall during early and mid-growth stages of the crop sown with pre sowing irrigation. Water deficit due to largely lower rainfall received during May to September 2020, coupled with incidence of foot stem rot twice during the crop growing period might have affected the crop growth and fibre yield. However, the performance of herbicides across years was stable. Less fibre yield with pendimethalin 525 g/ha PE might be due to its detrimental effect on mesta crop, which was clearly indicated by shorter plants with less basal diameter, low fibre yield, higher weed index, low WMI, HEI and negative IWMI compared

Table 2. Effect of integrated weed management on plant height, basal diameter and fibre yield of Mesta

Treatment	Plant height (cm)				Basal diameter (mm)				Fibre yield (t/ha)			
	2018	2019	2020	Pooled	2018	2019	2020	Pooled	2018	2019	2020	Pooled
Pretilachlor 900 g/ha (PE) *fb* HW 15 DAE	306	285	255	282	22.6	21.2	16.0	19.9	2.55	2.50	1.19	2.08
Quizalofop-ethyl 38 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	272	268	253	265	15.4	14.6	15.4	15.1	1.41	1.30	1.21	1.31
Quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha (PoE) at 15 DAE	287	272	253	271	19.1	18.1	15.2	17.4	1.96	2.06	1.23	1.75
Quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	301	282	277	287	20.5	18.9	16.9	18.7	2.07	1.91	1.38	1.79
Propaquizafop 90 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	305	285	253	281	21.9	19.5	15.3	18.9	2.15	1.98	1.10	1.74
Pendimethalin 525 g/ha (PE) *fb* HW 15 DAE	211	234	252	232	13.3	12.3	16.0	13.9	1.14	0.95	1.03	1.04
Nail weeder at 5 DAE *fb* quizalofop-ethyl 60 g/ha (PoE) at 25 DAE	273	260	248	260	12.8	13.6	14.8	13.7	1.75	1.61	1.06	1.48
Unweeded check	276	245	233	251	12.5	12.4	14.4	13.1	0.83	0.93	0.80	0.85
HW twice/nail weeder at 15-20 DAE and 35-40 DAE	310	320	264	298	19.3	19.9	15.4	18.2	2.00	2.35	1.33	1.89
Weed free check	328	332	335	332	24.8	23.8	23.9	24.2	2.80	3.16	1.95	2.64
Mean	287	278	262		18.2	17.4	16.3		1.87	1.87	1.23	
LSD (p=0.05) for Year				8.9				0.7				0.11
LSD (p=0.05) for Treatment				27.6				3.3				0.47
LSD (p=0.05) for Year x Treatment				28.1				2.2				0.35
CV (%)				6.2				7.9				12.8

PE – pre-emergence application within 48 hours of sowing with sufficient rain or irrigation; PoE – post-emergence application, *fb* = followed by; DAE - Days after emergence; HW – Hand weeding

Table 3. Economics of integrated weed management in Mesta (pooled data of 2018, 2019 and 2020)

Treatment	Gross returns (₹/ha)	Cost of cultivation (₹/ha)	Net returns (₹/ha)	B:C
Pretilachlor 900 g/ha (PE) *fb* HW 15 DAE	68018	27887	40131	2.44
Quizalofop-ethyl 38 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	44581	27668	16913	1.61
Quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha (PoE) at 15 DAE	58296	25225	33071	2.31
Quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	59941	26759	33181	2.24
Propaquizafop 90 g/ha (PoE) at 15 DAE *fb* HW 30 DAE	57519	28886	28633	1.99
Pendimethalin 525 g/ha (PE) *fb* HW 15 DAE	35678	21243	14434	1.68
Nail weeder at 5 DAE *fb* quizalofop-ethyl 60 g/ha (PoE) at 25 DAE	49190	26527	22663	1.85
Unweeded check	29172	17185	11987	1.70
HW twice/nail weeder at 15-20 DAE and 35-40 DAE	62924	32835	30089	1.92
Weed free check	88084	43268	44816	2.04

PE – pre-emergence application within 48 hours of sowing with sufficient rain or irrigation; PoE – post-emergence application, *fb* = followed by; DAE - Days after emergence; HW – Hand weeding to all other treatments. The root and shoot of young mesta seedlings might have absorbed pendimethalin which formed a thin layer at soil surface leading to inhibition of cell division and cell elongation, mitosis in growth of shoots and roots.

Economics

Economics of the weed management treatments pooled over three years of experimentation (**Table 3**) indicated thehighest net returns (₹ 44816/ha) with weed free check followed by pretilachlor 900 g/ha PE *fb* HW at 15 DAE (₹ 40131/ha), quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE (₹ 33181/ha). Weed free check which involved more number of weeding operations, recorded the highest cost of cultivation (₹ 43268). Highest B:C was recorded with pretilachlor 900 g/ha PE *fb* HW at 15 DAE (2.44) followed by quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE (2.31) and quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha PoE at 15 DAE *fb* HW at 30 DAE (2.24). Raju and Mitra (2020) recorded the highest net returns and B:C in mesta with pretilachlor 900 g/ha PE *fb* HW at 15 DAE, while Dutta and Kheroar (2020) reported the highest net returns and B:C in jute with application of quizalofop-ethyl 60 g/ha + ethoxysulfuron 100 g/ha PoE at 15 DAE *fb* HW 35 DAS.

Pretilachlor 900 g/ha PE *fb* hand weeding at 15 days after emergence effectively controlled the weeds in mesta upto 35 DAE, recorded lower weed index and higher fibre yield, net returns next to weed free check and higher B:C. Post-emergence application of quizalofop-ethyl 60 g/ha + ethoxysulfuron 50 g/ha at 15 days after emergence *fb* hand weeding at 30 days after emergence has recorded on par plant height, basal diameter and fibre yield with that of pretilachlor 900 g/ha *fb* HW at 15 DAE, higher WCE at 35 and 45 DAE, WMI, HEI, IWMI, net returns and B:C. Hence, farmers may use one of these two methods depending on the weed intensity and prevailing climatic conditions.

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RESEARCH ARTICLE

Effect of integrated weed management on growth, yield and economics of jute fibre production

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ABSTRACT

A field experiment was carried out at Jute Research Station, Katihar, Bihar to study the effect of integrated weed management practices on growth, yield and economics of *tossa* jute. The experiment was taken up with eight treatments comprising: use of butachlor with different formulations (50% EC and 5% granules) and dosages of (1.0 kg and 1.5 kg/ha), pretilachlor 1.0 kg/ha as pre-emergence application (PE) followed by (*fb*) one hand weeding (HW) at 20 days after emergence of crop (DAE), quizalofop-ethyl 60 g/ha + sticker 1 ml/ l as post-emergence application (PoE) at 15 DAE *fb* one HW at 35 DAE and other treatments include hand weeding twice at 15 and 35 DAE and weedy check. A randomized block design with three replications was used. Amongst tested weed control treatments, quizalofop-ethyl 60g/ha PoE at 15 DAE *fb* one hand weeding at 35 DAE was found effective in significantly increasing the plant height, basal diameter and fibre yield of jute over weedy check and was economical compared to hand weeding twice.

Keywords: Herbicidal efficiency index, Quizalofop-ethyl, Tossa jute, Integrated weed management

INTRODUCTION

Jute is the second most important natural fibre crop after cotton in India. It is largely cultivated in the alluvial plains of West Bengal, Bihar, Orissa and Assam. It plays an important role in the country's economy (Kumar *et al*. 2013). Jute fibre is a raw material for packaging industries and emerged as a versatile raw material for diverse applications in textile industries, paper industries, building and automotive industries, use as soil saver, decorative and furnishing materials, etc. In India jute is grown in 6.8 lakh hectares, producing 9.9 million bales (1bale =180 kg) with average productivity of 2.64 t/ha during 2019-20 (Agricultural statistics at a glance 2021). National average yield (2.64 t/ha) is low as compared to potential yield of 3 t/ha, mostly due to non-availability of quality seed of high-yielding varieties and traditional non-scientific cultivation practices (Price policy for jute 2020-21). In eastern India, jute is mostly cultivated by small and marginal farmers, where conventional manual weeding is a commonly adopted practice which accounts for 30 % of the total cost of cultivation. The yield reduction is up to 70%, if crop remains un-weeded (Ghorai 2013) as jute is a poor competitor with weeds because of its initial slow and erect growing nature. A survey on weed flora in jute growing area indicated that grassy weeds contributed about 60-70% of the total weed population (Kumar *et al.* 2013). Therefore, timely weed control is essential for optimizing the yield of jute. The age old practice of controlling weeds in jute by manual weeding is effective but time consuming, tedious, timely weed control may not be possible manually due to non -availability of labourers and high labour expenses due to high wage rates during peak period of weeding operations. Hence, integration of different weed management practices holds a great promise for effective, timely and economic weed management. Thus, the present study was carried out to evaluate the integration of different weed management practices and assess the weed control efficiency of integrated weed management practice and its influence on productivity of Jute.

MATERIALS AND METHODS

A field experiment was conducted for two years during *Kharif* season of 2013 and 2014 under All India Network project (AINP) on Jute & Allied fibres

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at Jute Research Station, Katihar of Bihar Agricultural University, Bihar, India. The farm is situated at approximately 25^0 31.8`N, latitude and $87^0$ 34`E, longitude with an average altitude 30 m above the mean sea level. The climate of the study area is characterized by hot and wet summer with the average annual rainfall of 1200 mm. The total amount of rainfall received was 1223 mm and 1434 mm during 2013 and 2014, respectively.

Soil of the experimental site was silty loam in texture with neutral soil reaction (pH 7.6), low in organic carbon (OC) (0.49%), available nitrogen (160 kg/ha) and available potassium (84 kg/ha) and medium in available phosphorus (20 kg/ha). Experiment was carried out with eight treatments comprising: use of pre-emergence application (PE) of butachlor, at 2 days after sowing (DAS), using different formulations (50% EC and 5% granular) and different doses of 1 kg and 1.5 kg/ha, pretilachlor 1.0 kg/ha were applied followed by (*fb*) one hand weeding at 20 DAE, post-emergence application (PoE) of quizalofop ethyl 60 g/ha + sticker (Dhanuvit) 1 ml/ litre at 15 DAE *fb* one hand weeding at 35 DAE and other treatments include hand weeding twice at 15 and 35 DAE and weedy check with three replications in a randomized block design. Jute variety JRO-524 was sown in April 28th and May 3rd during 2013 and 2014 respectively with seed rate of 5 kg/ha and spacing of 30 x 5 cm between rows and within a row was used. Fertilizer dosage of 60:30:30 N:P:K kg/ha was applied and two sprays of dimethoate was taken up to control Bihar hairy caterpillar.

All the herbicides were sprayed with battery operated knap-sack sprayer fitted with flat-fan nozzle using spray volume of 500 l/ha. Data on weed biomass were recorded at 15 DAE and 45 DAE using 0.25 m^2 quadrat placed randomly in each plot and the data was subjected to square root transformation of (X+1.0) before analysis.

Weed control index

Weed control index was calculated to compare the different weed control treatments on the basis of biomass. It indicates the per cent reduction in the dry weight (biomass) in the treated plots compared to weedy plots. The formula is as follows (Das 2008):

$$WCI = \frac{WDC\text{-}WDT}{DMC} \times 100$$

Where, WDC is the weed biomass in unweeded control (g/m^2) and WDT is the weed biomass in treated plot (g/m^2).

Weed index (WI)

Weed index is the per cent reduction in crop yield under a particular treatment due to the presence of weeds in comparison to weed free plot (Das 2008). WI is used to assess the efficacy of an herbicide. Lesser the WI, better is the efficiency of an herbicide. It is expressed in percentage and was determined with the help of following formula:

$$WI (\%) = \frac{X - Y}{X} \times 100$$

Where, WI = Weed index; X = Crop yield from weed free plot (hand weeding) and Y = Crop yield from the treated plot for which weed index is to be worked out.

Herbicide efficiency index (HEI)

This index represents the potential of a particular herbicide for controlling the weeds along with their phyto-toxicity effect on the crop (Krishnamurthy *et al.* 1975)

$$HEI = \frac{\frac{(Yt\text{-}Yc)}{Yt} \times 100}{\frac{WDMt}{WDMc} \times 100}$$

Where, Yt-crop yield from treated plot, Yc-crop yield from weedy check plot, WDMt-weed biomass in treated plot and WDMc-weed biomass in weedy check plot.

Observations on crop, *viz.* plant height was recorded with scale and basal diameter was estimated using caliper, whereas for fibre yield estimation, harvested jute plants are left in field for two days for drying, after drying they are bundled and immersed in pond for 15-20 days for retting process. After completion of retting, fibre is extracted from stem and dried, fibre weight is recorded. The economics of weed management was worked out. Since the results trend was same in 2013-14 and 2014-15, the pooled data of the two years are presented and used for discussion.

RESULTS AND DISCUSSION

Weed flora

The dominant weed flora observed in the experimental plots were *Cyperus rotundus,* the sedge and *Echinochloa crus-galli, Echinochloa colona, Cynodon dactylon, Digitaria sanguinalis, Eleusine indica,* among grasses. The predominant broad-leaved weeds include: *Digera arvensis, Portulaca* *oleracea, Physalis minima, Phyllanthus niruri etc.* Similar results were reported by Kumar *et al.* (2014), Masumi *et al.* (2011) and Mukherjee *et al.* (2011).

Weed biomass

Hand weeding twice at 15 and at 35 DAE provided weed free condition with 81% weed control (**Table 1**). Among the different herbicide treatments, quizalofop-ethyl 60g/ ha PoE at 15 DAE *fb* 1 HW at 35 DAE resulted in lowest weed biomass (1.23 t/ ha) at 45 DAE as it was more effective in suppressing the weed density and weed dry matter. The higher weed biomass at 45 DAE recorded with pre-emergence herbicide, might be due to decreased efficacy of herbicides on the subsequent flushes of weeds especially *Cyperus rotundus* and other dominant grassy weeds which quite commonly predominate after receiving rains. Similar results with use of PoE herbicides like quizalofop-ethyl and propaquizafop significantly controlled the grassy weeds which were problematic in raising successful jute crop were also reported by Ghoria *et al. (*2013), Sarkar *et al.* (2005) and Sarkar (2006).

Weed indices

The higher weed control efficiency (81.30%) and lowest weed index (WI) at 45 DAE was recorded with hand weeding twice at 15 DAE and 35 DAE (**Table 1**). The highest WI (55.54%) and lowest WCE was recorded with weedy check due to unchecked weed growth throughout the crop growth period and the consequent competition for growth resources resulted in the reduction of yield. Among weed control treatments, quizalofop ethyl 60 g/ha PoE at 15 DAE *fb* 1 HW at 35 DAE recorded highest WCE (77.41%), lowest WI and higher HEI (4.99%) which might be due effective control of grassy weeds dominant in the experimental field. Whereas, pre-emergence herbicides butachlor (50% EC) 1.5 kg/ha recorded the highest WCE (71.67%) at 45 DAE over other pre-emergence herbicides. Thus, quizalofop-ethyl PoE was found more effective than pre-emergence herbicides in managing weeds in jute as reported by Sarkar (2006) and Ghorai *et al.* (2013)

Crop growth and fibre yield

During both the years, quizalofop-ethyl 60 g/ha at 15 DAE *fb* one HW at 35 DAE recorded taller plants (291.8 cm) with highest basal diameter (1.80 cm) over other herbicidal treatments used in experimentation (**Table 2**), which might be due to suppression of weed growth resulted in better crop growth.

Significant improvement in jute fibre yield was observed with all the weed control treatments when compared to weedy check during both the years (**Table 2**) might be due to decreased crop weed competition for resources (sunlight, nutrients and space) The quizalofop-ethyl 60 g/ha *fb* one HW recorded highest fibre yield (2.77 t/ha) owing to highest plant height (291.8 cm) and basal diameter (1.80 cm). It provided better control of weeds during crop growth period resulting in better yield advantage compared to other herbicidal treatments used in experiment. Similar beneficial effects were reported by Ghorai *et al.* (2013), Sarkar (2006).

Economics

All the weed management treatments recorded better monetary returns compared to weedy check which recorded the lowest net returns (₹ 13470) and B:C (0.81) (**Table 3**). The hand weeding twice recorded high cost of cultivation (₹ 22698/-) with benefit:cost (2.0) and was superior to other

Table 1. Effect of weed control treatments on weed biomass, weed control efficiency (WCE), weed index (WI) and herbicide control efficiency (HCE)

Treatment	Weed biomass at 15 DAS (t/ha)		Pooled	Weed biomass at 45 DAS (t/ha)		Pooled mean	Weed management Indices Pooled mean of two years (2013-2014)		
	2013	2014		2013	2014		WCE (%)	WI (%)	HEI (%)
Butachlor 50% EC 1.0 kg/ha PE *fb* 1 HW at 20 DAE	1.15(1.33)	1.20(1.42)	1.18(1.38)	1.38(1.72)	1.56(1.91)	1.47(1.81)	65.96	22.26	2.42
Butachlor 50% EC 1.5 kg/ha PE *fb1* HW at 20 DAE	1.12(1.27)	1.13(1.29)	1.12(1.28)	1.24(1.51)	1.45(1.54)	1.34(1.53)	71.57	13.78	3.35
Butachlor 5% G 1.0 kg/ha PE *fb* 1 HW at 20 DAE	1.18(1.39)	1.23(1.52)	1.21(1.46)	1.50(2.07)	1.64(2.28)	1.57(2.17)	59.54	28.49	1.54
Butachlor 5% G 1.5 kg/ha PE *fb*1 HW at 20 DAE	1.14(1.31)	1.17(1.37)	1.16(1.34)	1.41(1.82)	1.56(1.98)	1.48(1.90)	64.59	21.04	2.28
Pretilachlor 50% EC 1.0 kg/ha PE *fb* 1 HW at 20 DAE	1.07(1.17)	1.15(1.33)	1.11(1.25)	1.28(1.74)	1.53(1.64)	1.40(1.69)	68.34	15.88	2.97
Quizalofop-ethyl 60 g/ha + sticker 1 ml/l PoE at 15 DAE *fb* 1 HW at 35 DAE	1.06(1.12)	1.10(1.22)	1.08(1.17)	1.12(1.15)	1.34(1.28)	1.23(1.21)	77.41	7.20	4.99
Unweeded check	1.67(2.83)	1.81(3.27)	1.74(3.05)	2.28(5.55)	2.06(5.19)	2.17(5.37)	0.00	55.54	-
Hand weeding twice at 15 DAE and 35 DAE	1.04(1.08)	1.06(1.10)	1.04(1.09)	1.01(0.98)	1.26(1.03)	1.14(1.01	81.30	-	-
LSD (p=0.05)	0.011	0.005	0.11	0.14	0.02	0.149	2.32	3.43	0.35

Data subjected to $\sqrt{x+0.5}$ transformation and figures in parentheses are original weed biomass in t ha; PE: pre-emergence; PoE: post-emergence; *fb*: followed by; HW: hand weeding; DAE: days after emergence

Table. 2. Effect of weed management practices on growth parameters at harvest (120 DAS) and fibre yield of jute

Treatment	Plant height (cm)		Pooled mean	Basal diameter (cm)		Pooled mean	Fibre yield (t/ha)		Pooled mean (t/ha)
	2013	2014		2013	2014		2013	2014	
Butachlor 50% EC 1.0 kg/ha PE *fb* 1 HW at 20 DAE	277.7	265.0	271.3	1.73	1.59	1.66	2.31	2.26	2.28
Butachlor 50% EC 1.5 kg/ha PE *fb1* HW at 20 DAE	291.0	288.7	289.8	1.82	1.71	1.77	2.54	2.52	2.53
Butachlor 5% G 1.0 kg/ha PE *fb* 1 HW at 20 DAE	271.0	256.3	263.7	1.68	1.49	1.59	2.17	2.03	2.10
Butachlor 5% G 1.5 kg/ha PE *fb*1 HW at 20 DAE	283.7	272.2	277.9	1.78	1.56	1.67	2.41	2.25	2.33
Pretilachlor 50% EC 1.0 kg/ha PE *fb* 1 HW at 20 DAE	285.3	280.0	282.7	1.80	1.66	1.73	2.53	2.42	2.48
Quizalofop-ethyl 60 g/ha + sticker 1 ml/l PoE at 15 DAE *fb* 1 HW at 35 DAE	290.0	293.7	291.8	1.85	1.75	1.80	2.77	2.69	2.73
Unweeded check	242.4	233.3	237.9	1.52	1.44	1.48	1.30	1.32	1.31
Hand weeding twice at 15 DAE and 35 DAE	324.1	301.7	312.9	1.90	1.80	1.85	2.98	2.93	2.96
LSD (p=0.05)	20.4	17.1	8.5	0.15	0.11	0.05	0.23	0.24	0.11

Table 3. Economics of weed management treatments in jute

Treatment	Cost of cultivation of 2 years (x10^3 `/)	Net returns (x10^3 `/ha)		Pooled mean	B:C		Pooled mean
		2013	2014		2013	2014	
Butachlor 50% EC 1.0 kg/ha PE *fb* 1 HW at 20 DAE	20.57	32.48	31.47	31.98	1.58	1.53	1.55
Butachlor 50% EC 1.5 kg/ha PE *fb1* HW at 20 DAE	20.68	37.74	37.30	37.52	1.83	1.80	1.81
Butachlor 5% G 1.0 kg/ha PE *fb* 1 HW at 20 DAE	20.75	29.24	25.86	27.55	1.41	1.25	1.33
Butachlor 5% G 1.5 kg/ha PE *fb*1 HW at 20 DAE	21.05	34.38	30.75	32.56	1.63	1.46	1.55
Pretilachlor 50% EC 1.0 kg/ha PE *fb* 1 HW at 20 DAE	20.95	37.32	34.68	36.00	1.78	1.66	1.72
Quizalofop-ethyl 60 g/ha + sticker 1 ml/l PoE at 15 DAE *fb* 1 HW at 35 DAE	21.65	42.14	40.34	41.24	1.95	1.86	1.91
Unweeded check	16.70	13.20	13.74	13.47	0.79	0.82	0.81
Hand weeding twice at 15 DAE and 35 DAE	22.70	45.92	44.77	45.34	2.02	1.97	2.00
LSD (p=0.05)	-	5.33	5.48	2.59	0.25	0.27	0.12

treatments but the cost of cultivation (₹ 22,648/ha) was higher compared to other treatments.

Quizalofop-ethyl 60 g/ha PoE at 15 DAE (when the grassy weeds were 3-4 leaf stage) not only controlled the grassy weeds but also resulted in higher fibre yield and net returns than other herbicides as reported by Sarkar (2006). It may be concluded that when the labour availability is scarce and costly, quizalofop-ethyl 60 g/ha PoE at 15 DAE *fb* one hand weeding at 35 DAE may be used as it was found effective in significantly increasing the plant height, basal diameter and fibre yield of jute over weedy check and was economical compared to hand weeding twice.

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RESEARCH ARTICLE

Management of bispyribac-sodium-resistant populations of small-flowered umbrella sedge (*Cyperus difformis*) using alternative herbicides

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ABSTRACT

The over-reliance on the acetolactate synthase-inhibiting herbicide bispyribac-sodium for broad-spectrum weed control in the rice-rice cropping system has led to an increase in the population of bispyribac-sodium resistant weeds. *Cyperus difformis* L. is one of the problematic and difficult-to-control weeds in the rice ecosystem with steady rise in the occurrence of bispyribac-sodium resistant populations. Therefore, to assist the rice farmers containing bispyribac-sodium resistant *C. difformis*, alternate options were tested. A pot study was carried out during the rainy season of 2019 and 2020 at the ICAR-Directorate of Weed Research, Jabalpur to evaluate herbicides with different sites of action against susceptible and resistant populations of *C. difformis*. Fluorpyrauxifen-benzyl at 31.25 g/ha at 3-5 leaves stage of *C. difformis* caused 100% reduction, over untreated check, in *C. difformis* density, plant height, fresh and dry shoot biomass, and visible mortality at 21 days after treatment. Next best herbicide was bentazone at 960 g/ha (>90%). Similarly, chlorimuron + metsulfuron at 4 g/ha and 2,4-D amine salt at 500 g/ha also resulted in a substantial reduction in the growth of susceptible and resistant populations. It can be concluded that fluorpyrauxifen-benzyl at 31.25 g/ha could be a potential herbicide against *C. difformis* and to be evaluated under field situations to verify and confirm its efficacy.

Keywords: Bispyribac-sodium, Herbicide resistance, *Cyperus difformis*, Resistant populations, Resistance management, Rice

INTRODUCTION

In the recent past, scarcity of labour and higher wages has forced the adoption of herbicide-based weed management in India (Rao *et al*. 2007). Although herbicide provides cost-effective weed control and saves labour, the sole dependence on herbicides for weed control with repeated use of the same mode of action can lead to the rapid development of herbicide resistance in weeds (Bhullar *et al.* 2017; Singh 2016; Chhokar *et al.* 2017; Zakaria *et al.* 2018 and Soni *et al.* 2021).

Bispyribac-sodium is an excellent herbicide that gives broad-spectrum weed control in rice. In the recent past, the lesser efficacy of herbicides or escape after herbicide applications (possibly herbicide resistance) has emerged as the major concern of contemporary agriculture. For weed management in rice, acetolactate synthase (ALS)-inhibiting herbicides have been extensively used for more than a decade mainly due to their broad-spectrum weed control, availability, and affordability by the rice growers (Choudhary and Dixit 2018; Mascazoni *et al.* 2018). However, these herbicides are more prone to the development of resistance in weeds (Heap 2021). The continuous use of bispyribac-sodium over a decade in rice-rice cropping systems along with inappropriate application techniques [*i.e.* lesser spray volume, faulty nozzle (hollow cone nozzle), late application, swing pattern of spraying, impure water, etc.] (personal observations by VK Choudhary) are the main cause of the development of resistance. In rice-rice system, the bispyribac-sodium resistant small-flowered umbrella sedge (*Cyperus difformis*) populations have been gradually increasing. This problem may further intensify mainly due to sharing of rice seeds among farmers, some of which may be contaminated with herbicide-resistant seeds. Thus, the main weed management tool is at a risk; thus, the sustainability of rice production is a serious problem as insufficient weed control also leads to low yield and grain quality losses and higher production costs (Marchesi and Saldain 2019).

Cyperus difformis is the most predominant *Cyperus* species in wetland/lowland rice cultivation systems. It forms dense mats of vegetation in young rice and reduces the rice yield by 12-50% (https://www.cabi.org/isc/datasheet/17495). Due to the intensification of rice cultivation and the repeated use of herbicides for weed management, *C. difformis* has evolved resistance to ALS-inhibiting herbicides in many rice areas worldwide (Merotto Jr *et al.* 2009).

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Some of the *C. difformis* populations from Chhattisgarh and Kerala states of India have developed resistance against bispyribac-sodium (Choudhary *et al.* 2021a). Herbicide resistance in weeds has become a major threat to the sustainability of wheat production in rice-wheat cropping system of Indo-Gangetic Plains (Kaur and Singh 2019). Early control of resistant populations using alternate herbicides with a different mode of action is important for sustainable rice production (Marchesi and Saldain 2019). Herbicide rotation with a diverse mode of action may reduce selection pressure and delays herbicide resistance evolution (Burgos 2015; Choudhary *et al.* 2021b). Thus, there is an urgent need to develop potential management strategies to control resistant populations of *C. difformis* to further overstate the problem in other areas. Hence, the present study was conducted to evaluate the efficacy of different alternate herbicides against bispyribac-sodium resistant populations of *C. difformis*.

MATERIALS AND METHODS

A pot study was conducted during the rainy season of 2019 and 2020 at ICAR-Directorate of Weed Research, Jabalpur (23°132'N and 79°592'E with an elevation of 388 m above mean sea level), Madhya Pradesh, India in a completely randomized design (CRD) with three replications. Three resistant populations (CGDCD-11, CGDCD-12, and CGRCD-20) with a resistance index of 10 - >20 based on ED_{50} and one population (CGDCD-1) of susceptible biotype of *C. difformis* were chosen for the study. These populations were collected from the previously conducted resistance study of bispyribac-sodium applied at 25 g/ha (field dose). The basic information about the populations was published earlier (Choudhary *et al.* 2021a). Five herbicides were evaluated at recommended dose along with untreated control (**Table 1)**.

Soil samples from 2-15 cm soil depth was taken from the field where rice-wheat system has been in practice for >10 years. The soil was clay-loam (Typic chromusterts) in texture with neutral in reaction with 7.1 pH and 0.21 dS/m of electrical conductivity. The organic carbon was 0.65% with available nitrogen, phosphorus and potassium were 254.0, 16.8 and 365.0 kg/ha, respectively. The soils were dried and autoclaved to kill the existing weeds and then filled in the pots with 17 cm x 17 cm dimensions.

Fresh seeds of *C. difformis* possess dormancy and do not germinate immediately after sowing (Derakhshan and Gherekhloo 2013). Therefore, to break the seed dormancy, seeds were first scarified in cotton cloth by rubbing and then mixed with autoclaved sand. The seed mixture (seeds+sand) was uniformly broadcasted on the saturated pots filled with autoclaved soils. Later, the seed mixture was smeared with soil. After 5 days, there was an excellent emergence. At 10 days after sowing, pots were thinned and 25 seedlings of *C. difformis* retained in the single pot and the rest were uprooted. The post-emergence application (PoE) of herbicides treatments was done at 20 days after sowing (DAS), as per the schedule using solar-cum-battery operated knapsack sprayer fitted with a flat-fan nozzle delivering 375 L/ha of spray volume at 350 kPa pressure. An untreated control was maintained for comparison.

Observations on the survived plants/pot, plant height, fresh and dry shoot biomass, and visible mortality were recorded 3 weeks after the treatments. All these observations were compared with untreated control and presented as % reductions. The plants that remained green at 21 days after treatment were considered as surviving plants. The dead plants were considered as a reduction in plant population and expressed in percentage. Plant height was recorded for green plants from the base to tip of the plant and expressed in cm. The reduction in plant height of survived treated plants was estimated by comparing with untreated plants and expressed in percentage. Fresh weight of green plants was recorded from the base of survived plants and compared with untreated control of the same population. Likewise, dry shoot biomass was recorded from survived plants and compared with untreated control of the same populations (samples were dried in a hot air oven at 65±2 ^{0}C till constant weight was achieved) and expressed in percentage. Visible mortality was recorded by three experienced persons giving a score of 0-100 (0 means no control and 100 means complete control), and the mean was used to compare against untreated populations. Statistical analysis of all the parameters was done using OPSTAT software.

RESULTS AND DISCUSSION

Reduction in *C. difformis* growth

Fluorpyrauxifen-benzyl 31.25 g/ha post-emergence (PoE) recorded an absolute reduction in population, plant height, effective suppression in fresh shoot weight with 100% control of susceptible and resistant populations of *C. difformis* followed by bentazone 960 g/ha, chlorimuron + metsulfuron 4 g/ha and 2,4-D 500 g/ha over untreated control (**Table**

2). Bispyribac-sodium 25 g/ha (field dose) completely controlled the susceptible biotype (CGDCD-1), whereas CGDCD-11 (biotype resistant up to 2X) had shown only 9% of reduction in plant population but CGDCD-12 and CGRCD-20 biotypes (resistant > 4X) had no reduction in populations, lesser reduction in plant height (4-8%), fresh shoot weight (1-3%), and lesser control/suppression (only 4-8%) (**Table 3**).

Visible plant mortality

Fluorpyrauxifen-benzyl 31.25 g/ha PoE has caused complete mortality (visual) of the resistant and susceptible populations of *C. difformis*. Bentazone 960 g/ha PoE recorded 87-95% mortality while chlorimuron+metsulfuron at 4 g/ha and 2,4-D at 500 g/ha caused 72-78% and 60-67% mortality, respectively over untreated control. Bispyribac-sodium recorded complete mortality of CGDCD-1, but it was ineffective in managing resistant populations (CGDCD-11, CGDCD-12, and CGRCD-20) (**Table 4**). Among different tested herbicides, fluorpyrauxifen-benzyl was found to be an effective treatment that provided excellent control of *C. difformis* followed by bentazone suggesting that these herbicides may serve as alternative options that may help rice growers to control bispyribac-sodium resistant populations. Their usage may also delay or stops the evolution of herbicide resistance when used as a component of integrated weed management

Table 1. Alternate herbicides tested to manage bispyribac-sodium resistant populations of *Cyperus difformis*

Herbicide	Dose (g/ha)	Site of action	WSSA	HRAC
Florpyrauxifen-benzyl	31.25	Synthetic auxins	4	O
Bentazone	960	Photosystem II inhibitors	6	C3
Chlorimuron + metsulfuron	4	Acetolactate synthase inhibitors	2	B
2,4-D amine salt	500	Synthetic auxins	4	O
Bispyribac-sodium	25	Acetolactate synthase inhibitors	2	B

WSSA: Weed Science Society of America; HRAC: Herbicide Resistance Action Committee

Table 2. Bispyribac-sodium resistant and susceptible *C. difformis* populations' control as measured by plant population and plant height reduction (%) at 21 days after treatments (mean of two years)

Treatment	Dose (g/ha)	Reduction in plant populations				Reduction in plant height			
		Susceptible	Resistant			Susceptible	Resistant		
		CGDCD -1	CGDCD -11	CGDCD -12	CGRCD -20	CGDCD -1	CGDCD -11	CGDCD -12	CGRCD -20
Untreated control		Plant population (#/pot)				Plant height (cm)			
		25	25	25	25	14.3	14.2	14.7	15.0
		% control over untreated control							
Florpyrauxifen-benzyl	31.25	100aA	100aA	100aA	100aA	100	100	100	100
Bentazone	960	93aB	95aB	91bB	91bB	49	50	49	50
Chlorimuron + metsulfuron	4	83aC	83aC	79bC	77bC	48	40	42	42
2,4-D	500	79aD	73bD	69cD	68cD	47	32	30	33
Bispyribac-sodium	25	100aA	9bE	0cE	0cE	100	8	5	4
Untreated control	-	0	0	0	0	0	0	0	0

Means for each population within a column followed by the same uppercase letters and means for each herbicide within a row followed by the same lowercase letters are not significantly different according to Fisher's protected LSD test (p = 0.05).

Table 3. Reduction (%) in fresh and dry shoot biomass of bispyribac-sodium resistant and susceptible *C. difformis* populations at 21 days after treatment (mean of two years)

Treatment	Dose (g/ha)	Reduction (%) in fresh shoot biomass				Reduction (%) in dry shoot biomass			
		Susceptible	Resistant			Susceptible	Resistant		
		CGDCD -1	CGDCD -11	CGDCD -12	CGRCD -20	CGDCD -1	CGDCD -11	CGDCD -12	CGRCD -20
Untreated control		Fresh shoot weight (mg/plant)				Dry shoot biomass (mg/plant)			
		330	332	327	334	46.8	46.6	45.7	46.4
		% control over untreated control							
Florpyrauxifen-benzyl	31.25	100aA*	100aA	100aA	100aA	100aA	100aA	100aA	100aA
Bentazone	960	93aB	90bB	88cB	89bB	93aB	92aB	91bB	90bB
Chlorimuron + metsulfuron	4	77aC	75bC	74cC	74aC	80aC	78bC	76cC	77cC
2,4-D	500	71aD	68bD	64cD	65cD	71aD	67bD	64dD	65cD
Bispyribac-sodium	25	100aA	3bE	1cE	1cE	100aA	8bE	4dE	5cE
Untreated control	-	0	0	0	0	0	0	0	0

*as suggested in Table 2

Table 4. Visible mortality (%) of bispyribac-sodium resistant and susceptible *C. difformis* populations at 21 days after treatments (mean of two years)

Treatment	Dose (g /ha)	Susceptible CGDCD-1	Resistant CGDCD-11	CGDCD-12	CGRCD-20
		% control over untreated control			
Florpyrauxifen-benzyl	31.25	100aA*	100aA	100aA	100aA
Bentazone	960	95aB	94aB	87bB	87aB
Chlorimuron + metsulfuron	4	78aC	76bC	72cC	72aC
2,4-D	500	67aD	65bD	62cD	60aD
Bispyribac-sodium	25	100aA	0bE	0bE	0aA
Untreated control	-	0	0	0	0

*as suggested in Table 2

including crop rotation, herbicides rotation with different sites of action and use of herbicide mixtures at field rates (Choudhary and Dixit 2021) with other agronomic manipulations (competitive cultivars, optimum sowing window, seeding rate, etc.) (Choudhary *et al.* 2021b). It is also suggested to remove weeds surviving the herbicide treatments before the seed is set to reduce weed seed bank and avoid seed dispersal. However, the price of the fluorpyrauxifen-benzyl has not been announced by manufacturers, thus based on the field trials and price of the product, the economics analysis need to be done and communicated to the rice farmers.

Based on the experiment, it can be concluded that fluorpyrauxifen-benzyl 31.25 g/ha PoE appeared to be a potential herbicide to control bispyribac-sodium resistant populations of *C. difformis* followed by bentazone 960 g/ha PoE . However, in the absence of resistant biotypes, bispyribac-sodium 25 g/ha PoE continues to provide excellent control of *C. difformis*. Therefore, it is suggested to rotate these herbicides in rice-growing areas to control >90% of *C. difformis*.

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RESEARCH ARTICLE

Effect of aqueous extracts of the invasive weed, creeping daisy (*Sphagneticola trilobata)* on the mortality of earthworm, *Perionyx excavatus*

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ABSTRACT

Sphagneticola trilobata (L.) Pruski is considered as one of the world's worst alien invasive species. The extent of mortality of earthworm *Perionyx excavatus* Perrier exposed to 2.5×10^2, 5.0×10^2 and 7.5×10^2 g/L of aqueous extracts of fresh and dry *S. trilobata* plants was studied. The experiment was carried out in plastic containers containing 3:1 mixture of compost and topsoil. The mortality of all the *P. excavates,* exposed to fresh plant extracts of 5.0×10^2, 7.5×10^2 g/L and dry plant extract of 7.5×10^2 g/L, occurred within four weeks. The percentage mortality of earthworms due to *S. trilobata* extracts was significantly higher than in the control (one-way ANOVA, p=0.05). Coiling, abnormal swelling, mucous secretion, blooding, and fragmentation were noticed in earthworms that were dead due to *S. trilobata* plant extracts. The percentage mortality of earthworms showed a strong positive, linear relationship (r^2=0.98; p=0.05) with the different concentrations of aqueous extracts of *S. trilobata*. *S. trilobata* should not be used in agricultural activities such as use of it as live mulch to improve soil conditions or producing compost fertilizer as the aqueous extracts of *S. trilobata* were highly toxic to *P. excavatus*.

Keywords: Earthworms, Invasive weed, Mortality, *Perionyx excavatus*, Soil, *Sphagneticola trilobata*, Weed toxicity

INTRODUCTION

Sphagneticola trilobata (L.) Pruski (creeping daisy, Singapore daisy, trailing zinnia), earlier named *Wedelia trilobata* is a creeping perennial herb of Asteraceae native to tropical Central and South America (Yan-qiong *et al.* 2005). It is considered as one of the world's worst 100 alien invasive species (GISD 2022). Invasive weeds once established in new environments, pose a significant threat to agriculture, forestry and the aquatic environment (Rao and Chauhan 2015). *S. trilobata* has become naturalized in many wet tropical areas of the world, including Australia, Bangladesh, China, Hawaii, India, Japan, Fiji, South Africa, South Florida, Sri Lanka and the West Indies (LiYing *et al*. 2009) forms mats covering the soil, allowing less chance for survival and growth of other plants (LiYing *et al*. 2009; Macanawai 2013). *S. trilobata* is commonly found in agricultural lands, coastal areas, roadsides, rail sides, open lots, garbage dumps and other disturbed sites. It grows well on almost all soil types, including bare limestone and nutrient poor sandy beaches and swampy waterlogged soils (GISD 2022). The major bioactive components of the plant were germacrene D,α-phellandrene, α-pinene, E-caryophyllene, bicyclogermacrene, limonene, α-humulene, sabinene, β-pinene, camphene, 10-nor-calamine-10-one and γ-morphine (De Silva *et al*. 2012; Verma *et al*. 2014). According to previous studies, bioactive molecules of *S. trilobata* have antimicrobial, insecticidal, larvicidal and antiparasitic activities (Huang 2006; Maldini *et al*. 2009; Toppo *et al*. 2013). However, Setyowati *et al*. (2014a, b) suggested to use *S. trilobata* to produce compost as a substitute for N, P, K fertilizer applications in agriculture. Dissanayake *et al.* (2002) have recommended *S. trilobata* as a phyto-remediator that can be used profitably to treat waste effluents and environments contaminated with heavy metal ions. At present *S. trilobata* is widely introduced as an ornamental or ground cover in gardens in many parts of the world.

However, the high concentration of phytochemicals in *S. trilobata* may have detrimental effect on the soil fauna where it is grown. Among soil organisms, earthworms are mainly used as objects in assessing soil quality because they play an important role in the fertility and structure of soils in general. *Perionyx excavates* Perrier is an epigeic earthworm species that mainly feed at or near the soil surface, on plant litter, dead roots, and other plant debris or animal dung. They produce casts at the soil surface, affecting its roughness and macro-pore distribution. *P. excavates* is one of the most widely used earthworms in compost and vermiwash production in tropical Asia (Reinecke *et al*. 1992; Ananthavalli *et al*. 2019). Because earthworms contribute significantly

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to soil quality, it is vital to understand the potential deleterious effects of invasive weeds on their activities and survival. It was hypothesized that an aqueous extract of *S. trilobata* reduces the survival of *P. excavatus* living in the soil-compost mixture. Therefore, the present study evaluated the effect of aqueous extracts of fresh and dry plants of *S. trilobata* on the mortality of *P. excavatus.*

MATERIALS AND METHODS

Preparation of aqueous extracts of wet and dry *S. trilobata*

S. trilobata were collected from home gardens in the Gampaha district, Western province, Sri Lanka, from November to December 2019. A voucher specimen has been deposited at the Department of Zoology and Environmental Management, University of Kelaniya. The flowers, dried leaves and dead stem parts were discarded and fresh *S. trilobata* plants were selected, washed and cut into pieces of approximately 1cm. Seventy-five grams of fresh plant parts were mixed with 100 mL of distilled water and ground well. The resulting solution was filtered and centrifuged and a stock solution of 7.5×10^2 g/L of aqueous extract of fresh plant parts was prepared. Pieces of fresh *S. trilobata* were also shade-dried for seven days at room temperature (28 °C) and a stock solution of 7.5×10^2 gL^{-1} of aqueous extract was prepared. Solutions with a concentration of 2.5×10^2 gL^{-1} and 5.0×10^2 gL^{-1} were prepared using stock solutions of fresh and dried plant extracts.

Rearing of earthworms

P. excavates used in the experiment were reared in a mixture of 3:1 (wet weight) compost and top soil in plastic barrels. The moisture level of the substrate was maintained around 65-70% throughout the study period by a periodic sprinkling of water. Barrels were placed in a humid and dark room at a mean temperature of 26 °C at the laboratory of the Department of Zoology and Environmental Management, University of Kelaniya. Experimental animals from stock culture were separated from the substrate material by hand sorting, after which worms were washed to remove the adhering material from their bodies. Individuals with well-developed clitella and a wet weight of 430 – 480 mg were selected for the experiment.

Effect of aqueous extract of *S. trilobata* on the mortality of *P. excavatus*

The study was conducted in 24 similar-sized plastic containers ($81\text{x}10^{-3}$ m^2 × 15cm) filled with a mixture of compost and topsoil in a ratio of 3:1. The containers were randomly arranged and there were three replicates for each treatment and the control. Twenty *P. excavatus* collected from earthworm culture were acclimatized to the test soil under test conditions for 24 h before use. Containers were placed on plastic plates to detect the outside movement of earthworms, if any. Then, 50 mL of each aqueous extract of fresh and dry plants (2.5×10^2, 5.0×10^2, 7.5×10^2 gL^{-1}) of *S. trilobata* were sprinkled separately to the soil in treatment containers once in two days for four weeks. A similar volume of distilled water was sprinkled into the control containers.

Containers were observed daily for surfacing and outside movement of *P. excavatus*. Soil mixtures were disturbed after two and four weeks and the number of *P. excavatus* in each container was recorded. Fresh carcasses of earthworms were observed for any physical damages, color variations and hemorrhages.

Physico-chemical parameters of the soil mixture

Total nitrogen (Kjeldahl method, Bremner 1960), pH (pH meter; IQ 150 pH meter - Spectrum Technologies, Inc) and organic matter content (Allison 1965) of the soil mixture in each container were determined at the end of the experiment.

Statistical analysis

Mortality of *P. excavates* in the treatment and control containers and soil physico-chemical properties were compared using one-way ANOVA followed by Tukey's pairwise comparison test at 95% confidence level. The percentage mortality of *P. excavates* was Arc Sine transformed before the analysis. The relationship between percentages of *P. excavatus* mortality and concentrations of aqueous extract of *S. trilobata* were studied by simple linear regression analysis. All the statistical tests were conducted using MINITAB (version 14) software.

RESULTS AND DISCUSSION

Each *S. trilobata* extract evaluated using the soil test showed a different degree of toxicity to *P. excavates.* One to three earthworms moved to the soil surface after 12 min of addition of the first dose of fresh plant extract of 5.0×10^2 and 7.5×10^2 gL^{-1} and died within the first 20 min of the experiment. Plant extracts sprinkled on the soil surface may have seeped into the soil, exposing earthworms to the toxic compounds of *S. trilobata*. When earthworms are directly exposed to plant extracts, the skin may act as a route to the uptake of toxicants (Jager *et al.* 2003; Vijver *et al.* 2003). None of the earthworms in the control containers moved to the soil surface and died within this period. The death of earthworms may be triggered by the damage caused to the mucopolysaccharide layer of the skin (Mulla *et al.*

2010). The percentage mortality of earthworms in the containers exposed to fresh and dry plant extracts of *S. trilobata* is given in **Table 1**.

None of the earthworms survived in the containers treated with 5.0 × 10^2 and 7.5 × 10^2 gL^{-1} of fresh plant extracts after four weeks showing higher toxicity of fresh plant extracts than dry plant extracts. The toxicity of bioactive compounds of *S. trilobata* that cause anti-annelid effect might have been reduced during the drying process (Hung and Duy, 2012; Mertz *et al.* 2012).

Table 1. Mean (±SD) percentage mortality of *P. excavates* exposed to aqueous extracts of fresh and dry plants of *S. trilobata* in the soil mixture

Type of extract	Concentration (g/L)	After two weeks (%)	After four weeks (%)
Fresh plants	Control	$3±3^a$	$7±3^a$
	2.5×10^2	$33±2^b$	$80±3^b$
	5.0×10^2	$67±6^c$	100^c
	7.5×10^2	$87±2^c$	100^c
Dry plants	Control	$2±3^a$	$3±3^a$
	2.5×10^2	$33±2^b$	$80±3^b$
	5.0×10^2	$60±4^c$	$90±3^{bc}$
	7.5×10^2	$80±4^d$	100^c

Different superscript letters in a column denote significant differences (p=0.05) indicated by One-way ANOVA followed by Tukey's pairwise significant difference test.

The concentrations of each crude extract affect the mortality of earthworms in a dose dependent manner. The percentage mortality of earthworms showed a strong positive, linear relationship with the concentration of aqueous extract of fresh (Linear regression analysis; R^2= 98; P<0.05) and dry (Linear regression analysis; R^2=0.98; P=0.05) plants of *S. trilobata* (**Figure 1**).

There were no significant differences in pH, nitrogen and organic matter content of the soil in the treatment and control containers of both experiments (**Table 2**).

As the pH, nitrogen and organic matter content of the soil mixtures were not significantly different, the mortalities observed in treatment containers could be attributed to the toxic effects of aqueous extracts of *S. trilobata* on earthworms. The anatomical symptoms like coiling, abnormal swelling, mucous secretion, blooding, damaged skin and fragmentation were observed in dead earthworms. Earthworms exposed to agrochemicals (Morowati 2000; Muthukaruppan *et al.* 2005; Reddy and Rao 2008) and chemicals such as lead acetate and Imidacloprid (Yvan *et al.* 2005) have also shown similar anatomical symptoms. However, the aqueous extracts of *Apodytes dimidiate* and *Persicaria hydropiper,* when absorbed through the skin, did not produce any acute toxic effects in *E. fetida* (Brackenbury and Appleton 1997; Govindharaj *et al.* 2022). Therefore, the toxic constituents of *S. trilobata* on earthworms need to be seriously considered in recommending this plant for various applications.

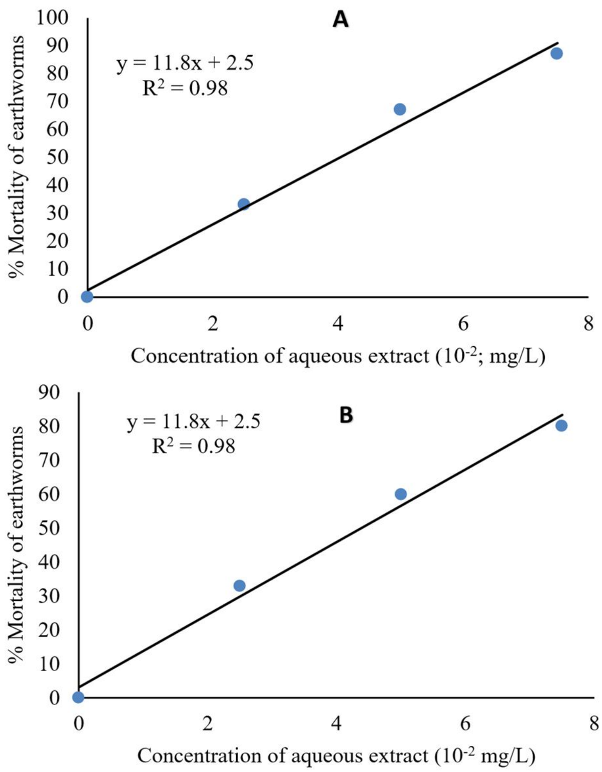

Figure 1. Relationship between concentration of fresh (A) and dry (B) plant extracts of *S. trilobata* and percentage mortality of *P. excavates* after two weeks

Table 2. Mean ± SEM of physico-chemical parameters of soil mixtures exposed to aqueous extracts of *S. trilobata* after four weeks

Type	Concentration (g/L)	pH	Organic matter content (%)	Soil nitrogen (mg/kg)
Fresh plants	Control	7.09±0.06	8.54±0.14	12.9±0.05
	2.5×10^2	7.08±0.06	8.75±0.68	11.4±0.18
	5.0×10^2	6.99±0.10	8.66±0.19	14.8±0.06
	7.5×10^2	7.01±0.08	9.32±0.36	12.9±0.04
Dry plants	Control	7.13±0.04	8.27±0.1	13.2±0.15
	2.5×10^2	7.15±0.04	8.52±0.14	11.2±0.05
	5.0×10^2	7.16±0.03	8.84±0.11	13.1±0.04
	7.5×10^2	7.21±0.02	8.04±0.29	14.5±0.05

Parameters in the columns of both experiments are not significantly different according to one-way ANOVA followed by Tukey's pairwise significant difference test (p>0.05).

The densely grown mats of *S. trilobata* covering extensive land areas in many countries may antagonistically affect the survival of earthworms that live under these plants. The antagonistic effect of *S. trilobata* on nematode *Meloidogyne incognita* has previously been shown by Silva *et al.* (2008). Therefore, *S. trilobata* should not be used in horticulture and as live mulch to condition the soil and produce biofertilizers. Further research is warranted to investigate the impacts of *S. trilobata* and other invasive weeds on the survival of earthworms and other fauna under natural environmental conditions.

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RESEARCH NOTE

Tillage, residue, and nitrogen management effects on weed interference, wheat growth, yield and nutrient uptake under conservation agriculture-based pigeonpea-wheat system

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ABSTRACT

A field experiment laid out in a randomized complete block design with three replications was undertaken to evaluate the impacts of 12-year old conservation agriculture (CA)-based pigeonpea-wheat system on weeds and wheat during winter (*Rabi*) 2021-22. There were 10 treatments comprising of conventional till flatbed (CT), zero till (ZT) permanent narrow bed (PNB), broad bed (PBB), and flatbed (PFB) with (PNBR, PBBR, PFBR) and without residue (R). Residue retention treatments (PNBR, PBBR, PFBR) had 75% and 100% of the recommended N for wheat (*i.e,* PNBR75N, PNBR100N; PBBR75N, PBBR100N; PFBR75N, PFBR100N) during 2021-22. The CA-based permanent flat, broad, and narrow beds with anchored residue led to significant reduction in weed density and biomass at 60 days after sowing (DAS) and at harvest compared to ZT residue removal and CT treatments. These CA-based treatments considerably improved wheat growth indices, yield, and nutrient uptake. Among them, the CA-based PFBR100N and PBBR100N increased wheat grain yield by 14.1-15%, biological yield by 10.2-10.8% and total NPK uptake by 23-23.6% compared to CT and were most superior. The permanent beds with residue produced comparable wheat yields at 75%N and 100%N. Therefore, the permanent flat or broad bed with residue and 100%N in early years of CA adoption and 75%N in later years may be adopted for better weed control, higher crop growth and productivity of wheat in pigeonpea-wheat system.

Keywords: Conservation agriculture, Nutrient uptake, Productivity, Residue retention, Weed interference

Sustainable conservation agriculture (CA) practices characterized by integration of three basic principles: minimal or no mechanical disturbance, permanent surface residue cover, and crop diversification can improve crop production and promotes natural resource conservation (Kassam *et al*. 2019). The continued monoculture of conventional rice-wheat system (RWS) has resulted in yield plateauing in the major productive areas of the Indo-Gangetic Plains (IGP) (Das *et al*. 2014, 2020). The degradation of soil physical properties, soil fertility deterioration, and incidence of multi-nutrients deficiency led into poor resource use efficiency. Several CA-based resource conservation technologies, such as zero tillage (ZT), raised bed planting, crop residue retention, crop diversification with the inclusion of legumes in cropping system have been assessed as another possibility to conventional practices (Das *et al*. 2014, Bhattacharyya *et al*. 2015). Extra-short duration pigeonpea varieties such as Pusa 855 (135-140 days), and Pusa Arhar 16 (120 days) has opened the diversification options of RWS in IGP (Das *et al.* 2014). Diversified crop rotation including a legume, under CA can reverse soil deterioration, reduces pests/diseases infestations, improved weed management, sustains crop yield and quality (Li *et al.* 2019).

Weeds are one of the major constraints in crop production under both conventional till (CT) and zero till (ZT) systems, causing yield losses and impairs produce quality. Seed distribution, seedling recruitments varies across tillage practices and shift from annual to perennial or bigger-seeded to small seeded annuals had been noticed under CA (Govindasamy *et al*. 2020). The dynamics and diversity in emerged weeds population can provide an indicator of accomplishment in weed management practices. Therefore, the knowledge of weed seedling emergence and population dynamics across management practices is helpful in designing effective chemical and non-chemical weed management strategy for CA. Conservation tillage improves above and below ground crop growth, resource use efficiency and eventually crop yield

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(Das *et al*. 2018). According to Susha *et al*. (2018), adopting CA in wheat lowered the weed biomass by 14.0% and enhanced wheat yields by 6.9% over CT. Furthermore, CA system, in conjunction with precision nutrient management tools, can boost yield, nutrient use efficiency, and profitability while reducing environmental footprints from wheat production (Sapkota *et al*. 2014). Improved soil physical, chemical and biological properties coupled with better crop growth leads to better nutrient uptake and crop quality under CA (Ghosh *et al*. 2022). Therefore, this experiment was undertaken to evaluate the effect of tillage, crop residue retention, land configuration and N application on weed interference, crop growth, crop productivity, and nutrient uptake in wheat under a long-term CA-based pigeonpea-wheat system.

A field study was undertaken at ICAR-Indian Agricultural Research Institute, New Delhi, India during winter (*rabi*) 2021-22 in the 12th year of a long-term CA experiment initiated in 2010. At 0-15 cm soil depth, soil was sandy clay loam in texture (sand 48%, silt 24%, clay 28%) having pH 7.90-8.36, EC 0.22-0.35 dS/m, soil organic C 6.5-9.7 g/kg, $KMnO_4$ oxidizable N 253.7-291.7 kg/ha, 0.5M $NaHCO_3$ extractable P 73-95 kg/ha and 1 N NH_4OAc extractable K 436.2-599.8 kg/ha. Treatments were conventional till flatbed (CT), ZT permanent narrow bed (PNBR & PNB), broad bed (PBBR & PBB), and flatbed (PFBR & PFB) with and without residue (R). Further, residue retention treatments (PNBR, PBBR, PFBR) had 75% and 100% of the recommended N for wheat (*i.e.*, PNBR75N, PNBR100N; PBBR75N, PBBR100N; PFBR75N, PFBR100N) during 2021-22. To appraise changes in weed species due to CT and CA (through non-destructive method), a randomly selected area of 1 m × 1 m was earmarked/fixed in three locations of each CA and CT plots, and no herbicide was applied throughout crop growing period. The emerged weeds from those areas were counted and collected periodically until harvest of wheat crop (fixed-plot study). Except these fixed areas, the rest area of all CA and CT plots received a common application of the tank-mix of clodinafop-propargyl 60 g/ha + metsulfuron-methyl 5 g/ha at 35 DAS for weed control in wheat. For destructive weed sampling, a quadrat of 50 × 50 cm was randomly placed in three locations considering two wheat rows, and weed count was made replication-wise across CA and CT plots at 60 DAS (herbicide-treated plot study). The collected weed samples were sun-dried for three days and kept in an oven at 65˚C till constant weight obtained for estimating dry weight. Weed data were subjected to square-root $[(\sqrt{x+0.5})^{1/2}]$ transformation (Das 1999) to reduce inherent variation in data. Mean crop growth rate (CGR), mean relative growth rate (RGR), leaf area index (LAI) and harvest index (HI) were estimated using the equation 1-4 (Das, 2008).

$$\text{CGR (g/m}^2\text{/day)} = \frac{1}{p} * \frac{(w_2 - w_1)}{(t_2 - t_1)} \quad [1]$$

$$\text{RGR (g/g/day)} = \frac{(\ln w_2 - \ln w_1)}{(t_2 - t_1)} \quad [2]$$

$$\text{LAI} = \frac{\text{Leafarea (cm}^2)}{\text{Land area (cm}^2)} \quad [3]$$

$$\text{HI (\%)} = \frac{\text{Grain yield}}{\text{Biological yield}} * 100 \quad [4]$$

where w_2 and w_1 are the crop dry weight at t_2 and t_1 are days after sowing, respectively and $t_2>t_1$.

Grain and biological yield were estimated from the net plot areas of 5 m^2 in flat bed and 7 m^2 in raised narrow and broad beds. The N, P, K uptake by wheat was calculated by multiplying nutrients concentrations with their respective grain and straw yield (Nath *et al*. 2015). Data were subjected to analysis of variance (ANOVA) for randomized complete block design using OPSTAT.

Weed interference

Weed species that existed after the common tank-mix application of clodinafop + metsulfuron to all CA and CT plots were *Phalaris minor* Retz. (grassy weeds); *Chenopodium album* L, *Coronopus didymus* L, *Melilotus indica* L, *Parthenium hysterophorus* L, *Sonchus oleraceous* L. (broad-leaved weeds); and *Cyperus esculentus* L. (sedge). Additionally, the emergence of some summer/rainy-season annual weeds such as *Dinebra retroflexa* L, *Setaria viridis* L, *Dactyloctenium aegyptium* L, *Eleusine indica* L. (grassy weeds), and *Polygonum aviculare* L. (broad-leaved weed) were found at harvest of wheat. It might be that these rainy/summer season weeds have gradually widened their ecological amplitude, leading to changes in their habit and getting adapted to occur in the seasonal transition period or in the season in which they used to rarely occur earlier. The probable effect of changing climate, particularly fluctuations/changes in temperature should not be ruled out/ ignored as well. After a common herbicide treatment to all plots, the destructive weed sampling done at 60 DAS revealed that the densities and dry weights of grassy and broad-leaved weeds (BLW) were drastically reduced and found non-significant across the treatments (**Table 1**). But, the density and biomass of sedges and total weed were significantly higher in CT treatment. The results confirmed findings of Tiwari *et al.* (2015) and Singh *et al.* (2017) in that this herbicide mixture controlled grassy and broad-leaved weeds effectively, but not sedges, which led to significantly higher sedge and total weed density in CT. At harvest, PBB had significantly higher grassy weed density and biomass, which was comparable with PBBR75N, PNB and PBBR100N (**Table 2**). This treatment also resulted in higher BLW density and biomass, which was at par with that in PNBR100N for weed density and PNBR75N, PNBR100N and PNB for weed biomass (**Table 2**). Sedges density and biomass, and total weed density were significantly higher in CT. Overall, the dominance of grassy and broad-leaved weeds was higher in ZT plots with or without residue retention, and the sedge density was significantly higher in CT treatment at harvest. Repeated application of glyphosate 1.0 kg/ha in zero tillage (ZT) practice during the short fallow period could have lowered the *C. esculentus* tubers population in CA soils. Moreover, crop residue retention and better crop stand supplemented with chemical weed management practices can contribute to weed suppression and weed seed bank exhaustion in CA over a long run. The PFBR100N, PFB, and PFBR75N were found more effective in reducing total weed density at harvest. However, the emerged weed seedlings at harvest under CT and CA can contribute to weed seed bank through seed rain during fallow period after wheat harvest. Therefore, tillage or non-selective herbicides under CT, and non-selective herbicides application under CA during fallow period may be advocated to manage the emerged weeds and restrict their seed accumulation.

Wheat growth, grain and biological yields and harvest index

Tillage, residue, land configuration and N management significantly influenced mean crop growth rate (CGR) and mean relative growth rate (RGR) at 0-30, 30-60, 60-90 and 90-130 DAS, and leaf area index (LAI) at 30, 60 and 90 DAS (**Table 3**). Residue retention had shown higher growth rates (CGR, RGR) than residue removal and CT. At 0-30 and 30-60 DAS, PFBR100N showed significantly higher CGR but all CA-based treatments (namely, PNBR75N, PNBR100N, PBBR75N, PBBR100N, PFBR75N and PFBR100N) and PFBR75N,

Table 1. Category-wise weed density and biomass in wheat across treatments at 60 DAS

Treatment	Weed density (no./m^2)				Weed biomass (g/m^2)			
	Grassy	Broad-leaved	Sedges	Total	Grassy	Broad-leaved	Sedges	Total
CT	0.9 (0.3)	2.6 (8.0)	6.1 (38.0)	6.7 (46.3)	0.74 (0.04)	0.96 (0.46)	1.42 (1.53)	1.58 (2.00)
PNB	1.2 (1.0)	2.7 (7.3)	4.2 (17.3)	5.1 (25.7)	0.79 (0.13)	0.97 (0.47)	1.04 (0.61)	1.30 (1.21)
PNBR75N	1.1 (0.7)	2.2 (4.7)	1.2 (1.3)	2.7 (6.7)	0.83 (0.20)	0.86 (0.24)	0.85 (0.26)	1.08 (0.70)
PNBR100N	0.7 (0.0)	2.3 (5.0)	0.7 (0.0)	2.3 (5.0)	0.71 (0.00)	0.86 (0.24)	0.71 (0)	0.86 (0.24)
PBB	1.2 (1.0)	2.2 (5.3)	3.4 (18.7)	4.4 (25.0)	0.81 (0.16)	0.85 (0.24)	0.89 (0.40)	1.07 (0.75)
PBBR75N	1.0 (0.7)	2.3 (6.0)	0.7 (0.0)	2.4 (6.7)	0.80 (0.15)	0.83 (0.2)	0.71 (0.00)	0.90 (0.34)
PBBR100N	1.0 (0.7)	2.4 (5.3)	0.7 (0.0)	2.5 (6.0)	0.78 (0.13)	0.81 (0.16)	0.71 (0.00)	0.88 (0.29)
ZTFB	0.7 (0.0)	1.2 (1.3)	1.2 (1.3)	1.7 (2.7)	0.71 (0.00)	0.73 (0.03)	0.73 (0.03)	0.75 (0.06)
ZTFBR75N	0.7 (0.0)	0.7 (0.0)	0.7 (0.0)	0.7 (0.0)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
ZTFBR100N	0.7 (0.0)	0.7 (0.0)	0.7 (0.0)	0.7 (0.0)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
LSD (p=0.05)	NS	NS	2.07	2.37	NS	NS	0.26	0.31

* Data are square-root transformed and the original values are in the parentheses

Table 2. Category-wise weed density and biomass in wheat across treatments at harvest

Treatment	Weed density (no./m^2)				Weed biomass (g/m^2)			
	Grassy	Broad-leaved	Sedges	Total	Grassy	Broad-leaved	Sedges	Total
CT	0.7 (0.0)	0.7 (0.0)	12.0 (148.0)	12.0 (148.0)	0.70 (0.00)	0.71 (0.00)	1.69 (2.40)	1.69 (2.40)
PNB	3.4 (12.0)	2.1 (4.0)	3.5 (16.0)	5.7 (32.0)	1.29 (1.16)	1.05 (0.60)	0.91 (0.40)	1.61 (2.10)
PNBR75N	2.8 (8.0)	1.9 (4.0)	3.7 (14.7)	5.2 (26.7)	1.05 (0.74)	1.16 (1.00)	0.80 (0.14)	1.44 (1.80)
PNBR100N	2.4 (5.3)	2.7 (6.7)	3.3 (12.0)	4.8 (24.0)	0.95 (0.42)	1.06 (0.60)	0.79 (0.13)	1.28 (1.20)
PBB	4.3 (18.7)	2.7 (6.7)	4.5 (22.7)	6.9 (48.0)	1.50 (1.82)	1.30 (1.20)	0.94 (0.40)	1.97 (3.40)
PBBR75N	4.0 (16)	1.7 (2.7)	3.1 (9.3)	5.3 (28.0)	1.49 (1.80)	0.87 (0.30)	0.85 (0.25)	1.64 (2.30)
PBBR100N	3.3 (10.7)	2.0 (4)	2.6 (8.0)	4.8 (22.7)	1.28 (1.17)	0.94 (0.40)	0.79 (0.10)	1.48 (1.70)
PFB	0.7 (0.0)	0.7 (0.0)	0.71 (0.0)	0.7 (0.0)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
PFBR75N	0.7 (0.0)	1.3 (1.3)	0.71 (0.0)	1.3 (1.3)	0.71 (0.00)	0.76 (0.10)	0.71 (0.00)	0.76 (0.10)
PFBR100N	0.7 (0.0)	0.7 (0.0)	0.71 (0.0)	0.7 (0.0)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
LSD(p=0.05)	1.11	1.02	2.52	1.82	0.38	0.31	0.29	0.51

* Data are square-root transformed and the original values are in the parentheses

PBBR100N, PBBR75N, PNBR100N were found comparable with it at 0-30 and 30-60 DAS, respectively. PBBR100N and PFBNR100N resulted in considerably higher CGR at 60-90 DAS and 90-130 DAS but found statistically at par with all ZT treatments except PNB. CA based treatments had 4.1-5.7%, 3.6-5.6%, 2.5-3.4%, 4.1-5.4% higher RGR than CT at 0-30, 30-60, 60-90 and 90-130 DAS, respectively. PFBR100N had shown higher RGR than other CA based treatments at 0-30, 30-60, and 90-130 DAS, whereas PBBR100N and PNBR75N were found superior at 60-90 DAS. The PFBR100N had significantly higher LAI at 30 DAS and found comparable with all residue retention plots including 75% and 100%N levels (**Table 4**). The PBBR100N had significantly higher LAI at 60 DAS and was comparable with PNBR100N, PBBR75N and PFBR100N in this regard. But, at 90 DAS, the PNBR100N had significantly higher LAI, which was comparable with those in all other CA based treatments (*i.e.* PNBR75N, PBBR75N, PBBR100N, PFBR75N, and PFBR100N). The CA-based residue retention treatments showed 28.6-42.9%, 14.6-31.7%, and 32.5-44.1% higher LAI than CT at 30, 60, and 90 DAS, respectively. Ghosh *et al.* (2022) have already reported higher growth rates owing to greater dry matter accumulation under CA.

Higher growth indices confirmed better growth in these treatments. Greater CGR, RGR and LAI under CA based treatments confirmed better growth and beneficial effects of residue retention compared to residue removal and CT. The ZT practices improved wheat grain yield by 8.1-14.9%, and biological yield by 4.9-10.8% over CT (**Table 4**). Among CA-based practices, PFBR100N led to significantly higher grain yield (5.37 t/ha) and biological yield (13.08 t/ha) and found comparable with all ZT practices with and without residue retention (PNBR75N, PBBR75N, PBBR100N, ZTFBR75N, ZTFBR75N, PNB, PBB and ZTFB). Harvest index did not vary significantly among the treatments. Similar results showing higher yield under CA were also reported by Das *et al*. (2014, 2018, 2020).

Nutrient uptake

The CA-based practices significantly improved N, P, and K uptake by wheat grain and straw (**Figure 1, 2, 3**). The ZT permanent beds with residue retention had significantly higher N, P, and K uptake than residue removal and CT. Also, the plots under residue retention and 100% N application showed greater nutrient uptake compared to treatments with 75% N application. Significantly higher uptake of N by wheat grain, straw and total N uptake (104.2, 28.1, 130.9 kg/ha N, respectively) were observed under the PFBR100N (**Figure 1**). Grain N uptake in this treatment (PFBR100N) was statistically at par with all ZT practices except PNB. For straw N uptake PBBR100N, PNBR100N, PFBR75N, PBBR75N, whereas for total N uptake, all CA based treatments were comparable. This PFBR100N registered 19.2, 27.7, 19.71% higher wheat grain, straw and total N uptake than CT, respectively. PBBR100N led to highest P uptake (17.1 kg/ha) by wheat grain and found statistically at par with all CA based treatments (**Figure 2**). Similarly, highest P uptake by straw (5.7 kg/ha) was recorded in PBBR100N, and comparable

Table 4. Wheat leaf area index (LAI), grain yield, biological yield and harvest index across the treatment

Treatment	LAI 30 DAS	LAI 60 DAS	LAI 90 DAS	Grain yield (t/ha)	Biological yield (t/ha)	Harvest index (%)
CT	0.28	3.09	4.06	4.67	11.81	39.5
PNB	0.30	3.34	4.96	5.05	12.39	40.7
PNBR75N	0.36	3.54	5.58	5.21	12.77	40.8
PNBR100N	0.39	3.88	5.85	5.30	12.95	40.9
PBB	0.31	3.30	4.87	5.09	12.51	40.6
PBBR75N	0.36	3.96	5.54	5.26	12.86	40.9
PBBR100N	0.38	4.07	5.78	5.33	13.01	41.0
PFB	0.31	3.22	4.84	5.11	12.57	40.7
PFBR75N	0.37	3.64	5.38	5.28	12.90	40.9
PFBR100N	0.40	3.77	5.72	5.37	13.08	41.0
LSD(p=0.05)	0.04	0.33	0.84	0.39	0.68	NS

Table 3. Mean wheat crop growth rate (CGR) and mean relative growth rate (RGR) across treatments at different growth stages

Treatment	CGR ($g/m^2/day$)				RGR (g/g/day)			
	0-30 DAS	30-60 DAS	60-90 DAS	90-130 DAS	0-30 DAS	30-60 DAS	60-90 DAS	90-130 DAS
CT	1.29	11.59	15.19	9.52	0.122	0.195	0.204	0.148
PNB	1.34	14.32	15.68	10.97	0.123	0.202	0.205	0.152
PNBR75N	1.50	14.28	18.67	11.92	0.127	0.202	0.211	0.154
PNBR100N	1.53	15.04	18.44	12.37	0.127	0.204	0.210	0.155
PBB	1.35	13.71	16.61	11.28	0.123	0.201	0.207	0.153
PBBR75N	1.47	14.95	18.16	12.15	0.126	0.204	0.210	0.155
PBBR100N	1.54	14.99	18.74	12.53	0.128	0.204	0.211	0.155
PFB	1.39	14.05	17.33	11.42	0.124	0.201	0.208	0.153
PFBR75N	1.56	15.36	17.86	12.25	0.128	0.204	0.209	0.155
PFBR100N	1.59	16.07	18.27	12.70	0.129	0.206	0.210	0.156
LSD (p=0.05)	0.17	1.68	2.33	1.71	0.004	0.004	0.004	0.004

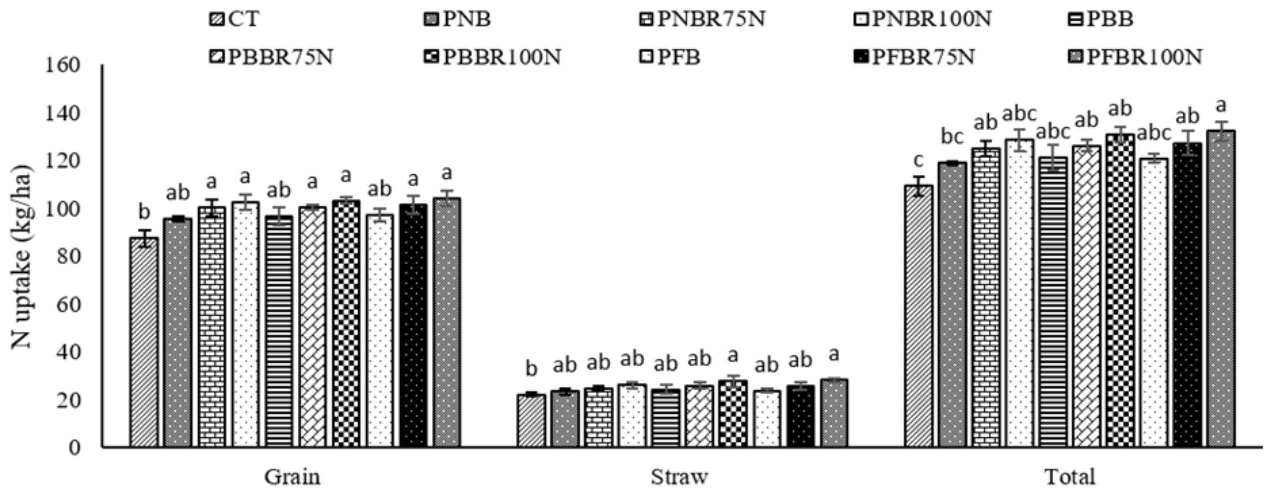

Figure 1. Wheat grain, straw and total N uptake across the treatments

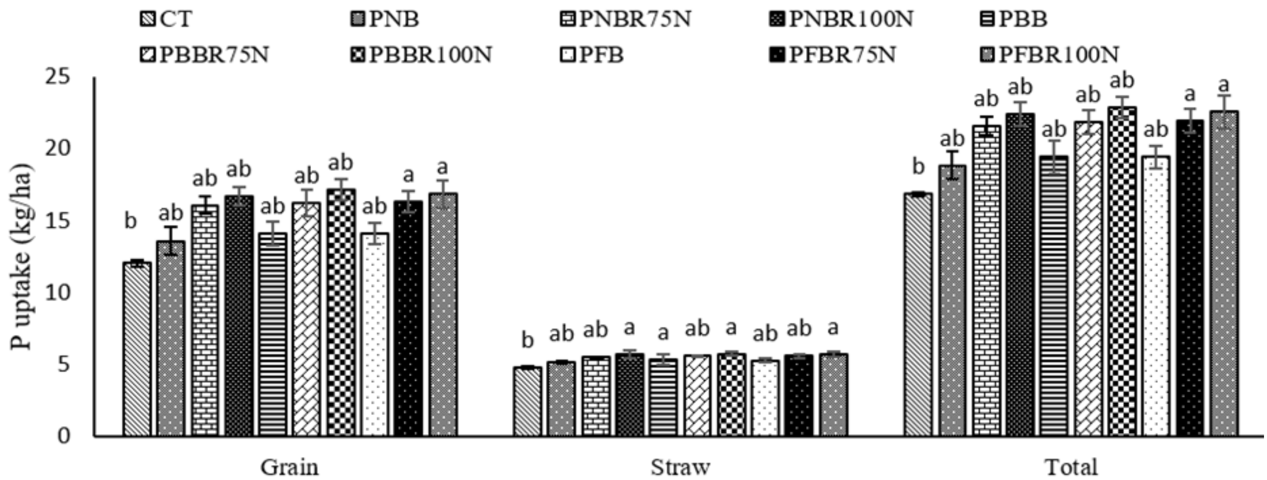

Figure 2. Wheat grain, straw and total P uptake across the treatments

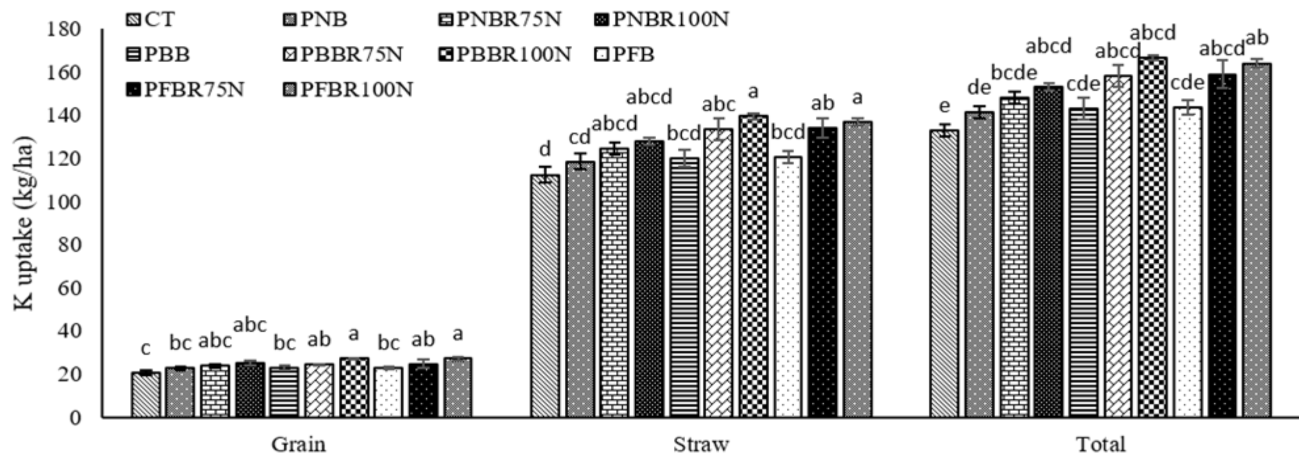

Figure 3. Wheat grain, straw and total K uptake across the treatments

values were obtained in all other ZT based treatments except PNB and ZTFB. This treatment resulted in 41.3, 20.8, 35.9% higher wheat grain, straw and total P uptake than CT, respectively. Again, PBBR100N resulted into significantly higher total P and K uptake. All CA based treatments showed comparable values for total P uptake whereas PFBR100N, PFBR75N, and PBBR75N were statistically at par with PBBR100N. Furthermore, significantly higher K uptake (27.2 kg/ha) by wheat grain was recorded under PBBR100N and found comparable with PFBR100N, PNBR100N, and PFBR75N (**Figure 3**). The same treatment showed highest K uptake by straw (139.7 kg/ha) and was comparable with

PFBR100N, PFBR75N, and PBBR75N in this regard. This treatment showed 32.7, 24.1, 25.5% higher wheat grain, straw and total K uptake than CT, respectively. The increased grain, straw and total nutrient uptake in CA may be attributed to improved root growth, greater foraging area under permanent beds, better soil physical, chemical and biological properties that led to more nutrient and water acquisition from nutrient-rich CA plots (Parihar *et al.* 2018; Ghosh *et al.* 2022). However, in CT practice the lower nutrient uptake might have resulted from higher weed infestation, nutrient losses, less soil water retention and impaired soil physical, chemical and biological properties and reduced crop yield (Nath *et al.* 2015, Das *et al.* 2018).

Results showed that seasonal boundary shift was noticed in some weeds' habit in CA and CT system. The CA-based ZT permanent bed with residue and N treatments, particularly PFBR100N, PFBR75N significantly lowered weed density and dry weight at harvest and restricted build-up of weed seed bank. Higher crop growth rates in terms of CGR, RGR, LAI under CA-base system improved grain and biological yields of wheat. CA based treatments had comparable yield at 75%N and 100%N application. The PFBR100N, PBBR100N, PFBR75N were found superior to other CA based practices for weed suppression, higher yield and nutrient uptake. Therefore, under CA based pigeonpea-wheat system, PFBR100N or PBBR100N at early years of CA adoption and 75%N treatments later years may be adopted in the Indo-Gangetic Plains of India and in similar agro-ecologies of the tropics and sub-tropics.

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RESEARCH NOTE

Weed management with pre- and post-emergence herbicide in rainfed pearl millet under conservation agriculture

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ABSTRACT

In order to assess the impact of various tillage and weed management practices on the weed dynamics and productivity of rainfed pearl millet [*Pennisetum glaucum* (L.) R. Br] under conservation agriculture, an experiment was carried out in 2019–20 at ICAR–IARI, New Delhi. Adoption of zero tillage + barley residue retention 3 t/ha (ZT + R) increased the pearl millet grain yield by 9.17 and 13.3%, respectively over the zero tillage (ZT) and conventional tillage (CT). At 60 days after sowing (DAS), hand weeding (HW) had the highest weed control efficiency (78.3%). Pre-emergence application (PE) of atrazine 0.75 kg/ha *fb* post-emergence application (PoE) of 2,4-D 0.75 kg/ha was the next successful treatments (77.5%). With HW twice at 30 and 50 DAS, grain yield was considerably higher (2.53 t/ha), and atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75 kg/ha PoE recorded next highest yield (2.42 t/ha). Atrazine 0.75kg/ha PE *fb* 2,4-D 0.75 kg/ha PoE recorded significantly greater net returns (₹ 29201) and B:C (1.08).

Keywords: Barley residue, Herbicides, Pearl millet, Weed management, Zero tillage

Next to maize, rice, wheat, barley, and sorghum, pearl millet [*Pennisetum glaucum* (L.) R. Br. emend Stuntz] is the sixth most significant cereal staple food crop in the world. As it is grown on 6.93 million hectares and contributes to 8.61 million tons of grain production with a productivity of 1.243 t/ha, India is the world's greatest producer of pearl millet (Directorate of Millets Development 2020). However, compared to its potential (3 t/ha), pearl millet yield in India is low (1.2 t/ha). Low yield is a result of a number of factors, including its growth in rainfed conditions combined with low fertility soils, the high prevalence of disease, severe weed infestation, and inadequate water management. One of the most important problems restricting the productivity of pearl millet is weed infestation. Weeds can deplete nutrients in Pearl millet up to 61.8 kg N, 5.6 kg P, and 57.6 kg K/ha (Ram *et al.* 2005). A key factor in reducing weed infestation is the use of various conservation agriculture (CA) practices under rainfed situations, as they aid in capturing and retaining moisture and so increases yield. Additionally, due to residue's ability to control weeds and the retention of residue under zero tillage, a greater visual negative effect on weeds may be seen. Weed infestation, on the other hand, is one of the main provocations in the early years of CA since it significantly reduces farm profitability and growth. Since weed ecology differs from that of conventional tillage, managing weeds is a difficult challenge in no-tillage farming. Under no-tillage, weed seeds are no longer dispersed throughout the soil profile but instead tend to gather on the soil surface, and weed communities gradually alter, especially in favour of perennial species (Streit *et al.* 2002). To achieve successful weed control in the pearl millet crops under these conditions, effective and affordable weed management practices are crucial. The goal of the current experiment was to assess the effect of different weed management and tillage practices on the performance of pearl millet in rainfed circumstances.

A field study was conducted at ICAR-IARI, New Delhi, India located at 28º 38' N, 77º 10' E, 228.6 m above the mean sea-level during the *Kharif* 2019 using split-plot design with three replications. The soil of the experimental field was sandy loam texture with 7.5 pH. During the crop duration (July-October), the mean minimum, maximum temperature, relative humidity, and total rainfall ranged from 31.0-36.5 ºC, 21.8-28.0 ºC, 33-98%, 780 mm. Main plot treatments consisted of three tillage practices: conventional tillage (CT), zero tillage (ZT), zero tillage with residue 3 t/ha (ZT + R) and sub-plots

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received seven weed management practices: weedy check(WC), hand weeding (HW) twice at 30 and 50 days after sowing (DAS), pre-emergence application (PE) of atrazine 0.75 kg/ha followed by (*fb*) post-emergence application (PoE) of 2,4-D 0.75 kg/ha at 30 DAS, atrazine 0.75 kg/ha PE, atrazine 0.75 kg/ha PE *fb* tembotrione 0.05 kg/ha PoE at 30 DAS, atrazine 0.75 kg/ha PE *fb* tembotrione 0.075 kg/ha PoE at 30 DAS, atrazine 0.75 kg/ha PE *fb* tembotrione 0.10 kg/ha PoE at 30 DAS. For zero tillage + residue (ZT+R) treatment, the barley crop residue from the previous season was scattered 3 t/ha after sowing creating a residue cover thickness of 3-5 cm. Pearl millet (Pusa composite-443) was sown at the seed rate of 5 kg/ha at a spacing of 50 cm × 10 cm on 16th July 2019 in ZT and CT plots. Full dose of P_2O_5 (40 kg/ha), K_2O (40 kg/ha) and half dose of N (30 kg/ha) was applied as basal at the time of sowing. Remaining N (30 kg/ha) was applied in two equal splits at 25 and 50 DAS. Pre-emergence application of atrazine was done within 24 hours of sowing and post-emergence herbicides 2,4-D and tembotrione at 30 DAS. First hand weeding was done manually at 30 DAS in the respective plots of the treatments and the second HW was done at 50 DAS. Weed density and biomass (dry matter accumulation) was recorded at 60 DAS by using a quadrat of 0.5 x 0.5 m (0.25 m^2) size from the center of the plot. The entire weeds inside the quadrat were uprooted and cut close to the transition of root and shoot in each plot and collected for weed biomass. The samples were first dried in sun and then kept in an oven at 70 ± 2°C. The dried samples were weighed and expressed as biomass (g/m^2). The weed index (WI) and weed-control efficiency (WCE) were calculated by using formulae as suggested by Gill and Vijayakumar (1969), and Mani *et al.* (1973). Data on yield and economics were statistically analyzed as per the standard procedures.

Effect on weeds

The main weed species in the weedy check included *Dactyloctenium aegyptium* (21.9%), *Echinochloa colona* (18.1%) among grasses, *Trianthema portulacastrum* (17.9%) and *Commelina benghalensis* (16.7%) among broad-leaved weeds, as well as *Cyperus rotundus* (25.4%), a sedge (**Table 1**).

At 60 DAS, tillage and weed management practices resulted in significant changes in overall weed density and weed biomass. Zero tillage + residue (ZT+R) 3 t/ha produced the lowest density for all weed species at 60 DAS when compared to conventional tillage (CT) and zero tillage (ZT) (**Table 1**). The density of grassy weeds like *Dactyloctenium aegyptium* and *Echinochloa colona* was reduced by 28.9% and 22.5%, respectively, in response to the ZT+R treatment. Additionally, *Commelina benghalensis* and *Trianthema portulacastrum*, two broad-leaved weeds, had lower density compared to CT plots by 55.9% and 34%, respectively. The proportion of broad-leaved weeds was lower in ZT+R compared to ZT and CT. The most common sedge, *Cyperus rotundus*, saw a 32% reduction in ZT+R when compared to other tillage practices. Due to the prevention or lack of light provided by the residue layer on the soil surface, the reduction in weed density was attributed to weed suppression beginning with the early growth stage. Furthermore, strong allelopathic activity from barley residue by the release of phenolic compounds and alkaloids (hordenine, gramine) added to the effective reduction in weed density (Zinia *et al.* 2020). The lowest weed density was produced by hand weeding at 30 and 50

Table 1. Effect of weed management treatments on weed density at 60 DAS on CA-based pearl millet

Treatment	Weed density at 60 DAS (no./m^2)				
	Dactyloctenium aegyptium	*Echinochloa colona*	*Commelina benghalensis*	*Trianthema portulacastrum*	*Cyperus rotundus*
Tillage practice					
Conventional tillage	17.6	13.3	17.7	15.0	18.6
Zero tillage	12.9	11.7	11.6	12.4	15.3
Zero tillage + residue 3 t/ha	12.5	10.3	7.8	9.9	12.6
LSD (p=0.05)	1.44	0.69	1.58	1.86	1.46
Weed management					
Weedy check	37.6	30.97	28.6	30.6	43.4
Hand weeding at 30 and 50 DAS	7.2	4.83	6.4	7.0	8.13
Atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75kg/ha PoE	8.9	7.70	7.9	7.7	9.4
Atrazine 0.75 kg/ha PE	18.5	15.69	19.5	16.8	19.6
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.05 kg/ha PoE	9.4	7.81	8.2	8.9	9.5
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.075 kg/ha PoE	9.7	7.74	8.0	8.1	9.3
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.10 kg/ha PoE	8.9	7.60	7.7	7.7	9.1
LSD (p=0.05)	2.4	1.23	2.22	2.07	2.13

DAS: Days after sowing; PE: Pre-emergence; PoE: Post-emergence; *fb*= Followed by

DAS among the weed management practices (**Table 1**). This was made possible by hand weeding at 50 DAS, which allowed for the lowest weed infestation to be recorded at 60 DAS. In comparison to weedy check, the density of grassy weeds such *Dactyloctenium aegyptium* and *Echinochloa colona* was decreased by 80.9% and 84.5%, respectively. In comparison to weedy check treatment, the density of broad-leaved weeds *Commelina benghalensis* and *Trianthema portulacastrum* was decreased by 77.6% and 77.1%, respectively, and the density of the sedge *Cyperus rotundus* was decreased by 81.3%. Atrazine 0.75 kg/ha PE *fb* tembotrione 0.10 kg/ha PoE and atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75 kg/ha PoE were the next-best treatments for lowering weed density at 60 DAS.

The biomass of grassy weeds like *Dactyloctenium aegyptium* and *Echinochloa colona* was considerably lower in the ZT+R 3t/ha plot than in the ZT and CT plots. Comparing ZT+R to the other tillage methods, *Commelina benghalensis* and *Trianthema portulacastrum* biomass decreased by 21.4% and 20.4%, respectively. For *Cyperus rotundus* biomass, a similar trend was also noted (**Table 2**). Hand weeding at 30 and 50 DAS recorded the lowest biomass of *Dactyloctenium aegyptium* and *Echinochloa colona*, followed by atrazine 0.75 kg/ha PE *fb* tembotrione 0.10 kg/ha PoE and atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75 kg/ha PoE. *Commelina benghalensis*, *Trianthema portulacastrum* and *Cyperus rotundus* biomass was reduced effectively and equally by these treatments (**Table 2**). The decreased weed biomass and density may be attributable to the broad spectrum weed control attained by using herbicides at several stages of the crop's growth, including pre-emergence and post-emergence. Atrazine 0.75 kg/ha PE efficiently reduced weeds in the early stages, and 2,4-D 0.75 kg/ha or tembotrione 0.10 kg/ha PoE effectively controlled the weeds during the later stages. The efficacy of integration of pre- and post-emergence spraying in reducing weed density and biomass was reported earlier (Guggari and Mallappa 2017, Mishra *et al.* 2017).

The highest weed control efficiency (WCE) of 67.2% was achieved by zero tillage + residue (ZT+R) 3 t/ha, which was followed by zero tillage (61.3%) at 60 DAS (**Table 3**).Weed biomass indicated weed control treatments effectiveness. High weed control effectiveness with ZT + R 3 t/ha may be attributable to the lack of weed seed germination-friendly settings due to minimal soil disturbance and light interference from residue, as well as the depletion of weed seed through seed predation (Mirsky *et al.* 2010 and Kumar *et al.* 2013). Two hand weeding at 30 and 50 DAS was found to be the most effective weed management treatment, with a WCE of 78.3%. The next two most effective treatments were atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75 kg/ha PoE and atrazine 0.75 kg/ha PE *fb* tembotrione 0.10 kg/ha PoE, with WCEs of 77.5 and 77.3%, respectively (**Table 3**). The broad-spectrum action and increased phytotoxic effects of pre- and post-emergence herbicides resulted in the higher WCE. Tembotrione caused complete chlorosis of all weeds, including grasses, sedges, and broad-leaved weeds. Weeds subsequently wilted and perished.

Zero tillage + residue 3 t/ha reported the lowest weed index (10.5%) based on weed biomass at 60 DAS, which was much lower than conventional tillage (19.9%). But no discernible difference between the weed index measured with that zero tillage +

Table 2. Effect of weed management treatments on weed biomass at 60 DAS on CA-based pearl millet

Treatment	Weed biomass at 60 DAS (g/m^2)				
	Dactyloctenium aegyptium	*Echinochloa colona*	*Commelina benghalensis*	*Trianthema portulacastrum*	*Cyperus rotundus*
Tillage practice					
Conventional tillage	9.2	33.0	8.4	6.4	18.6
Zero tillage	8.3	30.8	7.2	5.8	15.3
Zero tillage + residue 3 t/ha	7.8	29.6	6.6	5.1	12.6
LSD (p=0.05)	0.7	1.7	0.4	0.8	1.5
Weed management					
Weedy check	18.9	80.6	15.0	8.6	43.4
Hand weeding at 30 and 50 DAS	3.2	8.5	3.1	3.2	8.1
Atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75kg/ha PoE	5.1	17.2	5.9	5.1	9.4
Atrazine 0.75 kg/ha PE	10.7	57.4	8.7	7.7	19.6
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.05 kg/ha PoE	7.2	18.3	6.6	5.3	9.5
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.075 kg/ha PoE	7.0	18.0	6.3	5.2	9.3
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.10 kg/ha PoE	6.9	17.4	6.2	5.1	9.1
LSD (p=0.05)	1.0	2.2	0.6	1.1	2.1

DAS: Days after sowing; PE: Pre-emergence; PoE: Post-emergence; *fb*= Followed by

residue 3 t/ha and zero tillage were found. (**Table 3**). This was as a result of the application of barley crop residues under zero tillage, which creates a physical barrier with a residue thickness of 3-5 cm on the soil surface for light transmission and reduces crop weed competition, allowing the crop to better utilize the available resources, leading to higher crop yield and lower weed index. With atrazine at 0.75 kg/ha PE *fb* 2,4-D 0.75 kg/ha PoE, the lowest weed index was recorded among the weed management treatments, with a weed index of 4.3% as opposed to the highest of 33.4% seen under weedy check (**Table 3**) confirming Munde *et al.* (2012) and Das *et al.* (2013) in pearl millet.

Effect on grain yield

Compared to CT (2.08 t/ha) and ZT (2.18 t/ha), ZT+R produced a grain yield (2.40 t/ha) which was significantly higher (**Table 3**). Retaining barley residues had a synergistic impact on crop growth and yield characteristics, leading to a significantly larger grain production when compared to other practices. Reduced weed competition, improved and maintained soil moisture, control of soil temperature, and an increase in organic matter nutrients were all factors that contributed to an improvement in grain production with zero tillage + residue (Parameswari 2013). The best weed management treatment in terms of grain yield was hand weeding at 30 and 50 DAS, followed by atrazine 0.75 kg/ha (PE) *fb* 2,4-D 0.75 kg/ha (PoE) and atrazine 0.75 kg/ha (PE) *fb* tembotrione 0.075 or tembotrione 0.10 kg/ha (PoE) (**Table 3**). According to Sharma *et al.* (2018), applying tembotrione and atrazine together was significantly better than doing so separately because it resulted in significantly lower weed densities, dry weights, and weed index, higher weed control efficacy, and higher values for crop growth, yield attributes, and yield. The increase of the grain yield with HW twice at 30 and 50 DAS and a combination of pre- and post-emergence application of herbicides was due to effective control of broad-spectrum weeds, which is of prime importance to achieve a higher yield of pearl millet in rainfed conditions.

Economics

Due to the increased tillage intensity under the CT system, the cost of cultivation in CT (32.3×10^{3} ^{1} /ha) was greater than ZT and ZT + R. On the other hand, ZT and ZT+R had a reduced overall cost of cultivation (**Table 3**) confirming Gathala *et al.* (2011). Compared to herbicidal treatments, the cost of cultivation was higher with manual hand weeding twice at 30 and 50 DAS. The net return and net B:C ratio (0.73) under CT were lower than those in ZT+R (0.86) and ZT (0.74). Higher net returns are indicative of the benefits of ZT and ZT+R crop productivity and can be ascribed to lower cultivation costs when compared to the input costs of preparatory tillage and irrigation in CT. Higher net return in ZT+R have made up for the economic loss of agricultural residue returned. The atrazine 0.75 kg/ha PE *fb* 2,4-D kg/ha PoE yielded the highest net returns of 29.2×10^{3} ^{1} /ha with a net B:C ratio of 1.08 among the weed management treatments (**Table 3**).

Therefore, it can be concluded that zero-tillage with barley residue retention was the most productive and effective way to cultivate rainfed pearl millet. Hand weeding twice at 30 and 50 DAS, and atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75 kg/ha or tembotrione 0.075, 0.10 kg/ha PoE can be used to effectively control weeds in rainfed pearl millet.

Table 3. Effects of weed management treatments on weed control efficiency, weed index, grain yield and economics of CA-based pearl millet

Treatment	Weed control efficiency (%)	Weed index (%)	Grain yield (t/ha)	Total cost of cultivation (x 10^3 ₹/ha)	Net return (x 10^3 ₹/ha)	B:C
Tillage practice						
Conventional tillage	59.9	19.9	2.08	32.3	20.3	0.73
Zero tillage	61.3	10.6	2.18	27.8	23.3	0.74
Zero tillage + Residue 3 t/ha	67.2	10.5	2.40	29.2	23.9	0.86
LSD (p=0.05)	1.51	2.6	0.18	-	2.2	0.06
Weed management						
Weedy check	0	33.4	1.65	26.2	11.9	0.49
Hand weeding at 30 and 50 DAS	78.3	0	2.53	33.6	23.3	0.68
Atrazine 0.75 kg/ha PE *fb* 2,4-D 0.75kg/ha PoE	77.5	4.3	2.42	28.9	29.2	1.08
Atrazine 0.75 kg/ha PE	53.3	14.7	2.09	27.0	21.3	0.77
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.05 kg/ha PoE	76.7	7.3	2.27	31.1	24.6	0.85
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.075 kg/ha PoE	76.8	4.6	2.33	30.5	24.7	0.83
Atrazine 0.75 kg/ha PE *fb* tembotrione 0.10 kg/ha PoE	77.3	7.2	2.29	30.7	22.5	0.74
LSD (p=0.05)	0.7	3.2	0.22	-	2.4	0.08

DAS: Days after sowing; PE: Pre-emergence; PoE: Post-emergence; *fb*= Followed by

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RESEARCH NOTE

Weed management effect on weeds, productivity and economics of soybean

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ABSTRACT

A field experiment was carried out during *Kharif* season of 2016 at Agricultural Research Farm of Tirhut College of Agriculture, Dholi, Dr. RPCAU, Pusa to evaluate the efficacy of weed management treatments in soybean and identify most effective and economic weed management method. The experiment consisted of nine weed management treatments which were replicated thrice in randomized block design. Weed free [hand weeding twice 20 and 40 days after sowing (DAS)] followed by pre-emergence application (PE) of pendimethalin 1.0 kg/ha along with post-emergence application (PoE) of quizalofop-ethyl 50 g/ha at 25 DAS have significantly reduced total weed density and biomass and attained the highest weed control efficiency and soybean yield. The net returns and B:C were significantly higher with pendimethalin 1.0 kg/ha PE along with quizalofop-ethyl 50 g/ha PoE at 25 DAS due to lesser cost of herbicides usage compared to hand weeding.

Keywords: Economics; Hand weeding; Pendimethalin; Quizalofop-ethyl; Soybean; Weed management

Soybean (*Glycine max* (L.) Merril) is one of the most significant oilseed crops, which has got enormous potential as food, oil, fuel, and a variety of industrial applications (Gandhi 2009). High-quality protein (40–42%) and other minerals like calcium and iron are abundant in soybean. Bihar holds immense potential for the cultivation of soybean. Weeds are believed to be the main production factor restricting soybean productivity since they cause 84% yield reduction when left unweeded (Singh 2007). Due to intermittent rainfall during rainy season, manual weeding by farmers is constrained by limited availability and high wages of farm workers resulting in difficulty to control the weeds manually during critical period of crop growth. Thus, herbicides are being used to control weeds particularly at initial growth stages, as herbicides will control the emerging weeds for a considerable period of time (Nainwal *et al*. 2010). Mulching is also a good option to conserve moisture and reduce weeds (Bhardwaj 2013). Integration of different weed management strategies would result in better management of weeds as compared to any single management method (Rao and Nagamani 2010). Hence, this study was undertaken to assess the efficacy and economics of different weed management treatments to manage weeds in soybean effectively and enhance soybean productivity economically.

The experiment was carried out during *Kharif* 2016 at Agricultural Research Farm of Tirhut College of Agriculture, Dholi, Dr. RPCAU, Pusa. The experiment was laid out in randomised block design with 3 replications. The treatment details of the experimental plot includes: straw mulch 5 t/ha, post-emergence (PoE) of quizalofop-ethyl 50 g/ha + chlorimuron-ethyl 9.0 g/ha at 25 days after seeding (DAS), quizalofop-ethyl 50 g/ha PoE at 25 DAS, pre-emergence (PE) of pendimethalin 1.0 kg/ha, pendimethalin 1.0 kg/ha PE + quizalofop-ethyl 50 g/ha PoE at 25 DAS, imazethapyr 100 g/ha PE, imazethapyr 100 g/ha PE + fenoxaprop 100 g/ha PoE at 25 DAS, weed free (hand weeding twice at 20 DAS and 40 DAS) and weedy check. The soil of the experimental plot was sandy loam in texture, alkaline in reaction (pH 8.46), low in organic carbon (0.48), available N (217.3 kg/ha), P (17.62 kg/ha) and K (120.05 kg/ha). The soybean variety "*JS – 335*" was sown at a spacing of 45 cm × 5 cm using the seed rate of 75 kg/ha by following recommended package of practices. The gross plot size was 4.5 × 5 m. The uniform dose of fertilizer used was 30:60:20:20 (N-P-K –S kg/ha). Stock solution of respective quantity of each herbicide was prepared separately, by dissolving in half litre of water and made up to required quantity of spray solution (spray volume) by adding water. The spray solution was dissolved in water as per requirement (600 litre/ha) and applied with knapsack sprayer by using the flat fan nozzle. All the necessary cultural practices were carried out uniformly to bring the crop at maturity. Weeds were counted using a quadrat of 0.25 square meter (0.5 × 0.5 m), and data obtained were expressed as density (no./m^2). The percent composition of weed flora was estimated from weedy check plot. To record weed biomass

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weeds were cut at ground level, washed with tap water, sun-dried in hot air oven at 70 °C for 48 hrs and then weighed (weed biomass). For the statistical analysis weed density and biomass were converted to 1 m^2 and imposed square root transformation by using formula ($\sqrt{x+0.5}$) before analysis. The grain yield was taken from 1 m^2 area in the centre of each plot and expressed in t/ha at 14% moisture content. Economic analysis was done as per the prevailing cost of inputs and selling price of output as per the concerning years. Statistical analysis was done by adopting appropriate method of Analysis of Variance (Gomez and Gomez 1984).

Weed flora

The weed flora observed in the experimental plots were identified and classified based on their morphology **(Table 1).** There were 14 dominant weed species observed in the experimental field out of which 6 were broad-leaved weeds, 5 grasses and 3 sedges.

Table 1. Weed flora associated with the soybean

Broad-leaved	*Eclipta alba, Phyllanthus niruri, Physalis minima, Leucas aspera, Digera arvensis* and *Croton sparsiflorus*
Grasses	*Digitaria sanguinalis, Cynodon dactylon, Sorghum halepense, Dicanthium annualatum* and *Eleusine indica*
Sedges	*Cyperus rotundus, Cyperus diformis,* and *Fimbristylis milliaceae*

Effect on weeds

All the herbicidal treatments reduced the weed density and biomass as compared to weedy check (**Table 2**). Weed free recorded lowest weed density and biomass among all the treatments. Among the herbicidal treatments, pendimethalin 1.0 kg/ha PE + quizalofop-p-ethyl 50 g/ha PoE at 25 DAS showed lowest weed density and biomass. This might be due to the application of pendimethalin as pre-emergence herbicide that prevented cell division and elongation in weeds, which effectively hindered the germination of weed seeds. Subsequently applied quizalofop-ethyl PoE at 25 DAS effectively controlled latter emerged weeds, due to inhibition of fatty acid synthesis conforming findings of Andhale and Kathmale (2019), Nagre *et al.* (2017) and Jadhav (2013).

Weed control efficiency indicated the extent of effectiveness of weed biomass reduction by weed control treatments over weedy check. During the cropping period hand weeding twice recorded higher WCE (62.57%) while among the herbicidal treatments higher WCE (57.18%) was obtained with pendimethalin 1.0 kg/ha PE + quizalofop-ethyl 50 g/ha PoE at 25 DAS (**Table 2**). More reduction of weed biomass by reducing the weed density in these treatments has resulted in higher WCE.

Effect on soybean

Among the treatments, weedy check recorded significantly lower number of pods and number of seeds per pod (**Table 3**) due to weed competition. Durigan *et al.* (1983) reported that number of pods per plant was the most affected character among yield parameters due to heavy infestation of weeds. All the herbicide treatments and hand weeding produced heavier 100-grains (9.25 to 9.49 g) than weedy check (8.89 g) on account of favorable conditions under the reduced weed stress in these treatments than weedy check. Weed free situation proved significantly superior in respect of all crop growth parameters and yield attributes among the treatments but was found at par with pendimethalin 1.0 kg/ha PE + quizalofop-p-ethyl 50 g/ha PoE at 25 DAS. This enhanced yield attributes could be due to reduced weed-crop and interplant competition, which resulted in higher availability of moisture and nutrients to the crop and increased light interception. These results were in line with earlier finding of Sharma *et al.* (2016) in soybean.

The grain and stover yield obtained with hand weeding twice at 20 DAS and at 40 DAS (1.87 t/ha) was significantly superior over all other treatments and was statistically at par with pendimethalin 1.0 kg

Table 2. Effect of weed management on weed density, weed biomass and weed control efficiency in soybean

Treatment	Weed density (no./m^2)	Weed biomass (g/m^2)	Weed control efficiency (%)
Straw mulch 5 t/ha	9.26	8.85	38.88
Quizalofop-ethyl 50 g/ha + chlorimuron-ethyl 9.0 g/ha PoE (25 DAS)	8.84	7.65	47.17
Quizalofop- ethyl 50 g/ha PoE (25 DAS)	9.21	8.61	40.54
Pendimethalin 1.0 kg/ha PE	9.35	8.93	38.33
Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 50 g/ha PoE (25 DAS)	6.42	6.20	57.18
Imazethapyr 100 g/ha PE	8.62	8.41	41.92
Imazethapyr 100 g/ha PE + fenoxaprop 100 g/ha PoE (25 DAS)	7.58	6.38	55.94
Weed free	5.62	5.42	62.57
Weedy check	12.68	14.48	-
LSD (p=0.05)	1.37	0.74	-

PE: pre-emergence, PoE: post-emergence, DAS = days after sowing

Table 3. Plant height, yield attributes, yield and economics of soybean as influenced by weed management treatments

Treatment	Plant height (cm)	Pods/ plant	Seeds/ pod	100-seed weight (g)	Grain yield (t/ha)	Stover yield (t/ha)	Gross returns (x10^3 `/ha)	Net returns (x10^3 `/ha)	B:C
Straw mulch 5 t/ha	50.88	33.75	2.73	9.32	1.26	2.87	56.06	17.77	1.46
Quizalofop-ethyl 50 g/ha + chlorimuron-ethyl 9.0 g/ha PoE (25 DAS)	55.30	34.15	2.68	9.36	1.33	2.76	58.53	28.35	1.94
Quizalofop-ethyl 50 g/ha PoE (25 DAS)	52.68	32.38	1.98	9.25	1.23	2.78	54.55	25.37	1.87
Pendimethalin 1.0 kg/ha PE	53.25	32.62	2.25	9.31	1.25	2.84	55.59	26.30	1.90
Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 50 g/ha PoE (25 DAS)	56.87	36.25	2.20	9.48	1.64	3.15	71.97	40.79	2.31
Imazethapyr 100 g/ha PE	54.32	33.15	2.59	9.35	1.33	2.95	58.90	30.01	2.04
Imazethapyr 100 g/ha PE + fenoxaprop 100 g/ha PoE (25 DAS)	55.81	35.41	2.25	9.42	1.56	3.07	68.70	38.31	2.26
Weed free	58.75	38.50	2.85	9.49	1.87	3.43	81.47	40.59	1.99
Weedy check	42.85	28.63	1.55	8.89	0.66	1.89	29.97	2.68	1.10
LSD (p=0.05)	2.63	4.05	0.22	0.30	0.23	0.34	5.86	5.86	0.19

PE: pre-emergence, PoE: post-emergence, DAS = days after sowing

/ha PE + quizalofop-p-ethyl 50 g/ha PoE at 25 DAS (1.64 t/ha) and closely followed by imazethapyr 100 g/ha PE + fenoxaprop 100 g/ha PoE at 25 DAS (1.56 t/ha). The increased yield may be due to lesser competition and non phyto-toxicity resulted in better vegetative growth and favorable yield attributes as reported by Thirumalaikumar *et al.* (2017).

Economics

The highest gross returns (₹ 81466/ha) among the treatments was realized under weed free situation and was closely followed by pendimethalin 1.0 kg/ha PE + quizalofop-ethyl 50 g/ha PoE at 25 DAS (₹ 71970/ha) and imazethapyr 100 g/ha PE + fenoxaprop 100 g/ha PoE at 25 DAS (₹ 68704/ha). Pendimethalin 1.0 kg/ha PE + quizalofop-ethyl 50 g/ ha PoE at 25 DAS produced significantly highest net return (₹ 40790/ha) and B:C (2.31) over all other weed management treatments, whereas the weedy check gave least net return (₹ 2676/ha) and B:C (1.10) (**Table 3**). This could be due to higher growth parameters and yield attributes as a result of reduced competition between weeds and crop for water and nutrients. Though weed free treatment recorded highest yield but it failed to obtain highest net return and B:C due to higher labour wages. Similar findings were obtained by Jadhav and Kashid 2019, Parmer *et al.* (2016) and Patel *et al.* (2016).

Conclusion

Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 50 g/ha PoE at 25 DAS was found effective and most remunerative weed management practice in soybean under rainfed condition of Bihar and would be promising to control weeds of soybean in areas where labour is too expensive and time is a constraint.

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