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ANALYSIS ARTICLE

Indian quarantine weeds invasiveness assessment using bio-security tool: Weed Risk Assessment

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ABSTRACT

Introduced plants may contribute to the economic losses to agriculture and exert a substantial financial burden on the resources available for the management of natural areas. Most of these taxa have the ability to become agricultural or environmental weeds, and therefore prior to permitting their entry, the risk/s needs to be evaluated. Weed risk assessments (WRA) are used to identify plant invaders before introduction. Thus, in order to recognize plant introductions that are likely to cause damage, we examined the weed risk assessment (WRA) of quarantine weeds (Gazette notification issued on 24th October, 2019), that are listed in Schedule VIII of Plant Quarantine Order, 2003 issued under the Destructive Insect & Pest Act (1914) of India. The weeds species selected for the present study are already included in the quarantine weeds list. However, the data on how much risk is posed by these weed species is not available in Indian context. Therefore, we have made an attempt to assess of risk posed by these weed species. The present study revealed that among the evaluated 54 species, 33, 16 and 4 species showed high risk, intermediate risk and low risk, respectively. The highest WRA score (35) was recorded for the species *Senecio inaequidens* DC. The WRA score 34 was recorded for 3 species namely *Centaurea diffusa* Lam., *Senecio jacobaea* L. and *Solanum carolinense* L. Amongst these weeds the lowest WRA score (16) was observed in case of *Cichorium spinosum* L.

Keywords: High risk, Intermediate and low risk species, Plant invaders, Quarantine weeds, Weed risk assessment (WRA)

INTRODUCTION

It is predicted that by 2050 the world's population will surpass 9 billion. Global food production needs to be increased by 70 to 100% to feed this population (www.fao.org). In both developing and developed countries, weeds are the most significant biotic threats to agricultural production. Weeds typically have the maximum potential for agricultural productivity reduction, along with pathogens (fungi, bacteria, *etc*.) and animal pests (insects, rodents, nematodes, mites, birds, *etc*.) that are less of a concern (Oerke 2006). The economic losses due to weeds on the Indian economy was estimated to be around USD 11 billion in ten crops alone (Gharde *et al.* 2018).

Invasive plants (weeds) cause considerable damage to the ecosystem, reduce crop yields and raise farm production costs (Sinden *et al.* 2004, Rao *et al.* 2020). The management of the risks of entering, developing and becoming invasive of new plant species is dependent on the presence of an appropriate regulatory system and the ability to evaluate which plant species should be controlled.

Invasive plants come under the Convention on Biological Diversity (http://www.cbd.int) and International Plant Protection Convention (IPPC) (www.ippc.int). The IPPC mainly emphasizes on quarantine measures to avoid the introduction and spread of species that damage plants and plant products. Most of those IPPC International Phytosanitary Measurement Standards (ISPMs) are important for controlling the entry of new species.

Regulatory methods for actively introducing new plant species differ. Several countries do not have substantial border controls while others do have stringent border controls that require detailed risk assessments and approval to import and release a new species. For instance, both Australia and New Zealand have regulatory processes in place that require anyone planning to apply for approval to introduce a new species into these countries. If the species is not already on the approved list, the governing authority will conduct an assessment of the new species' invasive potential. If the possibility of

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invasiveness is deemed to be low enough, then consent is given to import and release, and the species is included on the approved list. If the invasive potential is deemed undesirable then the species are not allowed to import and release, and the species is listed on the restricted list. If there is limited information given to perform a risk assessment, permission may be denied until further information is provided and a reassessment can be carried out (Roberts *et al.* 2001).

The concept of quarantine acts in India began in the early 20th century when the British government ordered mandatory fumigation of imported cotton bales in 1906 to prevent the entry of the dreaded Mexican cotton boll weevil (*Anthonomus grandis* Boh.). On 3rd February 1914, the Destructive Insects and Pests Act (DIP Act) was introduced. The DIP Act (1914) has been revised over the years, and has been amended many times. However, it needs to be revised and updated regularly to address the demands of liberalized trade under the WTO. The Directorate of Plant Protection, Quarantine and Storage (DPPQS) was established under the Ministry of Food and Agriculture in 1946 and the plant quarantine operation was launched in 1946 by the Botany Division at the Indian Agricultural Research Institute (IARI), New Delhi. DPPQS began its quarantine activities at Bombay seaport in October 1949. First plant quarantine and fumigation station were officially inaugurated in India on 25th December, 1951. National Plant Genetic Resource Bureau (NBPGR) was established in August 1976. The Plant Quarantine Division was established in 1978, with the sections of Entomology, Plant Pathology and Nematology. The Plants, Fruits and Seeds (Regulation of Import into India) Order, popularly known as PFS Order, came into effect in October 1988 (Chand 2017).

A risk and risk assessment should be conducted before a conclusion is made on management of a weed species. The degree of risk imposed by an invading species depends on a variety of factors: its possible effects, including the overall area of its invasion; its spread rate and control sensitivity, along with its detectability. While these elements can also be modelled if there is ample information available, this is rarely the case with invasive plants and less quantitative approaches need to be implemented. One such collection of approaches, weed risk management systems (WRM) typically compare the characteristics of the species on specific qualitative levels.

Weed risk assessments (WRA) are used to identify plant invaders before introduction (Caton *et al.* 2018). The Australian WRA has been used in Australia since 1997 as an integral part of the federal regulatory framework for planned new plant introduction (Weber *et al.* 2009). This WRA has been adopted or evaluated, sometimes with minor modifications to suit local conditions, by others. For example, the WRA system has also been tested at varying levels in Japan (Kato *et al.* 2006, Nishida *et al.* 2009), the Czech Republic (Køivánek and Pyšek 2006), the U.S.A. (Gordon and Gantz 2008), Florida, U.S.A. (Gordon *et al.* 2008), Hawaii, U.S.A. (Daehler and Carino 2000), Tanzania (Dawson *et al.* 2009) and the Pacific Islands (Daehler *et al.* 2004).

WRA is required to make wise decisions about the best way of managing weeds on public land in India. To date, no previous risk assessment has investigated on quarantine weed species and there has been no evaluation of the quarantine weeds using WRA tool. Whereby, we strive to provide managers and policy makers with an appropriate method for managing new and emerging plant incursions (native or non-native) and building skills and capacity for the future in India, as well as helping to raise awareness of risks and action needs. These techniques have potential to solve contemporary problems in futuristic agriculture weed management practices. Thus, we examined the WRA using Quarantine weeds (Gazette Notification issued on 24th October, 2019) which are listed in Schedule VIII of Plant Quarantine (Regulation of Import into India) Order (2003), issued under the DIP Act 1914. The objective of the present study was to examine invasiveness of quarantine weeds, potential distribution and the influences on agricultural, economic, and environmental values using WRA method.

MATERIALS AND METHODS

Weed risk assessment method

Any exotic species that is not yet currently present in a particular region, has a small range in the risk field, and is expected to be introduced and commercially used on a wide scale are plant species deemed appropriate for risk assessment. For bio-geographical, ecological, and experience-related elements, the scoring system allocates ratings to the species. The scores of the 12 questions are summed up, and species are classified into high risk, intermediate risk, and low risk species. The details of the 12 questions are given in the **Table 1** (Singh *et al.* 2020). Weed species whose score value range from 3-20 will be categorized as low risk, 21-27 score will be categorized as intermediate risk and 28-39 will be categorized as high-risk species.

Table 1. Details of 12 question in weed risk assessment (WRA) (Singh *et al.* 2020)

1. Climatic match	Score
Does the known geographical distribution of the species include eco climatic zones similar with those of the risk area?	
• No	0
• Yes	2
2. Status of species in India	
Is the species native to India?	
• No	0
• Yes	2
3. Geographic distribution in India	
In how many countries does the species occur?	
• Species occurs in 0 or 1 country	1
• Species occurs in 2–5 countries	2
• Species occurs in >5 countries	3
4. Range size of global distribution	
How is the size of the global range (native and introduced)?	
• Range is small, species is restricted to a small area within one continent	0
• Range is large, extending over more than 15° latitude or longitude in one continent or covers more than one continent	3
5. History as an agricultural weed elsewhere	
Is the species reported as a weed from somewhere else?	
• No	0
• Yes	3
6. Taxonomy	
Does the species have weedy congeners?	
• No	0
• Yes	3
7. Seed viability and reproduction	
How *many* seeds do the species approximately produce?	
• Few seeds or no viable seeds	1
• Many seeds	3
• Do not know	2
If the species is present in the risk area, this question refers to plants within the risk area. If the species is present in Europe, this question refers to plants within the European range. If the species is not present in Europe, this question refers to the native or introduced range of the species	
8. Vegetative growth	
Allocate species to one of the following. If more than one statement applies, take the one with the highest score.	
• Species has no vegetative growth that leads to lateral spread	1
• If a tree or shrub, species has the ability to resprout from stumps or stem layering, or stems root if touching the ground	2
• Species has bulbs or corms	1
• Species has well developed rhizomes and/or stolons for lateral spread	4
• Species fragments easily, fragments can be dispersed and produce new plants	2
• Other or do not know	2
9. Dispersal mode	
Allocate species to one of the following. If more than one statement applies, take the one with the highest score.	
• Fruits are fleshy and smaller than 5 cm in diameter	2
• Fruits are fleshy and larger than 10 cm in length or diameter	0
• Fruits are dry and seeds have well developed structures for long-distance dispersal by wind (pappus, hairs, wings)	4
• Fruits are dry and seeds have well-developed structures for long-distance dispersal by animals (spikes, thorns)	4
• Species has mechanisms for self-dispersing	1
• Other or do not know	2
10. Lifeform	
• Species is a small annual (< 80 cm)	0
• Species is a large annual (>80 cm)	2
• Species is a woody perennial	4
• Species is a small herbaceous perennial (< 80 cm)	2
• Species is a large herbaceous perennial (>80 cm)	4
• Species is a free-floating aquatic	4
• Other	2
11. Habitats of species	
Allocate species to one of the following. If more than one statement applies, take the one with the highest score	
• Riparian habitats	3
• Bogs/swamps	3
• Wet grasslands	3
• Dry (xeromorphic) grasslands	3
• Closed forests	3
• Lakes, lakeshores, and rivers	3
• Other	3
12. Population density	
What is the local abundance of the species	
• Species occurs as widely scattered individuals	1
• Species forms occasionally patches of high density	2
• Species forms large and dense monocultures	4

Selection of plant species

We examined the WRA using 57 quarantine weeds (Gazette Notification issued on 24th October, 2019) which are listed in Schedule VIII of Plant Quarantine (Regulation of Import into India) Order (2003) issued under the DIP Act 1914.

Data collection

Assessment was made at ICAR-Directorate of Weed Research (DWR) in collaboration with Division of Plant Quarantine, ICAR-National Bureau of Plant Genetic Resources (NBPGR), New Delhi. A test to compare the model is problematic, since there are no absolute values for individual taxa's weediness (Perrins *et al.* 1992). However, anyone familiar with a taxon in a country may give a reasonable opinion on the taxon's real or possible weediness in that country, to which the score from the model can be compared. For this study, we analyzed the data collected from existing literature on-line databases (www.cabi.org/ isc/ datasheet) and the internet (*i.e.*, using Google searches based on species name) in order to address the questions. The number of questions answered in the WRAs varied greatly between species, with 4 species removed from the analysis because the required number of questions in each section had not been answered.

RESULTS AND DISCUSSION

The WRA score values of the 54 quarantine weed species ranged from 16 to 35. Among these 54 species, 33 species showed high risk, 16 species showed intermediate risk and 4 species showed low risk. The highest WRA score (35) was recorded for the species *Senecio inaequidens* DC. The WRA scores for the 3 species namely *Centaurea diffusa* Lam., *Senecio jacobaea* L. and *Solanum carolinense* L. was observed to be 34. The WRA score of *Helianthus californicus* DC. and *Cichorium pumilum* Jacq. was 17 and 19, respectively. Whereas, the lowest WRA score (16) was observed in case of *Cichorium spinosum* L.

In Asteraceae, the WRA score ranged from 16 to 35 among the 17 species. The three species namely *C. pumilum*, *C. spinosum* and *H. californicus* were categorized into low-risk species whose WRA scores were 19, 16 and 17 respectively. On the other hand, two species namely *Chrysanthemoides monilifera* and *Conyza sumatrensis* showed intermediate risk and their scores were 26 and 23, respectively. All the remaining species in Asteraceae family were categorized into high-risk species (**Figure 1, Table 2**).

Among the 9 species weeds belonging to Poaceae the WRA scores ranged from 24 to 32. The four species namely *Cenchrus incertus*, *Lolium multiflorum*, *Oryza longistaminata* and *Urochloa plantaginea* were categorized into intermediate risk species, whose WRA scores were found to be 24, 26, 27 and 25 respectively. While five species namely *Apera spica-venti*, *Bromus secalinus*, *Digitaria velutina*, *Echinochloa crus-pavonis* and *Pennisetum macrourum* were categorized into high-risk species. No species of Poaceae family was categorized into the low-risk species category (**Figure 2)**.

Despite advances of a structured post-border weed risk management system (Anon, 2006), its implementation has been limited to Australia (Auld 2012; Downey and Richardson 2016), although at a provincial level (Virtue 2010, Setterfield *et al.* 2010). In the present study we have made an attempt to evaluate the risk imposed by the Quarantine weeds, although these weeds have not been reported in India, their risk potential analysis can be used as source of information as well as post-border risk potential data in case these weeds if at all encountered at quarantine centers in India. Gordon *et al.* (2016) argued that cost–benefit analyses of weed risk should be conducted, regardless of their impact on strategic choices. The benefit of involvement is sometimes undervalued due to inadequate estimations of economic losses incurred due to invasive plant

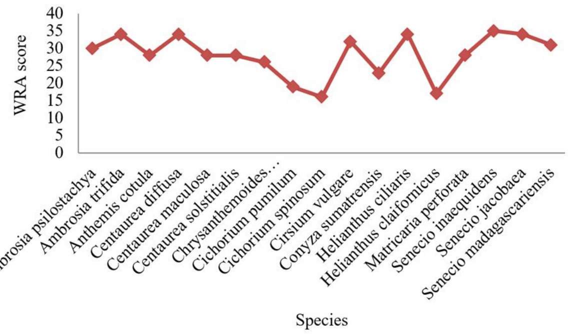

Figure 1. WRA score variation in Asteraceae family weeds

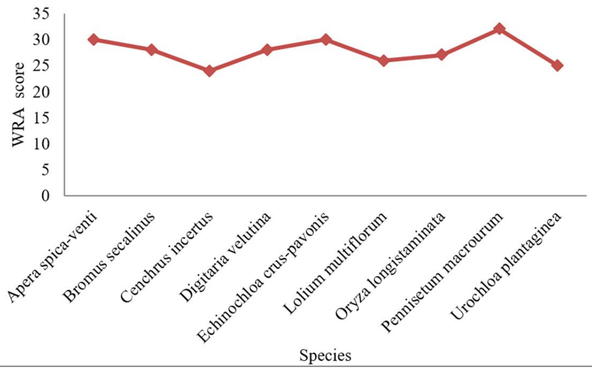

Figure 2. WRA score variation in poaceae family weeds

Table 2. Outcome of the weed risk assessment (WRA)

Sl. No.	Plant name	Family	Score	Risk level	Reference
1	*Alectra vogelii* Benth.	Scrophulariaceae	26	Intermediate risk	CABI
2	*Allium vineale* L.	Alliaceae	30	High risk	CABI
3	*Amaranthus blitoides* S. Wats.	Amaranthaceae	31	High risk	CABI
4	*Ambrosia psilostachya* D.C.	Asteraceae	30	High risk	CABI
5	*Ambrosia trifida* L.	Asteraceae	34	High risk	CABI
6	*Anthemis cotula* L.	Asteraceae	28	High risk	CABI
7	*Apera spica-venti* (L.) P.Beauv.	Poaceae	30	High risk	CABI
8	*Bromus secalinus* L.	Poaceae	28	High risk	CABI
9	*Cenchrus incertus* M.A.Curtis	Poaceae	24	Intermediate risk	CABI
10	*Centaurea diffusa* Lam.	Asteraceae	34	High risk	CABI
11	*Centaurea maculosa* Lam.	Asteraceae	28	High risk	Google
12	*Centaurea solstitialis* L.	Asteraceae	28	High risk	CABI
13	*Centrosema pubescens* Benth.	Fabaceae	22	Intermediate risk	CABI
14	*Chrysanthemoides monilifera* (L.) T. Norlindh	Asteraceae	26	Intermediate risk	CABI
15	*Cichorium pumilum* Jacq.	Asteraceae	19	Low risk	Google
16	*Cichorium spinosum* L.	Asteraceae	16	Low risk	Google
17	*Cirsium vulgare* Savi (Ten.)	Asteraceae	32	High risk	CABI
18	*Conyza sumatrensis* (Retz.) E. Walker	Asteraceae	23	Intermediate risk	CABI
19	*Cordia crassavica* (Jacq.) Roemer & Schultes	Boraginaceae	29	High risk	CABI
20	*Cuscuta australis* R. Br.	Convolvulaceae	23	Intermediate risk	Google
21	*Cynoglossum officinale* L.	Boraginaceae	28	High risk	CABI
22	*Digitaria velutina* (Forssk.) P. Beauv.	Poaceae	28	High risk	CABI
23	*Echinochloa crus-pavonis* (Kunth) J. A. Schultes	Poaceae	30	High risk	CABI
24	*Fallopia japonica* (Hout.) R. Decr.	Polygonaceae	30	High risk	CABI
25	*Froelichia floridana* (Nutt) Moq.	Amaranthaceae	20	Low risk	CABI
26	*Fumaria officinalis* L.	Papaveraceae	26	Intermediate risk	CABI
27	*Galium aparine* L.	Rubiaceae	28	High risk	CABI
28	*Helianthus ciliaris* DC.	Asteraceae	34	High risk	CABI
29	*Helianthus claifornicus* DC.	Asteraceae	17	Low risk	Google
30	*Heliotropium amplexicaule* Vahl.	Boraginaceae	33	High risk	Google
31	*Lolium multiflorum* Lam.	Poaceae	26	Intermediate risk	CABI
32	*Lonicera japonica* Thunb	Caprifoliaceae	30	High risk	CABI
33	*Matricaria perforata* (Mérat) M. Lainz	Asteraceae	28	High risk	CABI
34	*Orobanche cumana* Wallr	Orobanchaceae	28	High risk	CABI
35	*Orobanche minor* Sm.	Orobanchaceae	30	High risk	CABI
36	*Oryza longistaminata* A. Chev. & Roehr.	Poaceae	27	Intermediate risk	CABI
37	*Pennisetum macrourum* Trin.	Poaceae	32	High risk	CABI
38	*Polygonum lapathifolium* L.	Polygonaceae	26	Intermediate risk	CABI
39	*Proboscidea louisianica* (P. Mill.) Thellung	Martyniaceae	22	Intermediate risk	Google
40	*Pueraria montana var. Montana* (Lour.) Maesen	Fabaceae	30	High risk	CABI
41	*Raphanus raphanistrum* L.	Brassicaceae	32	High risk	CABI
42	*Richardia brasiliensis* Gomes	Rubiaceae	24	Intermediate risk	CABI
43	*Salsola vermiculata* L.	Chenopodiaceae	32	High risk	CABI
44	*Senecio inaequidens* DC.	Asteraceae	35	High risk	CABI
45	*Senecio jacobaea* L.	Asteraceae	34	High risk	CABI
46	*Senecio madagascariensis* Poiret	Asteraceae	31	High risk	CABI
47	*Solanum carolinense* L.	Solanaceae	34	High risk	CABI
48	*Striga aspera* (Willd.) Benth	Orobanchaceae	30	High risk	CABI
49	*Striga hermonthica* (Del) Benth	Orobanchaceae	32	High risk	CABI
50	*Thesium australe* R. Br	Santalaceae	19	Low risk	Google
51	*Thlaspi arvense* L.	Brassicaceae	26	Intermediate risk	CABI
52	*Urochloa plantaginea* (Link) RD Webster	Poaceae	25	Intermediate risk	CABI
53	*Veronica persica* Poir	Scrophulariaceae	23	Intermediate risk	CABI
54	*Viola arvensis* Murr.	Violaceae	26	Intermediate risk	CABI

species (Keller *et al.* 2007). In Indian perspective the current status of these developments is unknown, limiting broader adoption. Thus, our development of a WRA system for Quarantine weeds involving evaluation will make a significant contribution to future developments, testing and broader adoption of WRA systems in India.

Conclusion

The assessment of the WRA approach's significance depends mostly on the right outcomes and consideration of the time scale. In terms of invasive plants, if a country is risk-averse, the WRA strategy offers a conservative structure that can be used to determine risks and guide decision-making. A nation with a new plant species exploitation strategy may assume that relying on the WRA approach would lead to the rejection of plant species that could potentially provide economic benefits. Also in these situations, however, the WRA assessment can offer a valuable estimation of the possible consequences of introduction, adding to an informed consideration of the costs and benefits of a new species. The implementation of such programs will strengthen weed management decision-making, which can increase the ability of weed managers and scholars, which is crucial for enhancing the results of weed management in India. Countries like USA have standardized the processes for WRA and are being updated regularly (USDA 2019). India needs to finalize the processes to suit to Indian needs and update it regularly, to utilize the WRA for effective weed management decision-making.

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OPINION

The possible role of nanotechnological interventions in weed management – An opinion

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ABSTRACT

Nanotechnology is rapidly becoming one of the most essential tool in modern agriculture and it has the potentiality to play major role in managing weeds too in agroecosystems as the emerging weed problems can not be solved by adoption of conventional methods alone. Nanoparticles can be synthesized in many ways using top-down approach or bottom-up approach. Among these, the green synthesis of nanoparticles using plant or microorganisms is the eco-friendly and safest method of nanoparticle synthesis. Nanoparticles have wide range of applications in managing weeds and overcoming perennial weed menace through exhausting weed seed bank, breaking weed seed dormancy by degrading germination inhibitors, inhibiting viable underground plant parts by exhausting food reserves, improving foliar absorption and translocation *etc*. They can also be used in smart delivery mechanism of herbicides for rainfed ecosystems and as slow-release nano formulations for season long weed control. Nano formulations currently used in weed management are nano-encapsulation, nano-carrier, nano emulsion, nano-adjuvants, nano-biosensors *etc*. Nanotechnology reduces the application rate of herbicides per hectare and minimise environmental pollution and CO_2 emission. Nano formulations are effective against herbicide resistant weeds and enhances the rate of mitigation of herbicide residues in soils. The nanotechnology holds promise for attaining sustainable agriculture through their effective and judicious use in development and adoption of weed management technologies, particularly in under developed nations.

Keywords: Nanotechnology, Detoxification, Nanoencapsulation, Smart delivery, Weed management

Yield losses due to weeds are a major threat to crop production and farmers' economic well-being. In India, total actual economic loss of about USD 11 billion was estimated due to weeds in 10 major crops alone of which rice accounts for loss of USD 4420 million, wheat for USD 3376 million and USD 1559 million for soybean (Gharde *et al*. 2018). Weeds also impair product quality and cause health and environmental hazards. Herbicides are one of the effective management tools to control weeds either alone or in integration with physical, cultural, and biological methods. Herbicides account for 47.5% of the overall yearly pesticide use of 2 million tonnes. But the over-reliance on herbicides has adverse impact on environment, non-targeted organisms, pollution of soil and water bodies, and the emergence of herbicide-resistant weeds (Choudhary 2020). Weeds have acquired resistance to 164 different herbicides, as well as 21 of the 31 known herbicidal mode of action. Herbicide-resistant weeds have been discovered in 95 crops across 71 nations (Heap 2021). There are 509 distinct cases of weed resistance to herbicides in the globe, including 266 different species (153 dicots and 113 monocots).

In spite of significant developments in weed management research in India (Rao *et al*. 2020), several challenges still prevail including: the non or lesser impact of existing physical and cultural methods on underground plant parts of perennial weeds like *Cyperus rotundus*; labour intensiveness of currently used mechanical methods, restriction of herbicides effect to temporary inhibition of weed seed production due to marginal transfer of herbicides sprayed; the dependence of herbicide efficacy on factors like soil type, soil moisture, humidity and air temperature at the time of application; lack of selective herbicides for perennial weeds; increasing weed seed bank size due to management of currently used practices on emerged weeds only; the development of weeds herbicide resistance and issues related to herbicide residues. Thus, tackling of these challenges necessitates research and adoption of innovative technologies usage of which nano-technology is prominent.

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Nanotechnology

Nanotechnology is the science of altering nanoscale materials and has a wide range of uses in the agricultural industry. It uses a variety of chemical agents and new delivery mechanisms to boost agricultural output while also reducing the usage of bulk agrochemicals. Nanotechnology can provide better answers to existing agricultural challenges by reducing the use of herbicides and insecticides while increasing their efficiency.

Nanotechnology is a combination of applicable sciences such as chemistry, physics, biology, medicine, and engineering in which matter structure is controlled at the nanometre scale to develop materials with unique properties such as huge surface area, target site of action, and progressive release. It refers to materials, systems, and processes with a scale of less than 100 nanometers (nm). The size of nano-particles range from 1 - 100 nm in one dimension. The name "Nano" comes from the Greek word "nanos," which means "dwarf" (small). Nobel laureate Richard Feynman initially introduced nanotechnology in 1960 with his famous lecture "There's plenty of room at the bottom". Nanotechnology is mainly concerned with the separation, consolidation, and deformation of materials by a single atom, molecule, or ions. Nanoparticles have important characteristics such as morphology-aspect ratio or size, hydrophobicity, solubility-release of active ingredients, high surface area or roughness, surface species contaminations or adsorption during synthesis, reactive oxygen species (ROS), capacity to produce ROS, structure, composition, competitive binding sites with receptor, dispersion and aggregation (Somasundaran *et al.* 2010). Carbon-based nano particles (NPs), quantum dots and nanorods, metallic NPs, ceramics NPs, semiconductor NPs, polymeric NPs, lipid-based NPs, micro and nano encapsulation, and nano emulsion are all examples of nanomaterials now in use.

The nanotechnology has a number of advantages due to the unique functional qualities of nanoparticles and materials. The advantages include: the greater charge density and reactivity provided by the smaller size of the nano-particles; the enhanced activity of the atoms on their surfaces which exceeds that of the atoms inside the particles as the surface area of the particles increase with respect to their volume; nano particles' greater strength, increased heat resistance, decreased melting point, and variable magnetic properties as a result of the high surface-to-volume ratio; variations in atomic distribution across nanoparticles due to differences in exposed surfaces, which impact the rate of electron transfer kinetics between metal nanoparticles and corresponding adsorbed species; higher catalytic activity of tetrahedral nanoparticles, than cubic and spherical nanoparticles, which are recognised for improving chemical reactivity at sharp edges and corner. As per published European Commission (EC) recommendation, a nanomaterial is defined as "natural, incidental, or industrial material with particles, in an unbound state or in the form of aggregate or agglomerate where 50% or more of the particles in the number and size distribution, one or more than one dimensions lies in the range of 1–100 nm" (Neme *et al.* 2021).

The nanoparticle synthesis

A variety of methods are being used for the synthesis of nanoparticles, which are generally categorised into two categories (Royal Society and Royal Academy of Engineering).

(a) Top-down approach (which focus on reducing the size of bulk materials) and

(b) Bottom-up approach (where materials are synthesised from the atomic level)

Top-down: In top-down approach, mechanical-physical procedures such as grinding, milling, and crushing are used to manipulate a small number of atoms or molecules to construct exquisite patterns. This approach makes substantial use of nano composites and nano-grained bulk materials such as metallic and ceramic nanomaterials (10 - 1000 nm).

b) Bottom-up: In a 'Bottom-up' approach, several molecules self-assemble in parallel steps based on their molecular recognition characteristics. From atoms or molecules, this processing yields increasingly complex structures. This approach is mostly used to produce nanomaterials with consistent sizes, morphologies, and size ranges (1 - 100 nm).

Several microorganisms and higher plants were found to be effective, ecologically friendly nano-

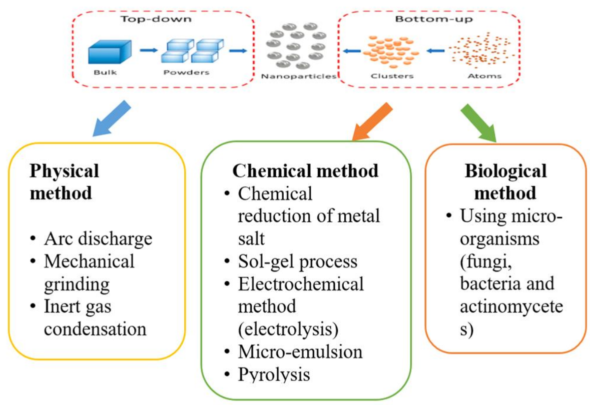

Figure 1. Synthesis of nanoparticles (Patra and Baek 2014)

factories for the production of nanoparticles, based on organism's natural systems for removing heavy metals and radionuclides from their environment (Singh *et al.* 2019). They include: a) plant-mediated biosynthesis and b) micro-organisms mediated and involving biosynthesis.

NANO TECHNOLOGY-BASED INTERVENTIONS IN WEED MANAGEMENT

Weed seed bank and perennial weeds perennating organs exhaustion

One of the most widely used applications of nano-herbicides is in the exhaustion of the weed seed bank. Instead of destroying the seedling, carbon nanotubes (CNTs) kill the weed seeds. These nano tubes induce cracks and openings in the seed coat, allowing water and chemicals to pass through. This breaks the seed's dormancy, speeds up germination and cuts the germination time in half.

Nanoherbicides are also used to overcome the perennial weed menace by killing viable underground plant organs of perennial weeds such as rhizomes and tubers, which help in faster propagation of those weeds. The use of H_2O_2 at 300 ml/m^2 followed by pendimethalin at 0.75 kg/ha + ZnO nanoparticles at 500 ppm/m^2 resulted in a significant reduction in weed emergence patterns due to the disruption in the seeds before and during their emergence, and resulted in increase in blackgram yield (Vimalrajiv *et al.* 2018).

Germination promotion by germination inhibitor degradation

In *Cyperus rotundus* (purple nutsedge) tubers, phenols are the major factor of dormancy because of which *C. rotundus* tubers persist and interfere with the growth of crops during the following season. Maximum degradation of the phenolic compound vanillic acid was reported with iron oxide (Fe_2O_3) nanoparticles at 25 mg *i.e.*, 60.6% degradation relative to control (Viji and Chinnamuthu 2019). The enhanced degradation of phenols and dormancy breakdown the enhanced germination of *C. rotundus* tubers was observed with the treatment of zinc oxide nanoparticle at 3 g/kg (Viji and Chinnamuthu 2015b) and iron oxide (Fe_2O_3) nanoparticles at 25 mg (Viji and Chinnamuthu 2019). Iron oxide nanoparticles resulted in a higher percentage of phenol breakdown (89%) than the control at 3.0 g/kg tubers (Viji and Chinnamuthu 2015a). According to Brindha and Chinnamuthu (2017) ZnO nanoparticles significantly decompose phenolic compounds in *C. rotundus*. Tubers of *C. rotundus* treated with ZnO nanoparticles at dosages of 1500 mg/kg in dry form (powder form) and 2250 mg/kg in wet form (liquid form) had a substantial impact on tuber germination via degradation of phenol and biochemical components.

Perennial weeds management through exhaustion of food reserves

The nano-particles encapsulated with herbicide molecules are used to target the receptors present in the roots of the weed. After their entry, their translocation in the system causes inhibition of glycolysis which deprives the plants of food reserves leading to starvation and death. The food reserves in the tubers of *C. rotundus* are depleted by silver nanoparticles. The degradation of starch into reducing sugars is brought by the interaction of á amylase with silver nano-particles (Viji *et al.* 2016).

Faster foliar penetration, movement and impact in the plant system of nano-herbicides

Depending on the entry point, several tissues (epidermis, endodermis) and barriers (Casparian strip, cuticle) must be traversed by herbicides before reaching the vascular tissues (roots or leaves). Nanomaterials can move up and down the plant using the apoplastic and/or symplastic pathways, as well as radial movement to switch from one to the other. Endocytosis, pore formation mediated by carrier proteins, and plasmodesmata has all been postulated as methods for the internalisation of nanoparticles within cells (Perez-de-luque 2017).

According to Nguyen *et al.* (2014), negatively charged nanoparticles had a faster foliar penetration than those with a positive zeta potential. The presence of polysaccharides rich in galacturonic or glucuronic acid units gives plant cell walls a negative charge. Nanoparticles having a positive charge collect and aggregate on the tissue surface as a result of electrostatic contact. Negatively charged nanoparticles, on the other hand, have a larger distribution inside plants due to their poor interaction with the cell wall (Zhu *et al.* 2012).

Nanoparticles and nanomaterials will effectively enhance the foliar absorption of herbicides by: lowering the size of herbicide particles to nanoscale; dissolving the wax-impregnated lipid polymer with the nanoparticle in an active energy-demanding procedure; which enhances diffusion via wax, cutin, and pectin corridors when nanoparticle is mixed with herbicide as it becomes ionic; by reducing the interfacial surface tension of the droplet when nano adjuvants are added to a water droplet, leading the droplet to spread across the leaf surface; by provision of electrically charged electrons by nanoparticles.

A significant increase in herbicidal efficacy with herbicidal activity directly through the vascular tissue of the leaves after a foliar contact of a nano-formulation of atrazine with Indian mustard (*Brassica juncea* L.) and the ability to maintain herbicidal action at low doses was demonstrated (Bombo *et al.* 2019).

By transpiration pull, also known as acropetal translocation, nanocomposites increase concentration and travel with water and solutes. The addition of nanoparticles causes them to conjugate with glucose and spread throughout the plant system. The glyphosate translocation to the major tubers was greater when it was encapsulated with TiO_2 nanoparticles. The encapsulated glyphosate coupled with Fe_2O_3, Ag, and TiO_2 nanoparticles, secondary tuber formation of *C. rotundus* was inhibited during a 40-day observation period and the encapsulated glyphosate with various nanoparticles was found to be safe and had no significant effect on earthworm activity (Viji and Chinnamuthu 2015a).

Enhanced herbicide efficacy in rainfed ecosystem by smart delivery of nano formulations

In rainfed ecosystems, herbicide use under insufficient soil moisture may result in herbicide volatilization and lesser herbicide efficacy. In order to reduce the weed competition, controlled release of the nano-encapsulated herbicides is useful as nano encapsulated herbicides will have a dispersion effect on receiving adequate moisture in rainfed farming. On receiving rains, the weed seeds mortality occurs by the immediate release of new herbicide molecules. The release of Pend-CuCts (Pendimethalin-Copper Chitosan) nanoparticles in pH 5.5 (acidic) medium was highest, while the lowest release was recorded in pH 7.0 (neutral) medium (Itodo *et al.* 2017).

Layer-by-Layer method (LBL) was used to coat manganese carbonate core material with appropriate polymers such as sodium Poly Styrene Sulfonate (PSS) and Poly Allylamine Hydrochloride (PAH) to obtain water soluble core-shell particles to load herbicide active ingredient for controlled release in rainfed agriculture. The etching procedure was used to create hollow-shell particles from core-shell particles. To achieve controlled release of the herbicide active ingredient, these hollow-shell particles were loaded with pendimethalin using a passive method. Even at 230°C, the formulation remained intact and without any microbial degradation (Kanimozhi and Chinnamuthu 2012). The herbicide was successfully enclosed in a MnO_2 core shell shielded with bilayer polymers that would open up and release the active ingredient with the receipt of rainfall.

Slow-release nano formulations for season long weed control

Nanostructures have been developed as smart delivery systems to target specific sites and as nanocarriers for controlled herbicide release. Nanotechnology can improve existing crop management techniques in the short to medium term. Using systemic herbicides against parasitic weeds as nano capsules would help to avoid phytotoxicity on the crop. Nanoencapsulation can also improve herbicide application, providing better penetration through cuticles and tissues and allowing slow and constant release of the active substances (Pradeesh and Chinnamuthu 2020). The herbicides encapsulated inside the polymer were produced using a solvent evaporation approach to produce nanostructures by encapsulating with protecting material for slow release, antimicrobial component to reduce the microbial degradation and capping agents to sustain under unfavourable weather condition. (Kumar and Chinnamuthu 2014, 2017). It was observed to get slowly released based on the availability of moisture apart from being protected from adverse climatic factors. Their efficacy in managing weeds needs to be thoroughly studied at different locations across India.

Detoxification of herbicide residues

The long-term usage of herbicides leaves a large amount of residue in the soil, which might harm subsequent crops and the surface and groundwater sources have been known to be contaminated by herbicide residues. Hence, herbicide residue detoxification is important. Under regulated conditions, the use of silver modified with Fe_3O_4 nanoparticles stabilised with carboxy methyl cellulose (CMC) resulted in an 88 % degradation of atrazine (Susha *et al.* 2011). Paraquat and atrazine nano formulations were more effective against target weeds than pure herbicides, whereas genotoxicity and cytotoxicity tests demonstrated that non-target plants such as onion (*Allium cepa* L.) were less hazardous (Grillo *et al.* 2014). The use of poly (epsilon-caprolictone) (PCL) as an atrazine carrier after encapsulation had no influence on the herbicide's long-term residual action on soybean as the mobility of atrazine was reduced, it resulted in a spectacular reduction in the phytotoxic accumulation of atrazine in soil, as well as increased herbicide activity (Pereira *et al.* 2014).

VARYING NANO FORMULATIONS AND WEED MANAGEMENT

Nano-encapsulation

Nano-encapsulation is the process of encapsulating solid, liquid, or gas nanoparticles (also known as the core or active) in a secondary substance (also known as the matrix or shell) to generate nano-capsules. Nano-encapsulation is a membrane-controlled method in which herbicides are coated with any semi-permeable membrane, which could be organic or inorganic. Chitosan, poly propylene, poly ethylene, poly styrene, poly vinyl alcohol, poly allylamine hydrochloride, poly sodium 4- styrene sulfonate, poly vinyl pyrolidone, starch, and others are some of the polymers used. Encapsulation of active ingredient (*a.i.*) is done by: indirect method of nanoencapsulation (IDM), direct method of nanoencapsulation (DM), solvent evaporation method (SEM) and nano spray method (NSM).

Herbicides can be encapsulated with nanoparticles to increase their efficacy by focusing at the unique receptor of a specific weed after entering the root system and inhibiting glycolysis, starving them to death.

Poly-å-caprolactone (PCL) nano capsules were utilised as carriers for three triazine herbicides, ametryn, atrazine, and simazine, and their stability and appropriateness for controlled release systems were evaluated. The nano capsules had an association effectiveness of roughly 84% and the nano-capsules were discovered to be stable. The in-vitro release investigations showed that the polymer chains relaxed, resulting in a regulated release. As a result, using PCL nano-capsules in environmental systems may be a potential strategy to improve herbicidal behaviour (Grillo *et al.* 2012).

The greater mortality of *Bidens pilosa* seedlings was observed even with a tenfold dilution (NC+ATZ at 200 g/ha) of PCL nanocapsules containing atrazine (NC+ATZ). The herbicide's long-term residual impact on soybeans was not improved by encapsulating it in poly-å-caprolactone (Preisler *et al.* 2018). The utilization of atrazine-containing PCL nanocapsules potentiated the post-emergence control of *Amarathus viri* and *B. pilosa* by the herbicide (Sousa *et al.* 2018) indicating the potentiality of nanoformulation as an efficient alternative for weed control. Most natural bioactive chemicals have a limited environmental half-life, which could be addressed via nanoencapsulation. This would enable for effective weed management with just one spray, lowering rates, costs, and threats to the environment. Furthermore, nanoencapsulation could allow for the simultaneous application of many substances while inhibiting interactions until they are released (Korres *et al.* 2019).

Nano-carrier

Herbicide nanocarrier research is primarily focused on decreasing the environmental impact of herbicides, specifically reducing herbicide non-target toxicity. A wide range of nanoparticles and materials are being used in the development of nanoparticle-based herbicides. The materials used include montmorillonite clay layers coated with a pH-dependent polymer (Han *et al.* 2010), core hollow shell manganese carbonate (Kanimozhi and Chinnamuthu 2012), nano-sized tubular halloysite and platy kaolinite (Tan *et al.* 2015), amino-activated iron (II, III) oxide magnetic nanoparticles (Viirlaid *et al.* 2009), and nanosized rice husks (Abigail *et al.* 2016). Some of the nanocarrier materials include: chitosan, tri-polyphosphate, alginate, poly -å-caprolactone, starch and rice husk

The zeolite Y surface changed with 1,1,3,3-tetramethyldisilazane (Zhang *et al.* 2006). Ion-exchange loading of paraquat in zeolite revealed a loading capability of 14% of the weight. The paraquat loaded with alginate/chitosan resulted in less herbicide leaching than paraquat alone with a two-hour delay in release time compared to the herbicide alone (Da Silva *et al.* (2013).

Chitosan/tripolyphosphate nanoparticles (NPs) with paraquat herbicide were less hazardous to crops and safe to use in weed management (Grillo *et al.* 2014). When sprayed pre-emergence, solid lipid nanoparticles containing both atrazine and simazine were found to be more effective in causing mortality of *Raphanus raphanistrum*, and when applied post-emergence, they were just as effective as the herbicide alone (De Oliveira *et al.* 2015). Imazapic and imazapyr herbicides were loaded onto chitosan nanoparticles to reduce their toxicity (Maruyama *et al.* 2016). Rice husk biochar was discovered to be an effective and environmentally friendly carrier for 2,4-D. The 2,4-D nano formulation based on rice husk biochar (DrBC) could operate as a herbicide carrier while also reducing herbicide leaching and providing long-term release abilities (Abigail *et al.* 2016)

The porous calcium carbonate was loaded by dissolving prometryn herbicide in ethanol and stirring it overnight. Herbicide could be held in the porosity to a maximum weight of 20% loading capacity and the composite showed 86 % prometryn release in 12 hours in aqueous solution, validated regulated release behaviour, and recorded 20 % greater efficacy in suppressing *Cynodon dactylon*. The composite demonstrated 3 times greater herbicide retention in the leachate test with the soil column than the control (Xiang *et al.* 2018).

Nano emulsion

Nano emulsions are emulsions that are nanoscale in size and are used to improve the delivery of active herbicidal substances. These are thermodynamically stable isotropic systems in which an emulsifying agent, such as surfactant and co-surfactant, is used to combine two immiscible liquids into a single phase. Nano-emulsion droplets are typically 20-200 nm in size. The nanoemulsion of pretilachlor microemulsion (ME) and monolithic dispersion (MD) was found to be much superior in managing *Echinochloa crus-galli* compared to the commercially available formulation (Kumar *et al.* 2016). At 1000 ìL/L, a nanoemulsion of *Satureja hortensis* L. essential oil totally reduced all growth characteristics of *Amaranthus retroflexus* (Hazrati *et al*. 2017). Even at a low dose of 0.05 wt %, nanoemulsions of *Foeniculum vulgare* essential oil completely inhibited the germination of *Phalaris minor*, *Avena ludoviciana*, *Rumex dentatus* L., and *Medicago denticulata* by affecting physiological processes such as membrane leakage and reactive oxygen species mediated cellular damage (Kaur *et al.* 2021).

Nano-adjuvants

There are commercially available herbicide adjuvants that claim to contain nanoparticles. Chandana *et al.* (2021) used a surfactant derived from nano-technology with a basis of soybean micelles to sensitise the crops resistant to glyphosate.

Nano-biosensors

Nano-biosensors can be used as a tool for detection of enzyme-inhibiting herbicides. The herbicide metsulfuron-methyl (an acetolactate synthase inhibitor) was detected in the soil using a novel nano-biosensor based on atomic force microscopy (Da Silva *et al.* 2013). Precision agriculture employs nanotechnology-based sensors to ensure the proper release of herbicide spray mixtures and precise control of herbicide applications. Herbicides could be used more effectively and efficiently with nano biosensors while being environmentally friendly (Duhan *et al.* 2017).

The advantages and limitations of nano formulations

The advantages of nano formulations include: phytotoxicity elimination or minimization; reduction of herbicides application rate per hectare and minimizing environmental pollution and CO_2 emission; enhanced soil herbicide residues mitigation; safety to the microbiota in the soil with encapsulated nano herbicides (Maruyama *et al.* 2016); enhanced efficacy of herbicides under rainfed agriculture due to slow-release nano formulations; greater selectivity against the target weeds; greater effectiveness against herbicide resistant weeds and improved quality of crop produce.

In addition to advantages, there are certain limitations of nano formulations which include: inhibition of seed germination, shoot, and root growth of crops like wheat, barley and onion by nanoparticles such as Ag, TiO2, and others; human health concerns as nanoparticles can easily enter the human body through the skin; environmental concerns as nanoparticles can persist in soil, water, and plants, posing a threat to human health. The greatest concern is the high production cost of nanomaterials.

Future research needs on nano formulations in India

India has a wide range of agroclimatic conditions and soil types. The highly diverse agriculture and farming systems are beset with different types of weed problems. Invasive alien weeds are a major constraint to agriculture, forestry and aquatic environment. Crop-specific problematic weeds (*eg:* weedy rice in rice) are emerging as a threat to cultivation, affecting crop production, quality of product and income of farmers. Traditionally, weed control in India has been largely dependent on manual weeding. However, increased labour scarcity and costs are encouraging farmers to adopt labour and cost saving option of herbicides usage. The efficacy of herbicides used for weed management can be enhanced through the application of nanoherbicides in agricultural fields. Encapsulation of herbicides in nanomaterials minimizes the loss of herbicide along with its sustained release and increased specificity toward target weed. Several polymeric nanoparticles, nanocapsules, and nanospheres are used as carriers for herbicides. Polymers such as alginate, chitosan, pectin, poly(epsilon-caprolactone), poly (methyl-methacrylate), and poly (lactic-*co*-glycolic acid) are considered as ideal nanocarriers for several herbicides such as paraquat, 2,4-dichloro-phenoxyacetic acid, diuron, ametryn, atrazine, and simazine, whereas other nanocarriers such as rice husk nanosorbents, mesoporous silica nanoparticles, and nanoclay can be applied for fabrication of nanoherbicides. Nanoherbicides are effective against a variety of weed species in India some of which include *Echinochloa crus-galli*, *Chenopodium album*, *Bidens pilosa*, *Amaranthus viridis*, and *Raphanus raphanistrum* (Ghosh *et al.* 2022).

Nanoherbicidal formulations under development in the current decade could be a new strategy to address all the problems caused by the conventional herbicides. The potential use of nanostructured materials enables the use of herbicides effectively and rules out the emergence of weed resistant population at an early stage. Newer weed management approaches must be developed considering the threat of HR weeds appearance in addition to the recurrence and persistence of weeds and the need to bring down weed management costs to enhance profit for farmers while protecting the environment.

A few research areas that need to be focused in this regard include: assessment of long-term effect of nano-herbicides on plant system, soil organisms and ground water. Significant research efforts should be made to develop nano bio formulations using plant extracts, fungal nanotechnology or myco-nanotechnology, for evolving efficient and ecologically friendly weed management approaches. The fate of nano- herbicides in soil and plant system, behavior, routes of uptake and entry into the atmosphere has to be evaluated. Systems that enhance the release profile of nano-herbicides without altering their characteristics with less environmental damage should be developed. Weed Identification tool kit with nanoparticles has to be designed. Broad spectrum weed based nano formulations and i*n situ* low-cost herbicide residue estimation procedures should be formulated.

Conclusion

In the present agricultural scenario, herbicides are widely used in weed management to improve agricultural production leading to adverse impact on soil, water and food resources and alternative techniques must be evolved to manage weeds effectively with lesser environmental impact. The nanotechnology has potentiality to revolutionise agriculture. It will boost crop output by reducing the quantity of herbicides used, which will indirectly reduce environmental pollution. Greater research efforts need to be carried out for nanotechnological solutions in weed management and for their wide adoption in agricultural systems of India.

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RESEARCH ARTICLE

Effect of crop establishment and weed management methods on weed dynamics and productivity of direct-seeded rice in middle Indo-Gangetic Plains

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ABSTRACT

A field experiment was conducted during rainy seasons of 2018 and 2019 at the ICAR-Research Complex for Eastern Region Patna, Bihar to evaluate the effect of crop establishment methods and weed management treatments on weeds and productivity of direct-seeded rice (DSR). The treatments consisted of three upland DSR establishment methods, *viz.* zero-till direct-seeded rice:(ZT-DSR); conventional-till (CT)-dry DSR (CTDSR) and CTDSR-dust mulching, and three weed pressure maintenance treatments including: low weed pressure: maintained with pre-emergence (PE) application of pendimethalin (1.0 kg/ha) at 2 days after seeding (DAS) followed by *(fb)* post-emergence (PoE) application of bispyribac–Na (30 g/ha) PoE at 20 DAS *fb* hand weeding (HW) twice at 30 and 50 DAS; medium weed pressure: maintained with pendimethalin (1.0 kg/ha) PE at 2 DAS *fb* bispyribac–Na (30 g/ha) PoE at 20 DAS, and high weed pressure: maintained with pendimethalin (1.0 kg/ha) PE alone, in upland DSR under the middle Indo-Gangetic Plains (MIGPs). The major weeds recorded with upland DSR were *Cyperus rotundus*, *Cynodon dactylon*, *Echinochloa colona*, *Brachiaria ramosa*, *Caesulia axillaris* and *Physalis minima*. Significantly the lowest relative weed abundance, weed density and biomass were recorded in CT-DSR-dust mulching compared to ZT-DSR and CTDSR. Among the weed management treatment, maximum weed suppression was recorded in low weed pressure in comparison to medium and high-weed pressure management practices. Significantly higher grain yield (2.14 t/ha) and net returns (₹ 20869/ha) were obtained with CT-DSR-dust mulching. Hence, it may be concluded that for better rice productivity and weed management in upland DSR, CT-DSR-dust mulching with low weed pressure maintenance is the most potential and viable practices under the MIGPs.

Keywords: Direct-seeded rice, Dust mulching, Establishment method, Rice productivity, Weed management, Weed pressure

INTRODUCTION

Direct-seeded rice (DSR), in place of conventional puddled transplanting (PTR), provides an opportunity for labour and water savings, and has gained momentum in certain states of India. Globally, nearly 23% of rice area is under DSR (Rao *et al.* 2007). Weed control is challenging in DSR due to severity and diversity of the weed infestation, absence of standing water layer to suppress weed at rice emergence, and no seedling size advantage of rice over weed seedlings as both emerge simultaneously (Hassan and Upasani 2015). Many a times, it is very difficult to differentiate between grassy weeds like *Echinochloa* spp. and rice plants during early stages of growth (Rao 2021). Hand weeding is the most common method to suppress the weeds in rice. Scarcity of labor for timely weeding and high labor cost are major limitations of hand weeding. Herbicides are an alternative/supplement to hand weeding (Kumar *et al.* 2016). Although several pre-emergence herbicides provide good control of weeds but due to continuous use of such herbicides, a shift in weed flora and evolution of herbicide resistant weeds has been reported (Nazir *et al.* 2020). The sequential application of pre- and post-emergence herbicides is essential for broad-spectrum weed control. The present study was conducted to evaluate the effect of DSR establishment methods and weed management practices on weed management and rice productivity.

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MATERIALS AND METHODS

This study was carried out for two consecutive years from 2018 and 2019 at the ICAR-Research Complex for Eastern Region, Patna, Bihar (25^{o}30'N, 85°15'E, 52 m above mean sea levels). Total rainfall received during cropping season (June–October) was 715.7 and 911.5 mm in 2018 and 2019, respectively. Soil was clay loam (42% sand, 35% silt and 23% clay), low in organic carbon (0.46%), and N (212 kg/ha), and medium in available P (26 kg P/ha) and K (215 kg K/ha). Soil test was based on samples taken from upper 30 cm depth just prior to start of experimentation.

Experiment was laid out in a split-plot design with three replications. Three DSR establishment methods, *viz*. zero-till direct-seeded rice (ZTDSR); conventional-till direct-seeded rice (CTDSR) and CTDSR-dust mulching were assigned to main-plots and three weed control treatments in sub-plots include: low weed pressure [maintained by pre-emergence application (PE) of pendimethalin (1.0 kg/ha) at 2 DAS followed by *(fb)* post-emergence application *(*PoE*) of* bispyribac-Na (30 g/ha) at 20 DAS) *fb* HW twice at 30 and 50 DAS], medium weed pressure [maintained by pendimethalin (1.0 kg/ha) PE at 2 DAS *fb* bispyribac-Na (30 g/ha) PoE at 20 DAS] and high weed pressure [maintained by pendimethalin (1.0 kg/ha) alone at 2 DAS]. In ZTDSR, rice was directly drilled with Happy seeder without any field preparation. In CTDSR, field was prepared by ploughing twice with cultivator followed by rotavator to get a fine tilth for ensuring easy movement of seed drill on dry soil. Dry seeding was done in both ZTDSR and CTDSR, where as in CTDSR-dust mulching, field was first irrigated and prepared at proper tilth, followed by sowing of seed with available soil moisture. In this case rice seeds were primed with water for overnight before sowing. We hypothesize that the dry upper soil surface reduces weed seed germination, but available soil moisture at lower depth allows rice seeds to germinate. Rice variety '*Naveen*' (115 days duration) was sown using seed rate of 25 kg/ha on 6th June in 2018 and 11th June in 2019, respectively in rows, 20 cm apart. To ensure the proper seed germination, seed priming (over-night soaking of seed followed by drying in shades before sowing) was done before crop sowing. Seeds were treated with carbendazim 2 g/kg seed before sowing.

Recommended dose of fertilizer (120, 60, 40 and 5 kg/ha N, P, K and Zn) was applied. Total quantity of P, K and Zn was applied basal, whereas nitrogen was applied in 3-equal split-each at basal, maximum tillering and panicle initiation. Weed density and biomass were recorded at 60 DAS with help of a quadrat (0.5 × 0.5 m) placed randomly at 4 places in each plot. Weeds within each quadrat were uprooted, separated species wise and counted. Weed samples were oven dried before weighing at 70°C till constant weight (biomass) was achieved. Weed species abundance is the number of individuals per species. Relative species abundance was calculated by dividing the number of species from one group by total number of species from all groups. Observation on crop growth parameters, *viz*. plant height (cm), total leaves/hill (nos.) total green leaves/hill (no.), tillers/m^2, effective tillers/m^2, days to 50% flowering (nos.), days to physiological maturity (nos.) and yield attributes like panicle length (cm), grains/panicle (nos.), filled grains/panicle (nos.), 1000-grain weight (g), grain yield (t/ha) and crop productivity (kg/ha/day) were recorded at harvest. Sampling was done from an area of 25 m^2 in each plot to determine the above ground total dry weight (total biomass). Biomass (sum of straw dry weight and grain dry weight) was calculated using grain and total dry weight of each treatment. Crop was threshed manually; grains were cleaned and weighed for yield and expressed in t/ha. Data on weed density were subjected to square root transformation ($\sqrt{x+0.5}$) before statistical analysis to normalize their distribution. Data were analyzed statistically as per standard method (Panse and Sukhatme 1978). Test of significance of treatment differences was done on the basis of t-test. Significant difference between treatments mean was compared with the critical differences at 5% levels of probability.

RESULTS AND DISCUSSION

Effect of weather

There were large variations in rainfall intensity and distribution patterns during the experimentation. Average of mean rainfall during rice season (June–October) was 715.7 mm and 911.5 mm in 2018 and 2019, respectively. Rainfall was distributed quite uniformly during 2018, but during 2019, crop faced early and late-season drought during cropping periods resulted in decline crop yields. Mean monthly maximum and minimum temperature ranged between 28.7-37.4 and 16.1-28.2 °C during 2018 and 2019, respectively **(Figure 1)**.

Relative density (%) of weeds

Major weed associated with DSR were *Cyperus rotundus*, *Cynodon dactylon*, *Echinochloa colona*, *Brachiaria ramosa*, *Caesulia axillaris* and *Physalis minima* **(Table 1)**. Relative density varied according to crop establishment methods and weed management practices. Maximum relative abundance of *C. dactylon*, *E. colona*, *B. ramosa*, *C. axillaris* and *P. minima* was recorded in ZTDSR followed by CTDSR. While the maximum relative abundance of

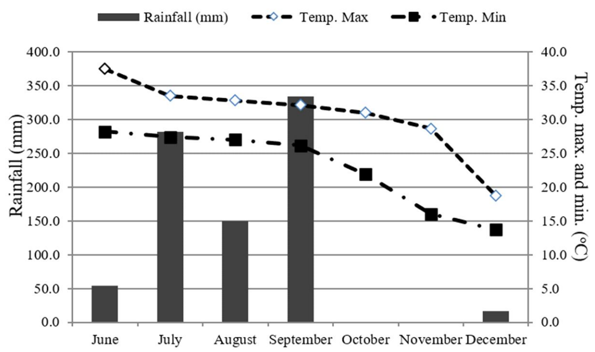

Figure 1. Mean monthly rainfall and temperature during rice growing period

Trianthema portulacastrum was noted with CTDSR-dust mulching followed by CTDSR. Higher weed density in ZTDSR during first year might be due to presence of more weed seeds on soil surface, which could have promoted greater and quick emergence of weed species that require light to germinate or smaller seeds that cannot emerge after burial by tillage. The highest relative density of *C. rotundus, C. dactylon, E. colona*, *T. portulacastrum*, *C. axillaris* and *P. minima* was recorded in low weed pressure followed by medium weed pressure. The highest relative density of *B. ramosa*, *C. axillaris* and other weeds was recorded with high weed pressure.

Weed density and biomass

Among the crop establishment method, CTDSR-dust mulching was the most effective in reducing density of *C. rotundus*, *C. dactylon*, *E. colona*, *B. ramosa*, *C. axillaris* and *P. minima* in comparison to other methods (**Table 2**). Significantly the lowest density of *T. portulacastrum* was found in ZTDSR followed by CTDSR. The lowest total weed biomass (14.5 g/m^2) was also recorded with CTDSR-dust mulching, and it was significantly superior to other crop establishment methods. Most of the weed seeds remain on top soil layer. Dust-mulching creates dry zone in top-soils resulting in lower germination of weed seeds due to moisture stress (Nazir *et al*. 2020).

Table 1. Effect of direct-seeded rice (DSR) establishment methods and weed management treatments onrelative density of weeds (%) (pooled data of 2 years)

Treatment	*Cyperus rotundus*	*Cynodon dactylon*	*Trianthema portulacastrum*	*Echinochloa colona*	*Brachiaria ramosa*	*Caesulia axillaris*	*Physalis minima*	Other weeds
Rice establishment method								
ZTDSR	29.6	5.66	15.8	4.02	13.3	24.3	4.75	2.54
CTDSR	32.6	2.48	27.6	2.49	11.4	17.7	3.89	1.93
CTDSR- dust mulching	23.7	1.38	53.0	1.13	5.0	12.8	1.99	1.12
Weed management treatment								
Low weed pressure	31.9	3.83	29.6	3.35	7.6	18.5	4.03	1.39
Medium weed pressure	31.6	3.65	29.7	2.68	9.2	18.2	3.74	1.37
High weed pressure	26.2	3.40	29.0	2.63	12.4	20.3	3.67	2.61

Table 2. Effect of direct-seeded rice (DSR) establishment methods and weed management treatments on weed density and biomass (pooled data of 2 years)

Treatment	Weed density (no./m^2)									Total weed biomass (g/m^2)
	Cyperus rotundus	*Cynodon Dactylon*	*Trianthema portulacastrum*	*Echinochloa colona*	*Brachiaria ramosa*	*Caesulia axillaris*	*Physalis minima*	Other weeds	Total	
Rice establishment method										
ZTDSR	8.49 (73.4)	3.74 (14.0)	6.19 (39.3)	3.16 (9.92)	5.24 (32.9)	7.42 (60.3)	3.46 (11.75)	2.28 (6.28)	15.4 (248)	18.1 (338)
CTDSR	7.59 (59.0)	2.16 (4.52)	7.01 (50.0)	2.22 (4.50)	4.48 (20.6)	5.50 (32.1)	2.71 (7.08)	1.91 (3.50)	13.3 (181)	16.2 (273)
CTDSR-dust mulching	5.99 (36.3)	1.58 (2.10)	8.67 (81.3)	1.45 (1.73)	2.75 (7.60)	4.28 (19.7)	1.86 (3.06)	1.46 (1.73)	12.1 (153)	14.5 (216)
LSD (p=0.05)	0.34	0.39	0.74	0.42	0.61	1.59	0.47	0.37	1.0	1.4
Weed management treatment										
Low weed pressure	5.84 (34.4)	2.00 (4.11)	5.67 (31.9)	1.94 (3.62)	2.85 (8.25)	4.24 (19.9)	2.09 (4.34)	1.35 (1.50)	10.3 (108)	13.3 (179)
Medium weed pressure	7.78 (60.3)	2.48 (6.95)	7.29 (56.7)	2.28 (5.11)	4.14 (17.65)	5.80 (34.7)	2.66 (7.12)	1.71 (2.61)	13.8 (191)	15.7 (253)
High weed pressure	8.45 (73.9)	3.00 (9.56)	8.93 (81.9)	2.62 (7.45)	5.58 (35.2)	7.16 (57.4)	3.20 (10.38)	2.59 (7.39)	16.6 (283)	19.8 (395)
LSD (p=0.05)	0.25	0.30	0.51	0.32	0.46	1.31	0.30	0.29	0.71	1.0

*Data subjected to square root transformation ($\sqrt{x+0.5}$), Values in parentheses are original; Low weed pressure: pre-emergence application (PE) of pendimethalin (1.0 kg/ha) at 2 DAS followed by *(fb)* post-emergence application (PoE) *of* bispyribac–Na. (30 g/ha) at 20 DAS fb HW twice (30 and 50 DAS); Medium weed pressure: application of pendimethalin (1.0 kg/ha) PE. at 2 DAS *fb* bispyribac-Na (30 g/ha) PoE at 20 DAS; High weed pressure: pendimethalin (1.0 kg/ha) PE at 2 DAS

Among the weed management practices, low weed pressure maintenance treatment recorded significantly lower infestation of all weeds compared to medium and high weed pressure. In previous studies, Nazir *et al.* (2020) reported lowest weed biomass with sequential application of pendimethalin PE *fb* azimsulfuron PoE. Bispyribac-Na + azimsulfuron PoE would be a potential herbicide combination if both grassy and broadleaved weeds are present in field. These results were in close conformity with the findings of Singh *et al.* (2017) and Saha *et al.* (2021).

Rice growth, yield attributes, grain yield and economics

Rice growth, yield attributes and grain yield were significantly influenced by the crop establishment methods and weed management treatments (**Table 3** and **4**). Maximum plant height (105.2 cm), days to 50% flowering (88.3), days to physiological maturity (119), total green leaves/hill (61.5), tillers/m^2 (127.7) and other yield attributes, *viz.* panicle length (26.0 cm), grains/panicle (205.4), 1000-grain weight (22.8 g), rice grain yield (2.14 t/ha) and crop productivity (18.6 kg/ha/day) were recorded in CTDSR-dust mulching due to lesser crop-weed competition, followed by CTDSR. The lowest values of these parameters were recorded in ZTDSR. Dust-mulching conditions enabled crop to make the maximum use of inputs for crop growth, and thereby for formation and development of yield attributes. Similar findings were also reported by Saha *et al.* (2021).

Among the weed management practices, growth attributes *i.e.,* plant height (104.2 cm), days to 50% flowering (87.5), days to physiological maturity (120.7), total green leaves/hill (63.5), tillers/m^2 (161.3) and other yield attributes, *viz.* panicle length (25.5 cm), grains/panicle (181.5) and 1000-grain weight (22.6 g), grain yield (2.88 t/ha) and crop productivity (25.1 kg/ha/day) were significantly higher in low weed pressure management practices compared to medium and high weed pressure due to lower infestation of weeds in low and medium weed pressure compared to high weed pressure which reduced the crop-weed competition for nutrients and moisture supply, resulting in proper pollination and seed setting in rice(Kumar *et al.* 2020).

Table 3. Effect of direct-seeded rice (DSR) establishment methods and weed management treatments on rice growth attributes (pooled data of 2 years)

Treatment	Plant height (cm)	Days to 50% flowering (no.)	Days to physiological maturity (no.)	Total leaves/hill (no.)	Tillers/ m^2 (no.)	Panicle length (cm)	Grains/ panicle (no.)	1000-grain weight (g)
Rice establishment method								
ZTDSR	95.0	79.8	110.3	35.2	66.2	17.9	130.6	19.2
CTDSR	99.6	83.7	114.8	47.7	121.1	21.6	134.7	21.1
CTDSR-dust mulching	105.2	88.3	119.0	61.5	127.7	26.0	205.4	22.8
LSD (p=0.05)	2.2	1.8	3.2	5.8	10.0	1.6	18.5	1.2
Weed management treatment								
Low weed pressure	104.2	87.5	120.7	63.5	161.3	25.5	181.5	22.6
Medium weed pressure	99.1	83.2	116.8	50.6	80.0	21.6	159.6	21.4
High weed pressure	96.5	81.1	106.6	30.3	73.7	18.5	129.8	19.2
LSD (p=0.05)	1.9	1.6	2.3	3.4	3.8	1.0	7.6	0.9

Table 4. Effect of direct-seeded rice (DSR) establishment methods and weed management on rice yields and economics (pooled data of 2 years)

Treatment	Grain yield (t/ha)			Cost of cultivation (x10^3 ₹/ha)	Gross returns (x10^3 ₹/ha)	Net returns (x10^3 ₹/ha)	Crop productivity (kg/ha/day)	Economic efficiency (₹/ha/day)
	2018	2019	Pooled					
Rice establishment methods								
ZTDSR	1.82	1.17	1.50	31.01	42.57	11.44	13.0	100
CTDSR	2.03	1.56	1.80	36.71	50.04	13.33	15.6	116
CTDSR-dust mulching	2.34	1.93	2.14	38.70	59.57	20.87	18.6	182
LSD (p=0.05)	0.20	0.34	0.27	2.44	6.40	7.89	2.3	69
Weed management practices								
Low weed pressure	3.18	2.57	2.88	34.76	75.71	40.95	25.1	40949
Medium weed pressure	2.65	1.48	2.07	34.94	52.83	17.78	18.0	17778
High weed pressure	0.36	0.61	0.49	36.74	23.65	-13.09	4.2	-13086
LSD (p=0.05)	0.17	0.27	0.22	1.81	4.59	5.59	1.9	5589

Low weed pressure: pre-emergence application (PE) of pendimethalin (1.0 kg/ha) at 2 DAS followed by (*fb*) post-emergence application (PoE) of bispyribac–Na. (30 g/ha) at 20 DAS *fb* HW twice (30 and 50 DAS)], Medium weed pressure: application of pendimethalin (1.0 kg/ha) PE. at 2 DAS *fb* bispyribac-Na (30 g/ha) PoE at 20 DAS); High weed pressure: pendimethalin (1.0 kg/ha) PE at 2 DAS

Table 5. Interaction effect of direct-seeded rice (DSR) establishment methods and weed management treatments on rice grain yield (pooled data of 2 years)

Weed pressure/Rice establishment method	ZTDSR	CTDSR	CTDSR-dust mulching	Mean
Low weed pressure	2.21	2.93	3.49	2.88
Medium weed pressure	1.83	1.96	2.43	2.07
High weed pressure	0.46	0.50	0.50	0.48
Mean	1.50	1.80	2.14	
			SEm±	LSD (p=0.05)
Direct-seeded rice (DSR) establishment method (E) at same weed pressure			0.13	0.38
Weed pressure (W) at same/different crop establishment method (E)			0.12	0.34
Rice establishment method (E)			0.07	0.27
Weed pressure (W)			0.08	0.22
ExW			0.13	0.38

Low weed pressure: pre-emergence application (PE) of pendimethalin (1.0 kg/ha) at 2 DAS followed by (*fb*) post-emergence application (PoE) of bispyribac–Na. (30 g/ha) at 20 DAS fb HW twice (30 and 50 DAS)], Medium weed pressure: application of pendimethalin (1.0 kg/ha) PE. at 2 DAS fb bispyribac-Na (30 g/ha) PoE at 20 DAS); High weed pressure: pendimethalin (1.0 kg/ha) PE at 2 DAS

The interaction effect between crop establishment method and weed management for grain yield clearly indicated that crop establishment methods have their effects on yield when weeds are controlled effectively (low and medium weed pressures). CTDSR with dust mulching under low weed pressure provided the maximum grain yield (3.49 t/ha). There was no response of crop establishment methods under high weed pressure due to very poor grain yield obtained during both the years (**Table 5**). Results of current research are in congruity with previous reports of superior weed control in DSR with pendimethalin PE *fb* bispyribac-Na PoE (Mahajan *et al*. 2009). In spite of higher cost of cultivation, net returns (₹ 20869/ha) were significantly higher with CTDSR-Dust mulching compared to ZTDSR (**Table 4**), due to higher grain yield. Among the weed management treatments, low weed pressure resulted in maximum net returns. High weed pressure resulted in to net loss of ₹ 40949/ha.

Thus, it may be concluded that growing of rice in CTDSR-dust mulching along with pendimethalin (1.0 kg/ha) PE at 2 DAS *fb* bispyribac-Na (30 g/ha) PoE at 20 DAS *fb* HW twice at 30 and 50 DAS is better options to manage weeds and improve rice productivity under rainfed ecosystem of middle Indo-Gangetic plains.

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RESEARCH ARTICLE

Effect of weed interference on rice yield under elevated CO_2 and temperature

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ABSTRACT

Rice (*Oryza sativa* L.) is one of the major staple food source for more than half of the global population. To attain the food needs of the world's growing population, further increase in rice productivity is needed. To assess the sensitivity of agricultural output, a greater comprehension of the possible interactions amongst crops and weeds in the face of climate change, especially under elevated CO_2 (EC) and elevated temperature (ET), is essential. This study was conducted to quantify the influence of elevated temperature, CO_2, weed density and their interactions on crop-weed competition, rice yield parameters and grain yield. The experiment was conducted in four separate Open Top Chambers (OTCs), *viz.* with ambient CO_2 (A), elevated CO_2 [550±50 ppm] (EC), elevated temperature (ambient±2 °C) (ET) and combined effect of elevated CO_2 and temperature (EC+ET) with and without weed competition. The EC alone enhanced the rice grain yield by 42.30% in weed-free conditions when compared to ambient CO_2, however substantial change was not observed under ET. In the EC+ET condition, however, regardless of weeds presence or absence, crop output was reduced by 22.02 percent. *Alternanthera paronychioides* A. St.-Hil. competition caused rice yield reduction of 79.72, 83.04, 62.98 and 62.01% at A, EC, ET, EC+ET, respectively. The EC and ET interactions will certainly exert a profound influence on weed growth and competition against crops, which ultimately enhances crop yield losses in futuristic climate change scenario.

Keywords: Climate change, Crop-weed interaction, Rice, Elevated CO_2, Elevated temperature, Weed competition

INTRODUCTION

The rising CO_2 levels and temperatures are of major concern to agriculture in the era of climate change. Atmospheric CO_2 levels have increased at a record-breaking rate (https://www.co2.earth/). Atmospheric CO_2 levels are already rising and will potentially exceed 800 ppm by the ending of the 21st century. Global surface temperature was estimated to rise by 1.5 °C relative to 1850 by the end of the 21st century (IPCC 2014). The increasing levels of CO_2 and predicted climate change may benefit the establishment and proliferation of weeds over crops which can have negative consequences for agricultural productivity (Peters *et al*. 2014, Ziska 2007). Therefore, for the assessment of the vulnerability of crop production in different parts of the world and a broader perception of the possible interactions between crops and weeds under the climate change scenario, especially CO_2, high temperatures and drought, is important (Valerio *et al.* 2013). Changes in weed distribution have also been caused by climate change. The establishment of *Marsilea* spp. in India under wet rice conditions was attributed to climate change (Kathiresan and Gualbert 2016). The drought and the transition to direct-seeded rice, favored the predominance of recalcitrant grass weeds such as *Dactyloctenium aegyptium* (L.) PB, *Eleusine indica* (L) Gaertn and *Leptochloa chinensis* (L.) Nees (Chauhan *et al.* 2014, Matloob *et al*. 2015). Elevated atmospheric temperature changes have also triggered shifts in weed flora. For instance, *Ischaemum rugosum* Salisb. primarily seen in the tropical regions of India is now very widespread in northern India (Mahajan *et al.* 2012). Hence, in the climate change scenario, it is imperative to look at crop-weed competition case by case to establish successful weed management practices for the emerging species.

Rice (*Oryza sativa* L.) is a major food crop, being consumed every day by 50% of the population of the world (Wei and Huang 2019). It is also a main food in Asia, which is home to more than half of the world's poorest population. Losses in rice yield range

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from 10 to 79% globally in competition with *Echinochloa* spp. (Chin 2001, Rao *et al.* 2017, Rao 2021). In general, high temperatures and CO_2 levels can alter dominant weed species and exacerbate weed growth (Ziska and Dukes 2011). Nakagawa *et al.* (2002) observed about 14 per cent increase in the production of rice biomass due to elevated CO_2 in CO_2 temperature gradient tunnels compared to 9% in the FACE experiment. However, Kim *et al.* (1996) and Baker *et al.* (1990) recorded lower rice biomass accumulation in FACE investigations as compared to that of open top chambers (OTCs) and CO_2 temperature gradient tunnels. The doubling of CO_2 concentration resulted in a 30% increase in rice yield (Horie *et al.* 2000). The elevated CO_2 concentration was reported to promote tillering, rate of photosynthesis, biomass accumulation and yield in rice (Kobayashi *et al.* 1999, Sakai *et al.* 2001, Chakrabarti *et al.* 2012).

In order to maintain sustained rice productivity, to meet the increasing global food needs, it is vital to evaluate the influence of prospective changes in the climate on rice yield. Therefore, this study was conducted with an objective to quantify the interactive effect of high CO_2 and temperature, as well as their combinations, on rice crop under the interference of weeds. This study will help to understand the impacts of changing climatic factors, under changing climate scenario, on yield and yield attributes of rice and will provide a scientific basis for optimizing weed management practices and maintaining stable rice yields in the futuristic climate change scenario.

MATERIALS AND METHODS

Experiment site and weather conditions

The experiment was carried out in Open Top Chambers (OTCs) during the *Kharif* (rainy) season of 2020 and 2021 at ICAR-DWR, Jabalpur 23°13’58.62" N latitude and 79°58’05.03" E longitude). Climatic condition is humid subtropical, summer set about late March and lasts until June, and summer followed by South-West monsoon which lasts until early October and produces average yearly rainfall of ~1386 mm.

Crop management and plant sampling

The experiment was conducted in four different OTCs (5.30 m^2), each with its own set of environmental variables: Ambient temperature and ambient CO_2 [415 ± 30 ppm], ambient temperature (24-34 ºC) + elevated CO_2 [550±50 ppm], elevated temperature (ambient+2 ºC) + ambient CO_2, elevated temperature (ambient+2 ºC) + elevated CO_2 [550±50 ppm]. During the crop growing season, chambers were equipped with temperature sensors to control the temperature and the area in both chambers was further divided into three parts along the chamber to grow the rice crop with and without infestation of selected weeds. Rice variety ‘*IR-64*’ was sown (seed rate of 20 kg/ha and 25 cm row-to-row spacing) in the first week of July and all the standard agronomic practices were followed. Seeds of *L. chinensis* and *A. paronychioides* were dispersed in the OTCs and weed density of 50/m^2 was maintained throughout the season. Under elevated CO_2 treatment, 550±50 ppm was maintained inside the OTC by releasing the CO_2 gas from compressed CO_2 gas cylinders. The CO_2 gas was released with 45 kg capacity CO_2 cylinder using a perforated 13 diameter PVC pump. The required levels of CO_2 levels were maintained within the chambers by solenoid valves. Throughout the experiment, the elevated CO_2 and elevated temperature were maintained for up to 12 hours a day.

Observations

At maturity rice plants were uprooted and data were recorded for yield related criteria such as plant height (cm), number of tillers/plant, number of grains/panicle, yield/plant (g) and 1000-grain weight (g) were observed in rice. Five plants were randomly selected and considered as replication for observation of rice per treatment.

Statistical analysis

The data were analyzed and evaluated by Statistical Program for Social Science (SPSS v16.0) software with general linear model (GLM) for completely randomized design (CRD). All results were expressed as an average of five replications. Principal component analysis (PCA) was performed using Minitab software. Significant differences (P= 0.05) between treatments were determined using Duncan’s multiple range test.

RESULTS AND DISCUSSION

Effect of elevated CO_2

CO_2 concentration in the atmosphere is rising and increased CO_2 level is generally thought to promote rice biomass production (Kumar *et al.* 2017) but may inhibit growth of plants in some circumstances by affecting the primary metabolism (Takatani *et al.* 2014). Plant senescence, leaf withering and anthocyanin buildup, is also accelerated by higher CO_2 levels in combination with inadequate nitrogen (Aoyama *et al.* 2014).

In this study, increase in grain yield of rice (40.13%) was observed under higher CO_2 concentrations (550±50 ppm). The increased production corroborated with increase in number of grains/panicle (21.56%), plant height (14.52%), panicle length (11.21%), number of tillers/plant (27.27%) and 1000-grain weight (16.65%). Horie *et al*. (2000) observed around 30% increase in rice output with doubled CO_2 level due to enhancement in the plant height, panicle length, and no. of tillers/ plant. A significant increase in grains/panicle (21.50%), plant height (16.61%), panicle length (11.21), number of tillers/plant (9.09%) and 1000-grain weight (2.5%) of rice was observed under elevated CO_2 as observed earlier by Kobayashi *et al.* (1999); Sakai *et al.* (2001); Chakrabarti *et al.* (2012). The enhanced growth may be because of enhanced photosynthesis due to competitively inhibition of the *Rubisco* catalyzed oxygenation at increased CO_2 levels (Ainsworth *et al.* 2003).

Effect of elevated temperature

Increase in temperature by 2 ºC had significant negative effect resulting in 17.03% reduction in yield/ plant of rice compared to ambient condition. The increased temperature also reduced the plant height, panicle length, number of grains/panicle, number of tillers/plant, and 1000-grain weight of rice by 16.42, 6.64, 24.61, 13.64 and 9.34%, respectively, over the ambient condition as reported earlier by Rani and Maragatham (2013).

Combined effect of elevated CO_2 and temperature interactions on rice yield

Under the combined effect of elevated CO_2 levels and temperature the rice yield/plant has increased by 13.47% as reported by Krishnan *et al.* (2007), Satapathy *et al*. (2015) and Madan *et al*. (2012). The plant height of rice was increased by 7.18% due to the combined effect of elevated CO_2 levels and temperature as reported by Dwivedi *et al.* (2015) and Kaur *et al.* (2019).

The no. of tillers/plant of rice increased by 18.18% as observed earlier by Jitla *et al*. (1997) and Kim *et al.* (2003). The 1000-grain weight of rice was also increased by 12.61% as reported by Dwivedi *et al.* (2015) and Rosalin *et al.* (2018) in rice. Other attributes like panicle length, number of grains/ panicle of rice were also increased by 7.84%, 16.21%, respectively, under the combined effect of elevated CO_2 and elevated temperature.

Effect of weeds on yield and yield attributes of rice under elevated CO_2 and temperature

This is the first report of effect of weed interference on rice yield attributes under the climate change scenario. The competitive interference of two weeds, *A. paronychioides* and *L. chinensis*, caused significant variation in yield and yield attributes of rice across different treatments. Weed interference causes higher yield losses since weeds and the crop plants have identical photosynthetic pathways and nutritional levels (Pagare *et al.* 2017). Weeds, as with most crop plants, have stronger physiological adaptations, higher interspecific genomic diversity, and physiological adaptability under dynamic environmental conditions (Upasani *et al.* 2018).

Plant height: Plant height of rice was reduced by 20.78, 15.56, 21.72, and 23.20%, at A, EC, ET and EC+ET, respectively in association with *A. paronychioides* when compared to weed free. Similarly, the plant height also decreased by 18.05, 11.24, 15.51 and 10.09% at A, EC, ET and EC+ET, respectively, in association with *L. chinensis* plot when compared to rice grown in weed free condition (**Figure 1a**).

Panicle length: Panicle length of rice was reduced by 26.64%, 31%, 11.81% and 26.54% at A, EC, ET and EC+ET, respectively, when raised with *A. paronychioides* plots when compared to weed free rice. Similarly, *L. chinensis* caused reduction in panicle length by 13.71, 27.52, 3.69 and 6.39% at A, EC, ET and EC+ET, respectively, as compared to weed free rice (**Figure 1b**).

Number of grains/panicle: Number of grains/ panicle of rice were greatly reduced by 56.27, 60.88, 47.87 and 78.42% at A, EC, ET and EC+ET, respectively, in *A. paronychioides* plots as compared to weed free condition rice. Similarly, number of grains/panicle were also reduced by 21.71, 20.75, 38.95 and 51.45% at A, EC, ET and EC+ET, respectively, in *L. chinensis* plots as compared to weed free condition rice (**Figure 1c**).

Number of tillers/plant: Number of tillers/plant of rice were reduced by 36.36, 25, 31.58 and 53.85%, at A, EC, ET and EC+ET, respectively in *A. paronychioides* plot as compared to weed free condition. Similarly, number of tillers/plant were reduced by 22.72, 17.86, 15.79 and 23.08%, at A, EC, ET and EC+ET, respectively in *L. chinensis* plots as compared to weed free condition rice (**Figure 1d**).

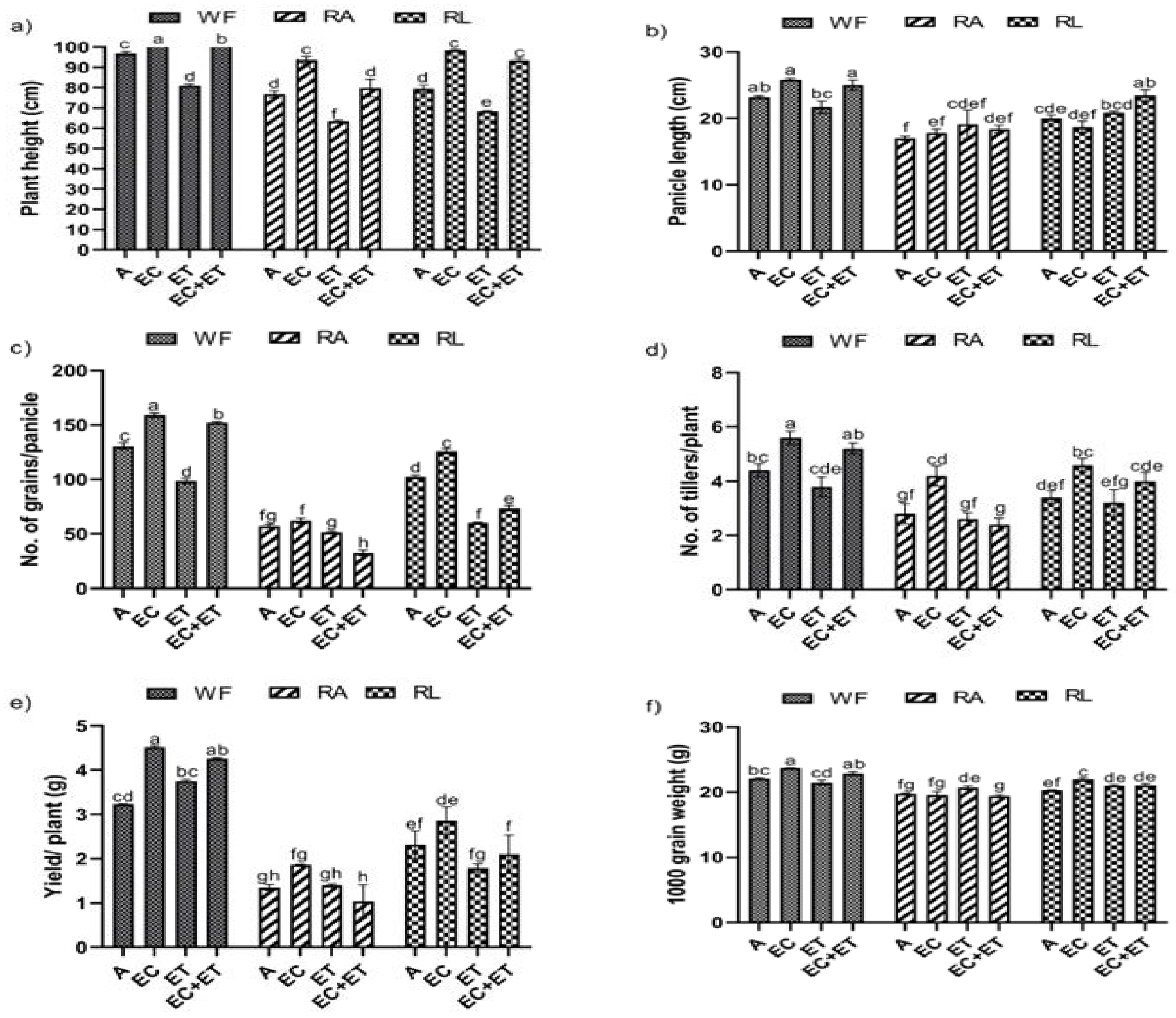
Yield/plant: Yield/plant of rice was found to be reduced by 58.04, 58.77, 62.73 and 75.65% at A, EC, ET and EC+ET, respectively, in *A. paronychioides* plots as compared to weed free condition rice plot. Similarly, yield/plant was found to be reduced by 28.05%, 36.69%, 52.38% and 50.68% at A, EC, ET and EC+ET, respectively, in *L. chinensis* plots as compared to weed free condition rice (**Figure 1e**).

1000-grain weight: 1000-grain weight was found to be reduced by 10.47, 17.65, 3.63 and 15.31% at A, EC, ET and EC+ET, respectively, in *A. paronychioides* plots as compared to weed free condition rice. Similarly, 1000-grain weight was found to be reduced by 7.99, 7.26, 2.24 and 7.87%, A, EC, ET and EC+ET, respectively, in *L. chinensis* plots as compared to weed free condition rice (**Figure 1f**).

Effect of elevated CO_2 and temperature on *L. chinensis* and *A. paronychioides*

The growth and biomass of weeds was significantly increased under elevated CO_2 and temperature compared to ambient. However, the positive influence was more on *A. paronychioides* in comparison to *L. chinensis* under elevated CO_2 and temperature. Therefore, *A. paronychioides* may become a major problematic weed in futuristic climate change scenario (**Table 1**).

Principal component analysis (PCA): In weed free condition, the PCA resulted in three independent principal components had a cumulative variance of 92%. Corresponding eigen values attribute for the importance of character. The first two principal components having an eigen values greater than



EC = elevated CO_2; *ET* = elevated temperature; *EC+ET* = combined effect of elevated CO_2 and temperature. *WF* = weed free Rice; *RL* = rice in association with *L. chinensis*; *RA* = Rice in association with *A. paronychioides*. Vertical bars represent the mean ± SE of five replicates. Means denoted by the same letter were not significantly different at P = 0.05 level according Duncan's test

Figure. 1 Effect of *L. chinensis* and *A. paronychioides* competition on rice yield and yield attributes under elevated CO_2 and temperature (pooled data of two years)

Table 1. Effect of elevated CO_2 and temperature on weed biomass characteristics

Weed biomass characteristics	Climatic factor	*Alternanthera paronychioides*	*Leptochloa chinensis*
Shoot fresh weight (g)	Ambient	63.40 ± 2.84d	9.43 ± 1.88d
	EC	80.00 ± 2.08a	12.83 ± 0.39c
	ET	74.67 ± 3.18c	13.77 ± 0.18b
	EC+ET	78.33 ± 3.51b	15.13 ± 1.04a
Shoot dry weight (g)	Ambient	1.35 ± 0.08d	1.35 ± 0.27d
	EC	2.23 ± 0.20b	2.21 ± 1.10c
	ET	1.96 ± 0.34c	2.52 ± 0.20a
	EC+ET	2.27 ± 0.21a	2.22 ± 0.15b
Root fresh weight (g)	Ambient	1.33 ± 0.18d	0.13 ± 0.03b
	EC	2.18 ± 0.02a	0.17 ± 0.07b
	ET	1.90 ± 0.66c	0.23 ± 0.03a
	EC+ET	2.00 ± 0.20b	0.20 ± 0.06a
Root dry weight (g)	Ambient	0.13± 0.01a	0.03 ± 0.01a
	EC	0.18 ± 0.00a	0.05 ± 0.02a
	ET	0.15 ± 0.06a	0.06 ± 0.02a
	EC+ET	0.16 ± 0.01a	0.04 ± 0.01a

EC Elevated CO_2; *ET* Elevated temperature; *EC+ET* combined effect of elevated CO_2 and temperature. Means denoted by the same letter were not significantly different at p=0.05 level according Duncan's test

0.4974accounting for 92% of variation among 6 selected parameters. In PC-1 maximum variation contributed by number of tillers per plant (0.427), PL (0.426) and test weight (0.423), however, least variation contributed by Yield (0.334). Similarly, in PC-2 the highest variation contributed by plant height (0.340), whereas yield (-0.882), and test weight (-0.050) contributed least variation. (**Table 2; Figure 2a, b**).

In the presence of *A. paronychioides*, the PCA resulted in three independent principal components had a cumulative variance of 87.8%. Corresponding eigen values attribute for the importance of character. The first two principal components having an eigen values greater than 1 accounting for 87.8% of variation among 6 selected parameters. In PC-1, maximum variation contributed by number of tillers per plant (0.507), plant height (0.455) and yield (0.44), however, least variation contributed by panicle length (-0.332) and test weight (-0.251).

Table 2. Principal components showing the eigenvalues, the proportion of variation and principal component analysis for yield and yield attributes of weed-free rice under different environmental conditions (pooled data of two years)

Variable	PC1	PC2	PC3
PH	0.415	0.340	-0.208
PL	0.426	0.081	0.241
NSP	0.415	0.309	0.526
NTP	0.427	0.029	0.075
Yield	0.334	-0.882	0.172
TW	0.423	-0.050	-0.766
Eigenvalue	5.4727	0.4974	0.0298
Proportion	0.912	0.083	0.005
Cumulative	0.912	0.995	1.000

PH = Plant height, *PL* = Panicle length, *NSP* = Number of seeds per panicle, *NTP* = Number of tillers per plant, *TW* = Test weight

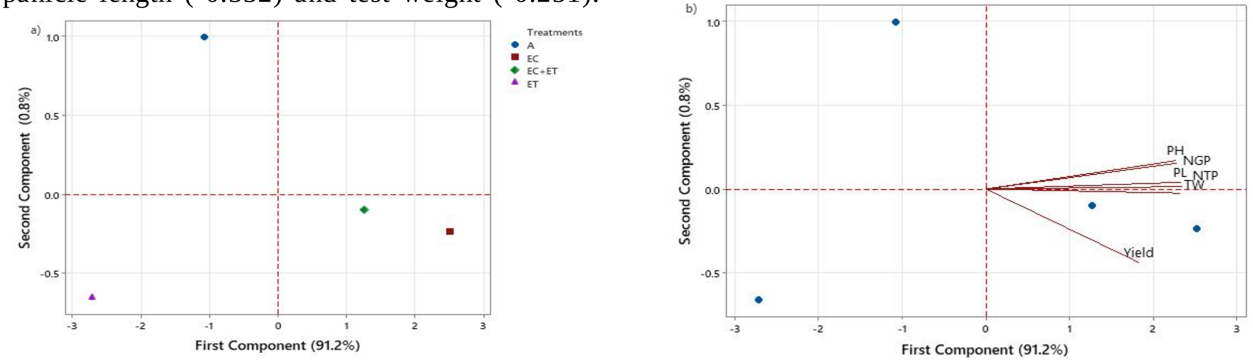


Figure 2. Score plot (a) and Biplot plot (b) analysis between various yield and yield attributes in weed-free rice under different climatic conditions. *PH* = plant height, *PL* = panicle length, *NGP* = number of grains per panicle, *NTP* =number of tillers per plant, *TW* = test weight

Similarly, in PC-2, the highest variation contributed by plant height (0.341), whereas test weight (-0.656) and number of grains per panicle (-0.441) contributed least variation (**Table 3; Figure 3a, b**).

In rice, in the presence of *L. chinensis,* the PCA resulted in six independent principal components and had a cumulative variance of 90.8%. Corresponding eigen values attribute for the importance of character. The first two principal components having an eigen values greater than 1.2568 accounting for 90.8% of variation among 6 selected parameters. In PC-1 maximum variation contributed by yield (0.472), number of tillers per plant (0.455) and plant height (0.414) and least variation contributed by panicle length (-0.271). Similarly, in PC-2 the highest variation contributed by panicle length (0.710), whereas, number of seeds per panicle (-0.335) and yield (-0.173) contributed least variation (**Table 4; Figure 4a, b**).

Pearson's correlation analysis: The results were further confirmed with Pearson's correlation analysis. In weed free rice, a strong positive correlation was observed between all the yield and yield attributes at P=0.01 (**Table 5**). In rice, with the presence of *A. paronychioides*, a strong positive correlation was observed between number of seeds per panicle and yield at P=0.01. Similarly, plant height showed a positive correlation with yield and number of tillers per plant at P=0.05 (**Table 6**). In rice the presence of *L. chinensis,* PH showed a strong positive correlation with number of seeds per panicle and number of tillers per plant at P=0.01. Similarly, yield was

Table 3. Principal components showing the eigenvalues, the proportion of variation and principal component analysis for yield and yield attributes of rice in the presence of *A. paronychioides* under different environmental conditions (pooled data of two years)

Variable	PC1	PC2	PC3
PH	0.455	0.341	0.314
PL	-0.332	-0.305	0.786
NSP	0.397	-0.441	-0.378
NTP	0.507	-0.145	0.307
Yield	0.454	-0.381	0.181
TW	-0.251	-0.656	-0.121
Eigenvalue	3.4804	1.7890	0.7307
Proportion	0.580	0.298	0.122
Cumulative	0.580	0.878	1.000

PH = plant height, *PL* = panicle length, *NSP* = number of seeds per panicle, *NTP* = number of tillers per plant, *TW* = test weight

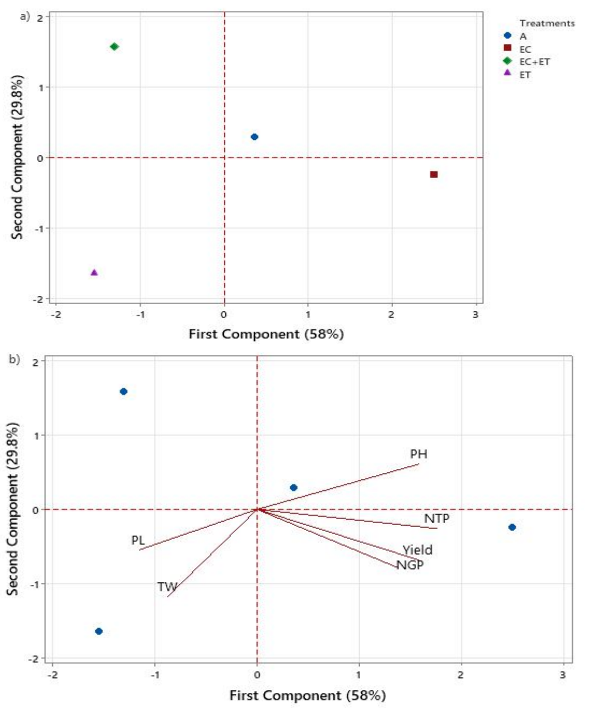


Figure 3. Score plot (a) and Biplot plot (b) analysis between various rice yield and yield attributes in the presence of *A. paronychioides* under different treatments. *PH* = plant height, *PL* = panicle length, *NSP* = number of seeds per panicle, *NTP* = number of tillers per plant, *TW* = test weight

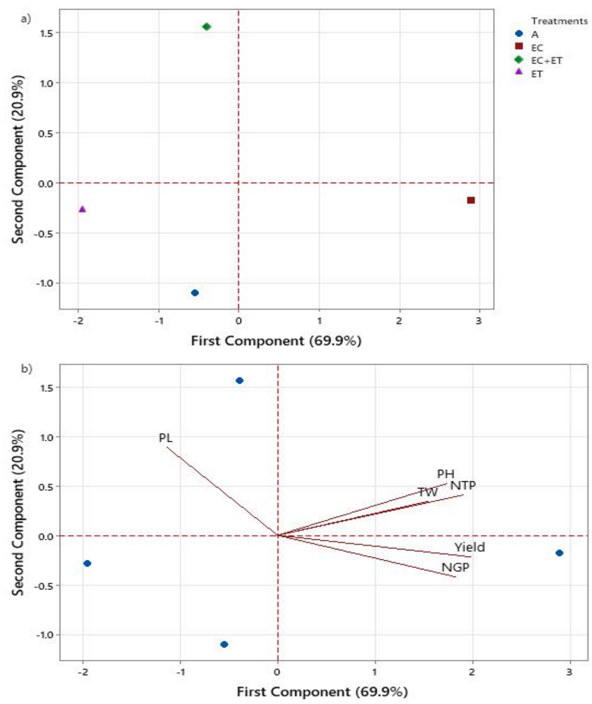


Figure 4. Score plot (a) and Biplot plot (b) analysis between various rice yield and yield attributes in the presence of *L. chinensis* different treatments. *PH* = plant height, *PL* = panicle length, *NSP* = number of seeds per panicle, *NTP* = number of tillers per plant, *TW* = test weight

Table 4. Principal components showing the eigenvalues, the proportion of variation and PCA for yield and yield attributes of rice in the presence of *L. chinensis* under different environmental conditions (pooled data of two years)

Variable	PC1	PC2	PC3
PH	0.414	0.417	0.343
PL	-0.271	0.710	0.327
NSP	0.437	-0.335	0.329
NTP	0.455	0.325	-0.033
Yield	0.472	-0.173	0.227
TW	0.368	0.273	-0.784
Eigenvalue	4.1934	1.2568	0.5498
Proportion	0.699	0.209	0.092
Cumulative	0.699	0.908	1.000

PH = Plant height, *PL* = Panicle length, *NSP* = Number of seeds per panicle, *NTP* = Number of tillers per plant, *TW* = Test weight

Table 5. Pearson's correlation coefficients of yield and yield attributes in weed free rice (pooled data of two years)

Attribute	PH	PL	NSP	NTP	YIELD	TW
PH	1					
PL	.757**	1				
NSP	.977**	.764**	1			
NTP	.758**	.817**	.787**	1		
YIELD	.594**	.565**	.604**	.574**	1	
TW	.851**	.579**	.820**	.675**	.658**	1

**. Correlation is significant at the 0.01 level (2-tailed).

PH = plant height, *PL* = panicle length, *NSP* = number of seeds per panicle, *NTP* = number of tillers per plant, *TW* = test weight

Table 6. Pearson's correlation coefficients of rice yield and yield attributes in the presence of *A. paronychioides* (pooled data of two years)

Attribute	PH	PL	NSP	NTP	Yield	TW
PH	1					
PL	-.071	1				
NSP	.290	-.081	1			
NTP	.534*	-.089	.480*	1		
Yield	.545*	.161	.647**	.327	1	
TW	-.500*	.293	.106	-.003	-.124	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

PH = plant height, *PL* = panicle length, *NSP* = number of seeds per panicle, *NTP* = number of tillers per plant, *TW* = test weight

positively correlated with number of seeds per panicle at P=0.05. However, panicle length showed a negative correlation with number of seeds per panicle p=0.01) and yield (p=0.05) (**Table 7**).

This study revealed that weed interference severely impaired rice grain yield and yield attributes under elevated CO_2 and temperature. It was also observed that the response of *A. paranochioides* was more under elevated CO_2 compared to *L. chinensis*. Elevated CO_2 had a positive effect on yield and yield attributes of weed free rice, whereas, elevated temperature had deleterious effect. Under the combined effect of elevated CO_2 and temperature the negative effect of elevated temperature was negated by elevated CO_2 in weed free rice.

Table 7. Pearson's correlation coefficients of rice yield and yield attributes in the presence of *L. chinensis* (pooled data of two years)

Attribute	PH	PL	NSP	NTP	Yield	TW
PH	1					
PL	.007	1				
NSP	.619**	-.593**	1			
NTP	.565**	-.034	.392	1		
Yield	.370	-.512*	.491*	.365	1	
TW	.534*	-.142	.284	.412	.209	1

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

PH = plant height, *PL* = panicle length, *NSP* = number of seeds per panicle, *NTP* = number of tillers per plant, *TW* = test weight

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RESEARCH ARTICLE

Variability in seed germination and dormancy of Indian weedy rice

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ABSTRACT

Seed dormancy is an adoptive trait of weedy rice to persist in rice production system. Weedy races and wild relatives of rice exhibit variation in seed dormancy, which allows weedy rice to escape weed management practices, and increases the flowering synchronization pattern resulting in gene flow between weedy and cultivated rice. In this study, eighteen weedy rice morphotypes collected from different rice growing areas in India, along with two rice cultivars, were evaluated for their germination pattern across time. Weedy rice seed germination was recorded periodically at weekly intervals up to 35 weeks after sowing (WAS) under controlled conditions. Dormancy duration was computed and germination index was calculated at 27 WAS. Significant variability was observed in germination pattern among the weedy rice morphotypes studied. The weedy rice morphotypes collected from Uttar Pradesh (T68) attained 50% germination after a maximum duration of 13.5 WAS, while five morphotypes of weedy rice remained ungerminated at 3 WAS. Seven weedy rice morphotypes germinated at 3 WAS at which both the rice cultivars (*BPT 5204* and *Pusa 1101*) have germinated (96.7 and 83.3%, respectively). Two weedy rice morphotypes had highest germination percentage (98.3%) at 35 WAS, while least (21%) was recorded with morphotype collected from Chhattisgarh (T41). This study indicated the existence of high degree of dormancy in weedy rice morphotypes. The findings of this study might be helpful for agronomists and farmers to develop and implement effective weedy rice management strategies at different rice production systems in India.

Keywords: Cultivated rice, Dormancy, Ecological variation, Germination, Morphotypes, Weed ecology, Weedy rice

INTRODUCTION

Rice is the major food and energy source for most of the world's population. In India, out of the total cultivated area of 143 mha, rice is cultivated in around 44.36 mha across the different agro-climatic zones. The transplanted rice production system is being used by farmers of the India and other Asian countries since many years (Ghosh *et al.* 2017**).** The puddled transplanted rice utilizes huge labour, water and energy (Rao *et al.* 2007, Mahajan *et al.* 2012) resources which are becoming increasingly rare and costly, thus making puddled transplanting less cost-effective (Rao *et al.* 2007, Mahajan *et al.* 2017). The transplanting practice also degrades the soil properties and adversely affects the productivity of succeeding upland crops. Thus, farmers are increasingly shifting from puddled transplanted rice to direct-seeded rice. Weeds are the major constraints in direct-seeded rice production system that affects plants growth and development as well as crop yield also (Rao *et al.* 2007, Ghosh *et al.* 2016). In direct-seeded rice (DSR), weedy rice (*Oryza sativa spontanea* f.) has become a menace in many DSR growing areas (Rao *et al.* 2007). About 5 to 60% of rice area among the different state of India was reported to be infested with weedy rice (Varshney and Tiwari 2005, Mishra *et al.* 2017). Weedy rice having attributes similar to cultivated and wild rice, regarded as biosimilar and therefore is difficult to manage. Characterization of functional traits of Indian weedy rice population from different agroclimatic zones revealed marked differences in morphological, growth and reproductive behavior (Rathore *et al.* 2016) with the ability to survive under water deficit and salt stress condition (Mishra *et al.* 2019). Weedy rice also possesses many adoptive characteristics including ability to germinate under flooding condition, high seed persistent in soil, seed dormancy, vigorous growth and greater nitrogen use efficiency for biomass production then cultivated rice

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(Rathore *et al.* 2013, Ghosh *et al.* 2017). Most of the weedy rice biotypes have colored pericarp which as contaminant of the final rice product reduce the market value (Cao *et al.* 2007). The adoptive characteristics variations existing in weedy rice population enable their wider adaptability to varied environmental conditions making its management in rice extremely difficult.

Among the weedy traits of weedy rice, seed dormancy is of major importance to its persistent infestation in rice. The seed dormancy in weedy rice may varies from few days to years depending upon its morphotype and storage condition (Gianinetti and Cohn 2008, Tseng *et al.* 2013). Xia *et al.* (2011) also reported about weedy rice morphotypes without having seed dormancy. The dormancy in weedy rice is only due to seed-covering-imposed dormancy, whereas, cultivated rice having seed-covering-imposed and embryo-imposed dormancy (Gu *et al.* 2003). Weedy rice seeds generally have higher seed longevity and remain viable over years that the cultivated rice. This is a challenge to farmers because such diversity allows weedy rice to escape and grow along with crop cultivar. The degree of seed dormancy also varied with ripening period, storage conditions, and genotype (Gianinetti and Cohn 2008). The research on variability of seed dormancy of weedy rice occurring in different rice production system of India is limited and needs to be evaluated. Hence, this study was undertaken with the objectives of evaluating the variation in the degree of seed dormancy of Indian weedy rice morphotypes collected from different agroclimatic zones of India along with rice cultivars.

MATERIALS AND METHODS

The collection of weedy rice morphotypes was done by extensive surveys in different agroclimatic zones of India *viz*. Upper Gangetic Plains Region, Middle Gangetic Plains Region, Lower Gangetic Plains Region, Central Plateau and Hills region, Eastern Plateau and Hills Region and Western Coastal Plains and Ghats Region. The survey covered total seven states, *viz*. Uttar Pradesh, West Bengal, Madhya Pradesh, Chhattisgarh, Jharkhand and Kerala. Eighteen weedy rice morphotypes were collected along with their GPS coordinates (**Table 1**) and were grown under field conditions along with two rice cultivars (*BPT 5204* and *Pusa 1101*) at the ICAR-Directorate of Weed Research (DWR), Jabalpur, Madhya Pradesh, India. The emerged panicles of each morphotypes were harvested before shattering. The harvested seeds were air dried and stored in cloth bag at room temperature for further experiments on dormancy profile. Experimental soil was collected from fields of the research farm and soil was sterilized and filtrated through a 3 mm sieve before use. The soil was clay loam containing 25, 26 and 49% silt, sand and clay, respectively.

The experiment was conducted in controlled conditions at net house during rainy season. Twenty seeds of each accession were placed in plastic pots (20 cm diameter and 2.2 cm height) filled with autoclaved soil and moistened with deionized water as per requirement. The pots were arranged in completely randomized design with three replicates. The germination was recorded periodically at weekly interval from first week after sowing (WAS) to thirty five WAS. The dormancy duration was computed as

Table 1. The weedy rice morphotypes samples collected agroclimatic zones and collection sites

Morphotype	Agroclimatic zones	Name of location/State	Longitude (N)	Latitude (E)
T21	Central Plateau and Hills	ICAR-DWR, Madhya Pradesh	$23^0$13′.45.6″N	$79^0$58′.17.9″E
T28	Central Plateau and Hills	Panagar, Madhya Pradesh	$23^0$16′04.0″N	$79^0$59′55.6″E
T30	Central Plateau and Hills	Panagar, Madhya Pradesh	$23^0$16′04.4″N	$79^0$59′53.6″E
T32	Central Plateau and Hills	Mehgawa, Madhya Pradesh	$23^0$19′05.9″N	$80^0$02′16.6″E
T34	Central Plateau and Hills	Mehgawa, Madhya Pradesh	$23^0$19′02.6″N	$80^0$02′22.2″E
T36	Eastern Plateau and Hills	Jharkhand	$23^0$14′51.6″N	$85^0$16′53.7″E
T39	Lower Gangetic Plains	West Bengal	$23^0$40′07.0″N	$87^0$38′25.0″E
T41	Eastern Plateau and Hills	Chhattisgarh	$21^0$13′31.4″N	$81^0$41′ 04.7″E
T42	Eastern Plateau and Hills	Chhattisgarh	$21^0$13′32.6″N	$81^0$41′01.8″E
T44	Central Plateau and Hills	Gwalior, Madhya Pradesh	$26^0$31′07.3″N	$78^0$00′10.5″E
T45	Central Plateau and Hills	Gwalior, Madhya Pradesh	$26^0$22′59.2″N	$78^0$18′24.5″E
T64	Middle Gangetic Plains	Bihar	$25^0$59′04.0″N	$85^0$39′32.6″E
T65	Upper Gangetic Plains	Uttar Pradesh	$26^0$38′44.0″N	$80^0$12′50.0″E
T68	Upper Gangetic Plains	Uttar Pradesh	$26^0$38′42.7″N	$80^0$12′49.3″E
T69	Upper Gangetic Plains	Uttar Pradesh	$27^0$11′43.0″N	$80^0$14′37.0″E
T75	Upper Gangetic Plains	Uttar Pradesh	$26^0$31′39.2″N	$79^0$49′53.8″E
T77	Western Coastal Plains and Ghats	Kerala	$10^0$45′52.8″N	$76^0$40′23.9″E
T79	Western Coastal Plains and Ghats	Kerala	$10^0$26′24.1″N	$76^0$10′06.3″E

the period from harvest till the maximum germination reached in each entry. No morphotype has germinated after 27 WAS. Therefore, germination index (GI) was calculated at 27 WAS by following formula as follows:

$$\text{Germination index (GI)} = \frac{n_1}{1} + \frac{n_2}{2} + \cdots + \frac{n_x}{x}$$

Where:

n_1 …….. n_x are the number of seeds germinated on day 1 to day x

1 …….... x are the number of days

The average of observations from three replications is presented. The dormancy profile of different weedy rice accessions and rice cultivars were analyzed using the general linear model procedure of the Statistical Analysis System (SAS Windows Version 9.4). Sample means of weedy rice accessions and rice cultivars were separated with the use of Tukey's Honest Significant Difference (HSD) test at a 5% level of significance. The cluster analysis of eighteen weedy rice morphotypes along with two rice cultivars was also done on the basis of their germination data at different WAS by using SAS 9.4. Dissimilarity coefficients were calculated using average linkage method of cluster analysis procedure.

RESULTS AND DISCUSSION

A significant variation was noticed in germination pattern among the 18 morphotypes of weedy rice and 2 rice cultivars at different times of the study (**Table 2**). Seven weedy rice morphotypes collected from Mehgawa, Madhya Pradesh; West Bengal; Chhattisgarh and Uttar Pradesh ('T32', 'T34', 'T39', 'T41', 'T65', 'T69' and 'T75') recorded less than 50% germination during the entire study period. The weedy rice morphotype of Uttar Pradesh (T68) recorded 50% germination at a maximum duration of 13.5 WAS, while 50% germination of five weedy rice morphotypes occurred at 1 to 1.33 WAS. The rice cultivar *BPT-5204* and *Pusa 1101* attained 50% germination at 1.33 and 2.00 WAS, respectively. The observed variation in dormancy amongst weedy rice morphotypes might be attributed to ecological conditions like temperature, moisture and other non-genetic and genetic factors (Toole *et al.* 1964). The variation in seed dormancy among the rice cultivars is due to the bred genetic characteristics (Wani *et al*. 2018, Sohn *et al*. 2021).

At 3 WAS, five morphotypes of weedy rice did not germinate while seeds of morphotypes from Eastern Plateau and Hills of Jharkhand (T-36) attained maximum germination up to 95%, while it

Table 2. The germination percentage pattern of weedy rice morphotypes and rice cultivars at different weeks after sowing (WAS)

Weedy rice morphotype accessions	50% germination at WAS	Germination (%) at 3 WAS	Germination (%) at 35 WAS	Maximum germination reached at WAS	Germination index at 27 WAS
T21 DWR	8.67	43.3[cd]	68.3[abc]	14.0[abcd]	4.25[fg]
T28 Panagar	1.00	81.7[ab]	81.7[ab]	3.00[cd]	6.65[cde]
T30 Panagar	1.00	88.3[a]	90.00[a]	3.33[cd]	7.29[bcd]
T32 Mehgawa	-	0.00[f]	28.3[cd]	25.7[a]	0.32[h]
T34 Mehgawa	-	26.7[def]	38.3[cd]	12.0[abcd]	2.39[gh]
T36 Jharkhand	1.33	95.0[a]	95.0[a]	2.00[d]	9.42[ab]
T39 West Bengal	-	0.00[f]	31.7[cd]	17.7[abc]	0.47[h]
T41 Chattishgarh	-	0.00[f]	21.7[d]	20.7[a]	0.30[h]
T42 Chattishgarh	2.00	85.0[ab]	96.7[a]	18.3[abc]	7.34[abcd]
T44 Gwalior	2.00	93.3[a]	96.7[a]	11.0[abcd]	8.34[abc]
T45 Gwalior	5.67	33.3[cde]	93.3[a]	16.0[abcd]	4.54[efg]
T64 Bihar	1.33	93.3[a]	98.3[a]	4.00[bcd]	9.49[a]
T65 Uttar Pradesh	-	6.67[ef]	45.0[bcd]	26.0[a]	0.95[h]
T68 Uttar Pradesh	13.50	15.0[ef]	65.0[abc]	19.0[ab]	2.39[gh]
T69 Uttar Pradesh	-	0.00[f]	46.7[bcd]	22.3[a]	1.01[h]
T75 Uttar Pradesh	-	0.00[f]	36.7[cd]	19.7[a]	0.59[h]
T77 Kerala	1.67	93.3[a]	98.3[a]	11.3[abcd]	9.38[ab]
T79 Kerala	3.00	60.0[bc]	91.7[a]	10.7[abcd]	5.79[def]
C2 BPT 5204	1.33	95.0[a]	96.7[a]	3.00[cd]	9.40[ab]
C10 Pusa Basmati 1101	2.00	80.0[ab]	83.3[ab]	3.67[bcd]	7.00[cd]
LSD (p=0.05)	-	15.0	22.4	8.25	1.17

was minimum (6.67%) in ‘T65’. Six morphotypes (T28, T30, T42, T44, T64 and T77) attained higher germination rate of 80 to 93% and five morphotypes (T21, T34, T45, T68 and T79) germinated ranging from 15 to 60% at 3 WAS when the rice cultivars, *BPT-5204* and *Pusa Basmati* attained germination 95 and 80%, respectively. The germination percentage attained by certain weedy rice morphotypes from Panagar, Madhya Pradesh; Jharkhand; Chhattisgarh; Gwalior, Madhya Pradesh; Bihar and Kerala (T28, T30, T36, T42, T44, T64 and T77) was similar to that of both rice cultivars at 3 WAS (**Table 2**).

Nine weedy rice morphotypes (T28, T30, T36, T42, T44, T45, T64, T77 and T79) had higher germination of 80 to 98% at 35 WAS at which two morphotypes (T21 and T68) germinated up to 68.3 and 65%, respectively. The germination percentage of the rest of the seven morphotypes (T32, T34, T39, T41, T65, T69 and T75) ranged from 21 to 46%. This variation may be due to the germination speed increase of red rice with the increment in temperature and changes in other climatic factors (Cho 2010). Weedy rice morphotype collected from Upper Gangetic Plains of Uttar Pradesh (T65) required longer time (26 weeks) for its maximum germination while four morphotypes of Eastern Plateau and Hills of Jharkhand, Central Plateau and Hills of Madhya Pradesh and Middle Gangetic Plains of Bihar (T36, T28, T30 and T64) required least time of 2.00, 3.00, 3.33 and 4.00 weeks, respectively for getting maximum germination. The rice cultivars *BPT-5204* and *Pusa 1101* have attained maximum germination at 3.00 and 3.67 WAS, respectively. The weedy rice morphotypes collected from different geographical location showed diversity in germination pattern, and morphotypes (T65, T68, T69 and T75) collected from same geographical location had more or less similar maximum germination time. The variability in seed dormancy among weedy rice was also observed by Rathanakumar *et al*. (2009), Wang *et al*. (2012), Gaikwad and Bharud (2016).

Significant variability in germination index (GI) of weedy rice morphotypes was observed in this study (**Table 2**). Among the tested entries, weedy rice morphotype ‘T64’ showed higher GI (9.49) over a period at 27 WAS. However, ‘T41’ morphotypes had lower GI (0.32). Seven weedy rice morphotypes (T28, T30, T36, T42, T44, T64 and T77) showed statistically similar GI to both rice cultivars. *BPT 5204* and *Pusa 1101* rice cultivars had GI of 9.40 and 7.00, respectively.

The cluster analysis of eighteen weedy rice morphotypes along with two cultivated rice was

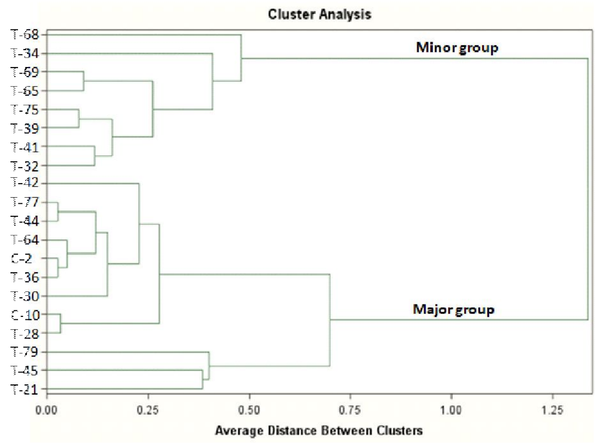

Figure 1. Cluster analysis of weedy rice morphotypes and rice cultivars on the basis of their seed germination data using dissimilarity coefficient

analyzed using their germination data at different WAS (**Figure 1**). In cluster analysis, there were two groups, *viz.* minor group of 8 morphotypes (T-68, T-39, T-69, T-65, T-75, T-39, T-41 and T-32) and major group of 12 morphotypes. Minor group did not include any cultivated rice members, and the morphotypes under this group showed very poor germination pattern during the course of observation. Major group was further divided into two sub-groups, *viz.* first sub-group of seven weedy rice morphotypes (T-42, T-77, T-44, T-64, T-36, T-30 and T-28) and two rice cultivars (C-2 and C-10), and second sub-group of three other weedy rice morphotypes (T-79, T-45 and T-21). In the first sub-group, weedy rice morphotypes showed promising germination pattern which was more similar to the rice cultivars. It was also noted that weedy rice morphotypes might be similar or dissimilar to that of rice cultivars. Variation in dormancy pattern in tested morphotypes might be due to genetic makeup of the seed (Wani *et al.* 2018, Sohn *et al.* 2021) or influence of the environment on the expression of the genetic capabilities (Klupczyñska and Paw³owski 2021). The impermeability of seed coat to water and the balance between the presence of germination inhibitors and promoters in the seed are also governing factor for seed dormancy.

Conclusions

The dormancy pattern of weedy rice varied as per their genetic make-up, regardless of their ecological requirements. The dormancy profile of weedy rice might be similar or dissimilar to the cultivated rice. This information will be helpful either to maintain a time lag for rice sowing as per production system or to follow suitable cultural methods for weedy rice management.

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RESEARCH ARTICLE

Management of weeds in transplanted rice with XR-848 benzyl ester + cyhalofop-butyl (ready-mix)

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ABSTRACT

A field experiment was conducted during rainy *(Kharif)* seasons of 2015 and 2016 at Agricultural Research Station, Dhadesugur, University of Agricultural Sciences, Raichur, Karnataka, India to evaluate the efficacy of XR-848 benzyl ester 20 g/l + cyhalofop-butyl 100 g/l EC (ready-mix) on weeds in transplanted rice. The dominant grassy weeds in the experimental field were: *Echinochloa colona, Panicum repens, Cynodon dactylon, Brachiaria mutica, Digitaria sanguinalis* and *Leptochloa chinensis*; broad-leaved weeds were: *Eclipta alba* and *Ludwigia parviflora* and the sedge was *Cyperus rotundus*. The post-emergence application (PoE) of XR-848 benzyl ester 20 g/l + cyhalofop butyl 100 g/l EC (ready-mix) 180 g/ha recorded significantly lower weeds biomass, higher weed control efficiency at 30, 45 and 60 days after transplanting (DAT) and higher rice grain yield during both the years and it was at par with XR-848 benzyl ester 20 g/l + cyhalofop butyl 100 g/l EC (ready-mix) 150 g/ha. The hand weeding twice at 20 and 40 DAT recorded significantly higher weed control efficiency and grain yield compared to other herbicide treatments.

Keywords: Cyhalofop-butyl, Transplanted rice, XR-848 benzyl ester, Weed management, Weed control efficiency

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important cereal crop grown in India as well as in Asia. It is being cultivated in the country over an area of 43.79 Mha with a production of 116.42 MT, which contributes to 40.86% of total food grain production of our country. The average productivity of rice in India is 2.66 t/ha (Anonymous 2020), which is lower than China and Egypt. In Karnataka, rice is cultivated in 0.99 Mha with a production of 4.53 MT and productivity of 4.56 t/ha (Pathak *et al*. 2020). The attainment of optimal productivity in rice is hindered by several factors, of which weeds are recognized as the major biological constraint. The yield loss caused by weeds resulted from their competition for growth factors, *viz.* nutrients, soil moisture, light, space, *etc.* (Walia 2006, Rao and Nagamani 2010). In order to achieve higher use efficiency of applied inputs, weeds must be kept below the economic threshold level through effective management practices (Rao *et al*. 2015). The optimal land preparation, effective water management and use of herbicides at correct dose and right time are often considered as cost-effective alternatives to manual weeding (Rao *et al*. 2017). This study was conducted to evaluate the efficacy of XR-848 benzyl ester 20 g/l + cyhalofop-butyl 100 g/l EC (ready-mix) in managing weeds and to increase the yield of transplanted rice.

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MATERIALS AND METHODS

An experiment was undertaken during rainy *(Kharif)* seasons of 2015 and 2016 at Agricultural Research Station, Dhadesugur, Raichur, Karnataka. The soil of the experimental site was medium deep black and neutral in pH (8.04) with an EC of 0.47 dS/m, medium in organic carbon content (0.41%), low in nitrogen (189 kg/ha), medium in phosphorus (58.5 kg/ha) and potassium (287.5 kg/ha). There were eight treatments, *viz.* post-emergence application (PoE) of XR-848 benzyl ester 20g/l + cyhalofop-butyl 100 g/l EC (w/v) (ready-mix) 120 g/ha; XR-848 benzyl ester + cyhalofop-butyl (ready-mix) 150 g/ha PoE; XR-848 benzyl ester + cyhalofop-butyl (ready-mix) 180 g/ha PoE; XR-848 benzyl ester 2.5 % EC (ready-mix) 31.25 g/ha PoE; cyhalofop-butyl 150 g/ha PoE; bispyribac-sodium 25 g/ha PoE; hand weeding twice at 20 and 40 days after transplanting (DAT) and weedy check. The size of each plot was 6 x 4 m (24

m^2) and the design followed for the experiment was randomized complete block design (RCBD) with three replications. All the herbicides were applied at 20 DAT using a knapsack sprayer fitted with a flat-fan nozzle at a spray volume of 500 l/ha.

The recommended dose of fertilizer (150:75:75 kg N:P:K/ha) was applied uniformly in three equal splits. Other agronomic and plant protection measures were followed as per the recommendation during the crop growth. The efficacy of different herbicides on weeds was evaluated at crop maturity. A quadrat of 0.25 m^2 was placed in each plot at random to estimate the weed density by counting the weeds within each plot of quadrat. The efficacy of weed control treatments was evaluated by comparing the density with the untreated control. Weeds were cut at ground level, washed with tap water, oven dried at 70 ^{0}C for 48 hours and then weighed for recording weed biomass. The weed control efficiency was calculated using the formula given by Tawaha *et al.* (2002). After harvest and threshing of crop, grain yield was recorded in the net plot and converted to grain yield per hectare. The data of each year was analyzed separately. Microcomputer Statistical Programme (MSTAT) was used for statistical analysis of data and means were separated using least significant difference (LSD) at p=0.05. The data on weeds were transformed by square root transformation by adding one before being subjected to ANOVA (Gomez and Gomez 1984).

RESULTS AND DISCUSSION

Effect on weed density and biomass

The weeds in experimental field were: *Echinochloa colona*, *Panicum repens, Cynodon dactylon, Leptochloa chinensis, Brachiaria mutica, Digitaria sanguinalis* among grasses; *Eclipta alba, Ludwigia parviflora* and *Commelina communis* among broad-leaved weeds and the sedge, *Cyperus rotundus*. The hand weeding twice at 20 and 40 DAT recorded significantly lower density of grasses, broad-leaved weeds and the sedge at 30, 45 and 60 DAT during both the years (**Table 1**). Among herbicide treatments, lower density and biomass of grasses, broad-leaved weeds and the sedge was observed with the application of XR-848 benzyl ester + cyhalofop butyl 180 g/ha PoE and was found on par with XR-848 benzyl ester + cyhalofop butyl 150 g/ha PoE in transplanted rice. The hand weeding twice and application of XR-848 benzyl ester + cyhalofop butyl (ready-mix) 180 g/ha PoE have recorded more than 80% weed control efficiency. The weedy check recorded significantly higher density of grasses, broad-leaved weeds and the sedge due to uncontrolled growth.

Similarly, the weed biomass was also influenced significantly by different weed management treatments. The hand weeding twice at 20 and 40 DAT recorded significantly lower weed biomass at 30, 45 and 60 DAT during both the years closely followed by XR-848 benzyl ester + cyhalofop-butyl 180 g/ha and XR-848 benzyl ester + cyhalofop-butyl 150 g/ha. The hand weeding twice at 20 and 40 DAT and application of XR-848 benzyl ester + cyhalofop butyl (ready-mix) 180 g/ha have recorded higher weed control efficiency due to lower weed biomass observed with these treatments as compared to other herbicide treatments and weedy check (**Table 2**). Similar results on WCE with broad-spectrum herbicides was reported by Abraham *et al.* (2010), Jabusch and Tjeerdema (2005), Jason *et al.* (2007), Mishra *et al.* (2007).

Table 1. Effect of weed control treatments on weed density in transplanted rice

Treatment	Weed density (no./m^2)																	
	Grasses						Broad-leaved weeds						Sedge					
	30 DAT		45 DAT		60 DAT		30 DAT		45 DAT		60 DAT		30 DAT		45 DAT		60 DAT	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
XR-848 benzyl ester + cyhalofop-butyl (ready-mix) 120 g/ha PoE	2.10 (3.41)	2.09 (3.36)	1.66 (1.77)	1.64 (1.68)	1.69 (1.85)	1.68 (1.83)	2.37 (4.62)	2.35 (4.54)	1.81 (2.26)	1.79 (2.22)	1.74 (2.02)	1.73 (2.00)	2.88 (7.31)	2.87 (7.21)	2.14 (3.56)	2.13 (3.52)	1.82 (2.33)	1.82 (2.32)
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 150 g/ha PoE	2.03 (3.13)	2.02 (3.08)	1.62 (1.62)	1.61 (1.59)	1.68 (1.81)	1.67 (1.78)	2.31 (4.33)	2.29 (4.24)	1.77 (2.12)	1.76 (2.09)	1.74 (2.02)	1.73 (2.01)	2.77 (6.67)	2.76 (6.61)	1.95 (2.79)	1.94 (2.76)	1.83 (2.34)	1.82 (2.31)
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 180 g/ha PoE	1.87 (2.51)	1.86 (2.46)	1.57 (1.48)	1.57 (1.46)	1.62 (1.64)	1.62 (1.63)	2.15 (3.64)	2.14 (3.59)	1.72 (1.96)	1.71 (1.94)	1.68 (1.82)	1.67 (1.80)	2.70 (6.29)	2.69 (6.26)	2.05 (3.20)	2.04 (3.16)	1.77 (2.15)	1.77 (2.14)
XR-848 benzyl ester 31.25 g/ha PoE	3.21 (9.29)	3.19 (9.20)	2.02 (3.07)	2.09 (3.35)	2.06 (3.26)	2.06 (3.24)	3.68 (12.5)	3.66 (12.4)	2.15 (3.63)	2.28 (4.19)	2.20 (3.86)	2.20 (3.84)	3.79 (13.4)	3.78 (13.3)	2.44 (4.95)	2.44 (4.93)	2.29 (4.26)	2.29 (4.25)
Cyhalofop-butyl 150 g/ha PoE	3.13 (8.81)	3.12 (8.72)	2.32 (4.36)	2.59 (5.71)	2.06 (3.25)	2.06 (3.24)	3.52 (11.4)	3.51 (11.3)	3.20 (9.23)	3.69 (12.6)	2.17 (3.72)	2.17 (3.70)	3.67 (12.5)	3.67 (12.5)	3.54 (11.5)	4.30 (17.5)	2.23 (3.99)	2.23 (3.97)
Bispyribac-sodium 25 g/ha PoE	2.18 (3.74)	2.16 (3.68)	1.76 (2.11)	1.75 (2.07)	1.77 (2.14)	1.77 (2.14)	2.43 (4.92)	2.42 (4.86)	1.90 (2.61)	1.89 (2.57)	1.82 (2.31)	1.82 (2.30)	2.93 (7.60)	2.91 (7.46)	2.22 (3.93)	2.21 (3.90)	1.91 (2.63)	1.90 (2.61)
Hand weeding twice at 20 and 40 DAT	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)	2.17 (3.70)	2.17 (3.70)	1.62 (1.64)	1.62 (1.62)	1.39 (0.93)	1.39 (0.93)
Weedy check	4.35 (17.9)	4.30 (17.5)	2.61 (5.80)	2.59 (5.73)	2.67 (6.12)	2.66 (6.10)	5.95 (34.4)	5.92 (34.0)	4.37 (18.1)	4.33 (17.8)	3.29 (9.85)	3.28 (9.79)	6.64 (43.1)	6.63 (42.9)	4.81 (22.1)	4.83 (22.3)	3.55 (11.6)	3.56 (11.7)
LSD (p=0.05)	0.21	0.20	0.08	0.05	0.05	0.04	0.21	0.20	0.07	0.05	0.04	0.04	0.15	0.15	0.06	0.07	0.03	0.03

Note: Figures in outside the parenthesis are square root transformed values (sq. root of x+1), DAT = days after transplanting; PoE = post-emergence application

Table 2. Effect of weed control treatments on total weed biomass and weed control efficiency in transplanted rice

Treatment	Total weed biomass (g/m^2)						Weed control efficiency (%)					
	30 DAT		45 DAT		60 DAT		30 DAT		45 DAT		60 DAT	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 120 g/ha PoE	3.94 (14.5)	3.81 (13.5)	4.69 (21.0)	4.49 (19.2)	5.22 (26.2)	5.24 (26.5)	80.1	81.8	81.3	83.0	82.9	82.8
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 150 g/ha PoE	3.66 (13.1)	3.66 (11.8)	4.42 (16.7)	4.42 (16.2)	4.85 (21.5)	4.85 (21.0)	82.0	84.0	85.1	85.7	85.9	86.4
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 180 g/ha PoE	3.16 (11.5)	3.16 (10.5)	4.15 (16.1)	4.15 (15.1)	4.38 (19.8)	4.38 (18.9)	84.2	85.8	85.7	86.6	87.0	87.7
XR-848 benzyl ester 31.25 g/ha PoE	4.72 (20.8)	4.72 (19.1)	4.94 (27.4)	4.94 (27.4)	6.16 (36.7)	6.16 (36.0)	71.4	74.1	75.6	75.9	75.9	76.7
Cyhalofop-butyl 150 g/ha PoE	4.16 (17.9)	4.16 (18.5)	4.65 (24.0)	4.65 (24.9)	6.00 (32.9)	5.92 (33.0)	78.2	75.0	78.7	78.1	78.4	78.6
Bispyribac-sodium 25 g/ha PoE	4.02 (15.9)	4.02 (16.6)	4.90 (23.3)	4.80 (24.3)	5.83 (31.3)	6.00 (31.8)	78.1	77.6	79.2	78.5	79.5	79.4
Hand weeding twice at 20 and 40 DAT	1.00 (0.0)	1.00 (0.00)	1.00 (0.0)	1.00 (0.00)	2.57 (5.4)	2.57 (5.40)	100	100	100	100	96.4	96.5
Weedy check	8.69 (72.8)	8.69 (74.0)	10.7 (112)	10.7 (113)	12.5 (153)	12.5 (154)	0	0	0	0	0	0
LSD (p=0.05)	0.52	0.56	0.34	0.36	0.61	0.57	-	-	-	-	-	-

Note: Figures in outside the parenthesis are square root transformed values (sq. root of x+1), DAT = days after transplanting; PoE = post-emergence application

Effect on rice grain yield

The herbicide treatments did not cause any phytotoxicity to transplanted rice. The maximum number of productive tillers/hills, grains/panicle and grain yield were recorded with hand weeding twice at 20 and 40 DAT followed by XR-848 benzyl ester + cyhalofop butyl (ready-mix) 180 g/ha and 150 g/ha (**Table 3**). The reduced competition due to weeds for growth resources throughout the critical growth resulted in the enhanced crop performance in the treatments effective to manage weeds. The weedy check recorded significantly lower number of productive tillers/hills, number of grains/panicle and grain yields due to extreme crop-weed competition caused by the excessive presence of weeds.

The higher rice crop growth and yield attributes achieved in effective herbicidal treatments was due to effective control of weeds as it is envisaged from negative correlation between grain yield and total weed biomass through correlation and regression analysis. There was negative correlation between grain yield and total weed biomass at 30 DAT (-0.975 and -0.978 during 2015 and 2016, respectively), 45 DAT (-0.968 and -0.973 during 2015 and 2016, respectively) and at 60 DAT (-0.963 and -0.967 during 2015 and 2016, respectively) as indicated from the regression studies. Whereas, there was positive correlation between grain yield and grains/panicle (0.936 and 0.939 during 2015 and 2016, respectively) indicating decrement of grain yield with increase in weed biomass and enhancement of grain yield with increase in grains/panicle of rice plants. The regression equations also indicated that, quantum of rice grain yield decrease with each g/m^2 increase in weed biomass was to the tune of 33.5 and 32.3 kg/ha at 30 DAT, 21.3 and 20.9 kg/ha at 45 DAT and 15.6 and 15.3 kg/ha at 60 DAT, in 2015 and 2016, respectively. The regression equations also revealed that with increase in number of grains/panicles would increase the grain yield of rice by 74 kg/ha and 70 kg/ha during 2015 and 2016, respectively. The results of the present study are indicative of the importance and significance of efficient weed management for enhancing growth and yield parameters of rice crop. These results are in conformity with the findings of Nithya *et al.* (2012), Raj and Syriac (2016).

The manual weeding was effective but being tedious, time consuming and expensive in large scale rice cultivation, farmers are increasingly looking for efficient herbicides for weed management in rice. It may be concluded that the post-emergence application of XR-848 benzyl ester 20 g/l + cyhalofop-butyl 100 g/l EC (w/v) (ready-mix) 150 g/ha was most effective in control of grassy weeds, broad-leaved weeds and the sedge and also recorded higher grain yield in transplanted rice.

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Table 3. Effect of weed control treatments on grain yield and yield parameters of transplanted rice.

Treatment	Productive tillers/ hill		Grains/ panicle		Grain yield (t/ha)	
	2015	2016	2015	2016	2015	2016
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 120 g/ha PoE	9.02	8.62	176	174	5.604	5.487
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 150 g/ha PoE	9.31	8.90	182	180	5.870	5.670
XR-848 benzyl ester + cyhalofop-butyl (ready- mix) 180 g/ha PoE	9.43	9.02	183	182	5.957	5.758
XR-848 benzyl ester 31.25 g/ha PoE	8.62	8.25	170	167	5.214	5.035
Cyhalofop-butyl 150 g/ha PoE	8.72	8.34	169	168	5.421	5.269
Bispyribac-sodium 25 g/ha PoE	8.79	8.41	173	170	5.504	5.451
Hand weeding twice at 20 and 40 DAT	9.63	9.21	189	186	6.319	6.134
Weedy check	7.93	7.59	159	155	3.814	3.662
LSD (p=0.05)	0.25	0.24	7.23	5.68	0.339	0.236

*PoE = post-emergence application

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RESEARCH ARTICLE

Harnessing the full potential of low-dose high-potency (LDHP) herbicide molecules by standardized spraying technique in rice and wheat

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ABSTRACT

Efficient and effective methods of weed control are needed to ensure higher crop productivity and profitability. Herbicides use is becoming popular amongst farmers because of ease, efficiency and lesser cost involved. The efficacy of herbicide depends on the proper spraying technique. Recently, the new generation effective low-dose high-potency (LDHP) herbicide molecules are being introduced but their compatibility to the existing spraying techniques and practices is unknown. Hence, it is necessary to standardize existing spraying technique for LDHP molecules. Thus, to standardize the existing spraying technique with two LDHP molecules (bispyribac-Na and clodinafop + metsulfuron), a field experiment was conducted for two years (2016-18) in rice during *Kharif* season and wheat *Rabi* season. The post-emergence (PoE) application of LDHP molecules, *viz*. bispyribac-Na at 25 g/ha in rice and clodinafop + metsulfuron at 60 + 4 g/ha in wheat were tested with flat fan (FF) and floodjet (FJ) nozzles using spraying volume of 250 and 500 l/ha. The weed control efficiency (WCE) obtained with different spray volume and nozzles usage was on par. The maximum WCE of 76% in rice and 89% in wheat was observed. A spray volume of 250 l/ha with either FF or FJ nozzle effectively controls the weeds and increases the field capacity by 60-100%.

Keywords: Bispyribac-Na, Clodinafop + metsulfuron, Low-dose high-potency (LDHP), LDHP herbicide, Rice, Spraying technique, Weed control efficiency, Wheat

INTRODUCTION

Weed control is one of the costliest and laborious practice in crop production (Rao and Nagamani 2010, Chethan and Krishnan 2017, Chethan *et al.* 2018a, Gharde *et al.* 2018, Singh *et al.* 2018). Chemical method of weed control in agriculture has become more popular because of its ease, efficient and effectiveness in controlling the weeds (Rao and Chauhan 2015, Chethan *et al.* 2019). Efficient and effective methods of weed control are the need of the hour as they invariably ensure higher crop productivity (Tewari and Chethan 2018, Kumar 2019). The usage of higher doses of the herbicides *i.e.* more than 1.0 kg/ha was a more common practice in chemical weed control during earlier days. Currently new generation low-dose-high-potency (LDHP) herbicide molecules are being introduced as they are effective and efficient in managing weeds control (Chethan *et al.* 2019) compared to higher dose molecules. In order to harness full potential of these molecules, their application must be accurate and uniform.

The selection of the pesticide spray application technique should be proper for the pesticide to be effective (Zhu *et al.* 2004). Spray nozzle used decides the spray quality, amount of spray applied per unit area, spray uniformity, spray coverage, amount of drift occurrences, application and pesticide efficacy (Grisso *et al.* 2013, Slocombe and Sharda 2015, Chethan *et al.* 2018b). A reliable uniform spray can be obtained in conventional flat fan (FF) nozzles at operating pressure of 140-420 kPa, but spray drift (Giles *et al.* 2002, Piggott and Matthews 1999) and requirement of proper spray overlap is a major problem. Thus, it is not recommended to use in single nozzle sprayers instead, even flat fan nozzles are recommended for the purposes as it produces uniform distribution of spray particles throughout spray pattern and spraying operation completed within a single pass. The flood nozzles are popular to apply the pesticides and fertilizers where clogging is a problem and it requires a hundred percent overlap and also special care has to be taken for nozzle orientation (Grisso *et al.* 2013, Slocombe and Sharda 2015, Chethan *et al.* 2018b). A perfect nozzle-pressure combination with proper amount of spray volume influences the spraying efficiency and

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herbicide efficacy (Smith *et al.* 2000). Using a spray volume of 400 to 500 liters per hectare for herbicide application is common practice followed in India. However, after introduction of LDHP herbicide molecules, no study as such was conducted with respect to standardizing the spraying techniques, spraying volume and nozzle types. Further, the suitability of existing spraying techniques to LDHP herbicide molecules is unknown. Thus, the trend of shifting the herbicide use from higher doses to LDHP molecules necessitates standardization of existing spraying technique. Hence, an experiment was carried out at Jabalpur to assess the suitability of popularly used knapsack sprayer for spraying LDHP herbicide molecules.

MATERIALS AND METHODS

A field experiment was conducted for two years during *Kharif* (rainy) and *Rabi* (winter) seasons of 2016-17 and 2017-18 in rice and wheat at ICAR - Directorate of Weed Research, Jabalpur (23°13'47.0"N 79°58'11.7"E). Soil properties of the study site had low organic carbon with clay loam texture and also had soil bulk density of ~1.3 g cm^{-2} with pH of 7.6. The study site was humid subtropical and had 1386 mm of annual rainfall and 1502 mm of evaporation.

The recommended LDHP molecules, *viz.* bispyribac-Na at 25 g/ha and clodinafop + metsulfuron at 60+4 g/ha was selected for rice and wheat, respectively as post-emergence (PoE) herbicides along with different nozzle types and spray volumes to standardize the spraying technique. Two nozzle types were studied, *viz.* even flat fan (FF) and floodjet (FJ) nozzles, which are recommended for the herbicide application (Anon 2015. Slocombe and Sharda 2015) along with two spray volumes of 250 and 500 l/ha. The experiment was conducted in split-split plot design and replicated thrice. The statistical analysis (ANOVA) of data was done using ICAR-IASRI, New Delhi online statistical portal (http://stat.iasri.res.in/SASLogon/index.jsp?_sasapp=Information+Delivery+Portal+4.3&). The main treatment includes the weed management practices, *viz.* PoE followed by (*fb)* one hand weeding (HW), PoE alone and weedy. The sub treatment includes nozzle type and sub-sub treatment includes the spray volume. A solar powered knapsack sprayer was used to maintain the uniform operating pressure during entire operation period. The detailed information of the selected nozzles for the study is given in **Table 1**.

The standardized spraying technique was compared with the conventional spraying method to obtain the operational difference. The different equations and parameters used for the comparison are given below and in **Table 2**.

Table 1. The characteristics of two nozzles studied in this experiment

Parameter	Nozzle type	
	Even flat fan	FloodJet
Cone angle, degrees	80^0	110^0
Discharge rate, liters per minute (lpm)	1.2	0.8
Spray releasing height, cm	50	50
Operating pressure, kPa	300	70
Droplet size, (v,0.5*) µm	236-340[ad]	341-403[ad]
Color code	Yellow[bc]	Blue[bc]
ASABE classification	Medium[c]	Coarse[c]
Body material	Brass	Brass

*Note: v,0.5: volume mean diameter (VMD)
(Source: Chethan *et al.* 2018b; BCPC; ASABE Standard S572.1; Department of Agriculture and Food, Govt. of Western Australia)

Table 2. Operational parameters of the spraying techniques

Parameter		Quantity
Sprayer used		Solar knapsack sprayer
Sprayer tank capacity, liters		16.0
Nozzle discharge rate, lpm	Flat fan	1.2
	FloodJet	0.8
Time required to spray 16 liters, minutes	Flat fan	13.3
	FloodJet	20
Time required from filling the tank to start the spray, minutes		7-10
Nozzle holding height above the ground level, meters		0.5

The spray operation was performed at morning hours (between 9-11 A.M.) to get the optimum spraying condition. The weather parameters *viz.* temperature, relative humidity (RH) and wind speed were not varied much during the respective seasons of both the years. A special care has taken to maintain the same operational parameters during respective seasons, as these parameters may affect the efficacy of herbicides, spray uniformity, drift potential, evaporation, degradation of the chemicals *etc.*

The effective field capacity (EFC) was calculated by using a following equation (Sarkar *et al.* 2016).

$$EFC = \frac{W \times S}{10} \times FE \qquad (1)$$

Where, W is the spray swath width in meter, S is the operator walking speed in kilometer per hour and FE is the field efficiency in percentage and it is considered 90% based on the previous studies for maximum output.

The weed control efficiency (WCE) was calculated by using the following equation (ISA 2009).

$$WCE = \frac{w_1 - w_2}{w_2} \times 100 \qquad (2)$$

Where, w_1 and w_2 are weed density in control and herbicide-treated plots, respectively.

The rice (cv. *Arize 6444 gold*) was dry-seeded at 25 kg/ha through Kamboj 11 tyne happy seeder under residue condition during last week of June and harvested in last week of October. In, wheat (cv. *GW-273*) was direct drilled at 100 kg/ha under residue condition during mid November and harvested during the first week of March. The recommended dose of fertilizers was maintained in both the crops and selected herbicides were applied as per the recommendations.

Bispyribac-Na in rice and clodinafop + metsulfuron in wheat were applied with proper precautions. The weed parameters such as weed density and weed dry biomass were recorded at 60 DAS by placing a quadrat having an area of 0.25 m^2 randomly at three different places within a plot. The year effect on the weed control was not significant, thus data's of different years were pooled.

RESULTS AND DISCUSSION

In rice, major weed flora observed were *Echinochloa crus-galli, Dinebra retroflexa, Alternanthera paronychioides, Physalis minima, Cyprus iria, Commelina benghalensis, Caesulia axillaris, Eclipta prostrata, Ludwigia prostrata* and others. However, it was observed a heavy infestation of *Echinochloa crus-galli* in both the years followed by *Alternanthera paronychioides* and others. In wheat, the major weed flora observed were *Medicago sativa, Chenopodium ficifolium, Avena fatua, Rumex dentatus, Chenopodium album, Sonchus Sp. Phalaris minor* and others. However, a heavy infestation of *Medicago sativa* mostly was observed in weedy plots. The recorded weed data in different years is given in the **Table 3** and **4**. The different weed management practices significantly affects the crop growth, weed control and grain yield. But the weed control efficiency was not significantly differed from nozzle types and spraying volumes (**Figure 1** and **2**). Treatments includes herbicide application *fb* one HW was more effective in controlling the weeds in both rice and wheat crops. Whereas in herbicide alone treatments, the scenario was totally different for both the crops. During *Kharif* season of 2016 and 2017 under rice the lowest weed density of 3.54 and 3.20 no./m^2, weed dry biomass of 3.83 and 3.73 g/m^2 and highest grain yield of 6.72 and 6.85 t/ha was recorded respectively in bispyribac-Na *fb* one HW (**Table 3**).

In *Rabi* (winter) season wheat, the lowest weed density of 2.36 no./m^2 and weed dry biomass of 2.11 g/m^2 was observed during 2016-17. The complete control of weeds was observed during 2017-18 with highest grain yield of 4.57 and 4.97 t/ha during 2016-17 and 2017-18 with clodinafop + metsulfuron *fb* one HW (**Table 4**). Similarly, the highest weed control efficiency was obtained in herbicide application followed by HW treatments for both the crops (**Figure 1** and **2**).

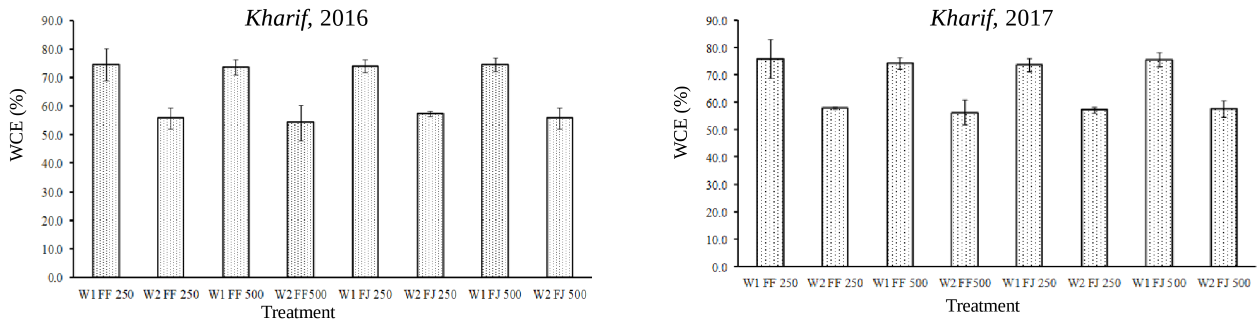
In *Kharif* (rainy) season weeds were suppressed initially after the application of herbicides [up to 15 days after application (DAA)]. However, during later period the regrowth of suppressed weeds started along with appearance of second flush of weeds due to seasonal favorability. Thus, the crop yield was slightly affected (**Table 3**) and weed control became problematic. Thus, the herbicide applied alone resulted in lesser crop yield and it can be managed by undertaking one hand weeding at 45-50 DAS. In *rabi* season the frequency and amount of weed appearance is very less, thus, an effective management of weeds and hundred percent weed control can be achieved by practicing herbicide application *fb* HW.

From the observed results it is evident that both the FF and FJ nozzle can be used at 250 and 500 l/ha of spraying volume per hectare to harness the full potential of bispyribac-Na and clodinafop +

Table 3. Weed density and biomass and grain yield of rice crop as influenced by different treatments during 2016 and 2017

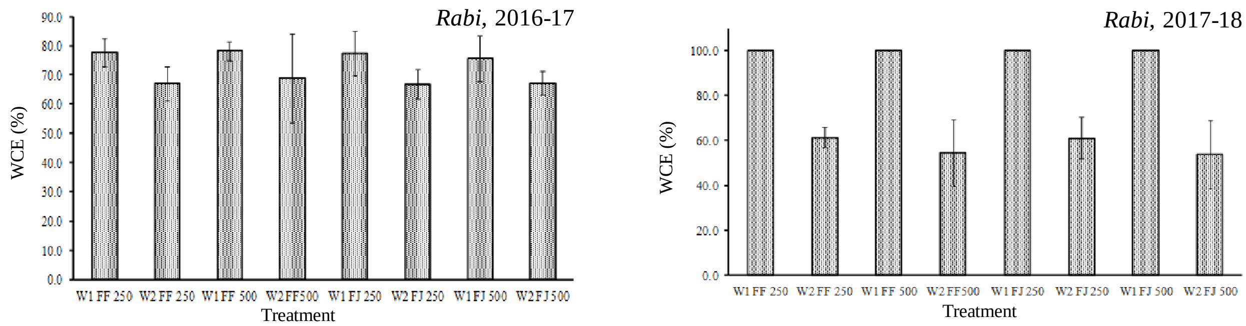
Treatment	Rice					
	Kharif, 2016			*Kharif*, 2017		
	Weed density (no./m^2)	Weed dry biomass (g/m^2)	Gain yield (t/ha)	Weed density (no./m^2)	Weed dry biomass (g/m^2)	Gain yield (t/ha)
Weed management						
Bispyribac (25 g/ha) + 1 HW	3.54^C	3.83^C	6.72^A	3.20^C	3.73^C	6.85^A
Bispyribac (25 g/ha)	5.73^B	6.58^B	6.06^B	5.58^B	6.38^B	6.08^B
Weedy check	7.63^A	14.98^C	4.81^C	7.74^A	15.00^A	4.85^C
LSD (p=0.05)	1.23	2.29	0.17	1.86	2.44	0.25
Nozzle type						
Flat fan	5.65	8.53	5.86	5.33	8.35	5.92
Floodjet	5.62	8.39	5.87	5.48	8.39	5.93
LSD (p=0.05)	NS	NS	NS	NS	NS	NS
Spraying volume (liter/ha)						
250	5.63	8.49	5.88	5.40	8.52	5.95
500	5.64	8.43	5.84	5.42	8.22	5.91
LSD (p=0.05)	NS	NS	NS	NS	NS	NS

*Weed data subjected to square root transformation



(W1 = Bispyribac (25 g/ha) + 1 HW; W2 = Bispyribac (25 g/ha); FF = Flat fan; FJ = Flood jet; 250 and 500 = Liters of water per ha)

Figure 1. Weed control efficiency (WCE) as influenced by different treatments in rice



(W1 = Clodinafop + metsulfuron (60+4 g/ha) + 1 HW; W2 = Clodinafop + metsulfuron (60+4 g/ha); FF = Flat fan; FJ = Flood jet; 250 and 500 = Liters of water per ha)

Figure 2. Weed control efficiency (WCE) as influenced by different treatments in wheat crop

Table 4. The weed density and biomass and grain yield of wheat crop as influenced by different treatments during 2016-17 and 2017-18

Treatment	Wheat					
	Rabi, 2016-17			*Rabi*, 2017-18		
	Weed density (no./m^2)	Weed dry biomass (g/m^2)	Gain yield (t/ha)	Weed density (no./m^2)	Weed dry biomass (g/m^2)	Gain yield (t/ha)
Weed management						
Clodinafop + metsulfuron (60+4 g/ha) + 1 HW	2.36^{B}	2.11^{B}	4.57^{A}	0^{C}	0^{C}	4.97^{A}
Clodinafop + metsulfuron (60+4 g/ha)	3.58^{B}	3.01^{B}	4.48^{A}	2.20^{B}	1.84^{B}	4.89^{A}
Weedy check	8.14^{A}	9.38^{A}	3.10^{B}	4.32^{A}	4.51^{A}	3.63^{B}
LSD (p=0.05)	1.98	1.57	0.67	0.22	1.43	0.23
Nozzle type						
Flat fan	4.59	4.83	4.14	2.18	2.08	4.56
Floodjet	4.80	4.83	3.96	2.17	2.15	4.42
LSD (p=0.05)	NS	NS	NS	NS	NS	NS
Spraying volume (liter/ha)						
250	4.77	4.74	3.98	2.21	2.10	4.48
500	4.62	4.93	4.12	2.14	2.13	4.50
LSD (p=0.05)	NS	NS	NS	NS	NS	NS

*Weed data subjected to square root transformation

metsulfuron (LDHP) molecules both in rice and wheat to manage weeds effectively. Even though, the rice and wheat yield with use of selected nozzle types and spraying volumes did not differ significantly results, but FF nozzle was slightly superior in terms of weed control and grain yield (**Table 3** and **4**). Further, the combination of either FF or FJ with spraying volume of 250 l/ha gave highest weed control efficiency of 76% in rice and 89% in wheat, which was either highest or equal to the results obtained in spraying volume of 500 l/ha during the year 2016 to 2018.

A comparison has been made with the existing spraying techniques with the standardized technique and given in Table 5. It has seen that, the existing spraying techniques obtained an actual field capacity of 0.07 to 0.09 ha/h with FF nozzle and 0.06 to 0.07 ha/h with FJ nozzle. The same results were also reported by Sharma and Mukesh (2013). Whereas, in standardized spraying techniques it has obtained an actual field capacity of 0.15 and 0.12 ha/h in FF and FJ nozzle respectively. This shows a decreased operational time and cost by 37.5 to 50% and an increased field capacity by 60 to 100%. Similarly, water required for spraying was also reduced from

Table 5. Comparison between conventional spraying and standardized spraying

Parameter	Flat fan nozzle		FloodJet nozzle	
	Conventional spraying	Standardized technique	Conventional spraying	Standardized technique
Spray volume used, l/ha	400 – 500	250	400–500	250
Number of tanks refill required per hectare, numbers	25–31.25 (approx. 32)	15.62 (approx. 16)	25–31.25 (approx. 32)	15.62 (approx. 16)
Time required for tank fill (approx. 10 minutes each time), minutes/ha	250 – 320	160	250–320	160
Time required to spay the solutions, minutes/ha	333.3–416.7	208.3	500.0–625.0	312.5
Total time includes filling spraying, minutes/ha	583.3–729.2 (9.7–12.2 hrs)	364.6 (6.1 hrs)	750.0–937.5 (12.5–15.6 hrs)	468.8 (7.8 hrs)
Field capacity, ha/hr	0.07–0.09	0.15	0.06–0.07	0.12
Operational cost per hectare based on the time required, `/ha	425–532	266	547–684	342
Percent increase in field capacity, %	-	60.0–100.0	-	60.0–100.0
Percent reduction in operational time and cost, %	-	37.5–50.0	-	37.5–50.0
Percent reduction in water required for spraying, %	-	37.5–50.0	-	37.5–50.0

37.5 to 50%. As the number of tank fills and operational time reduced in standardized spraying technique, which enhances the operator to work more efficiently by reducing the operational workload, human drudgery and physiological stress. The standardized spraying technique is also more useful and suitable to the places where water scarcity is a major problem and by adopting this technique an efficient weed control can be obtained. Therefore, presently using spraying volume of 500 l/ha can be shifted to standardized spraying technique *i.e.* 250 l/ ha with either FF or FJ nozzle, for spraying LDHP herbicide molecules, without compromising in weed control, crop yield and quality (Chethan *et al.* 2018b).

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RESEARCH ARTICLE

Wheat growth and physiological response and management of herbicide resistant *Phalaris minor* Retz. as affected by selective herbicides

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ABSTRACT

Weeds are a major constraint of wheat productivity improvement in India. Among the major weeds, *Phalaris minor* Retz. is the most problematic weed that mimics wheat. Herbicides are mostly used by farmers to manage weeds in wheat and dependency on single herbicide or herbicides with same mode of action resulted in the development of multiple herbicide-resistance in *P. minor*. A field study was conducted at CCS Haryana Agricultural University, Hisar during 2016-17 and 2019-20 with an objective to study the growth and physiological response of wheat and management of herbicide-resistant *P. minor* with selective herbicides in wheat. The sequential application of tank-mix (TM) pre-emergence application (PE) of pendimethalin + pyroxasulfone (1500 + 102 g/ha) or pendimethalin + metribuzin (1000 + 175 g/ha) followed by post-emergence application (PoE) of pinoxaden 60 g/ha or mesosulfuron + iodosulfuron 14.4 g/ha resulted in complete control of herbicide- resistant *P. minor* and other broad-leaved weeds (BLW). The better control of weeds resulted in higher wheat leaf area index (LAI) and crop growth rate (CGR) with 43-46% higher wheat grain yield over the weedy check. However, 0-9% visual toxicity on the crop was observed in metribuzin-associated treatments, which was nullified with the advancement of crop stage. The maximum marginal benefit was observed in weed-free check (39,192 ₹/ha) closely followed by pendimethalin + pyroxasulfone (TM) PE *fb* mesosulfuron + iodosulfuron PoE, while marginal benefit-cost ratio (MBCR) was highest with mesosulfuron + iodosulfuron (17.8) PoE followed by pinoxaden + metribuzin (50+150 g/ha) PoE. It was concluded that sequential application of PE followed by PoE herbicide with a rotational application of herbicides having different mode of action is suitable for management of herbicide-resistant *P. minor* in wheat.

Keywords: Herbicide-resistance, *Phalaris minor*, Physiology, Weed management, Wheat

INTRODUCTION

Wheat (*Triticum aestivum* L.) is the second most important food grain crop after rice in India with an area of 31.4 Mha with production of 107.9 MT and average productivity of 3440 kg/ha (INDIASTAT 2022a). Haryana is one of the major wheat-growing states of India, comprising an 8% wheat area, 12.3% share in national wheat production having a productivity of 4687 kg/ha (INDIASTAT 2022b). The rice-wheat cropping system has possessed diverse weed flora, which if not managed during the critical crop growth period, results in wheat crop yield reduction of 15-40% or even higher (Soni *et al.* 2021). Among all weeds, *Phalaris minor* Retz. (littleseed canarygrass) is the most problematic annual grassy weed which mimics the wheat crop.

Herbicide-resistant *P. minor* was found susceptible to pre-emergence (PE) herbicides (Dhawan *et al.* 2012) but is not enough to control all weeds and their cohorts. One of the best ways to manage resistance in *P. minor* is the use of herbicides with different modes of action (MOAs) in a sequential application of pre-emergence (PE) herbicide followed by post-emergence (PoE) (Dhawan *et al.* 2012). However, some herbicides like metribuzin and their combinations were found phytotoxic to the wheat crop (Punia *et al.* 2017b) with crop recovery in time. Thus, an experiment was conducted to study growth and physiological response of wheat against selective herbicides while assessing their efficacy in managing herbicide-resistant *P. minor* in wheat.

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MATERIALS AND METHODS

A field experiment was conducted at Agronomy Research Farm, CCS HAU, Hisar (29°8'56.62"N latitude and 75°41'4.24"E longitude) in *Rabi* (winter) season 2016-17 and 2019-20. This field has a history of poor control of *P. minor* with clodinafop. There were 16 treatments, *viz*. pendimethalin 1500 g/ha PE, metribuzin 210 g/ha PE, pendimethalin + metribuzin tank mix (TM) 1500 + 175 g/ha PE, pendimethalin + metribuzin (TM) 1000 + 175 g/ha PE followed by (*fb*) pinoxaden (60 g/ha) PoE, pendimethalin + metribuzin (TM) 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron ready mix (RM) 14.4 g/ha PoE, pendimethalin + pyroxasulfone (TM) 1500 + 102 g/ha PE, pendimethalin + pyroxasulfone TM 1500 + 102 g/ha PE *fb* pinoxaden 60 g/ha PoE, pendimethalin + pyroxasulfone (TM) 1500 + 102 g/ha PE *fb* mesosulfuron + iodosulfuron (RM) 14.4 g/ha PoE, pendimethalin + metribuzin (TM) 1500 + 175 g/ha pre-sowing application (PS) *fb* pinoxaden 60 g/ha PoE, pre-irrigation (PI) application of sulfosulfuron 25 g/ha PoE *fb* pinoxaden 60 g/ha PoE, pinoxaden 60 g/ha PoE, pinoxaden + metribuzin (TM) 50+120 g/ha PoE, pinoxaden + metribuzin (TM) 50+150 g/ha PoE, mesosulfuron + iodosulfuron (RM) 14.4 g/ha PoE, weed free and weedy check. A randomized block design (RBD) with three replications was used. Each plot size was 6 × 6 m. PE herbicides were sprayed just after sowing of wheat seeds, and PoE were applied at 35 days after sowing (DAS) of wheat and PI at 18 DAS. The hand weeding was done in weed-free whenever required in crop season and no weed management was done in weedy check.

The data on crop visual phytotoxicity of herbicides (%) was recorded at 15 and 45 DAS on a 0-100 scale (0 mean no mortality and 100 indicates complete crop failure). Leaf area index (LAI) was estimated at 90 and 120 DAS. Crop growth rate (CGR; g/m^2/day) was estimated at 30 days interval between 30-60, 60-90 and 90-120 DAS by using formula given below:

$$CGR = \frac{W_2 - W_1}{P\ (t_2 - t_1)}$$

Where, W_2 and W_1 are the dry weight of the crop at time t_2 and t_1, respectively and P is the ground area occupied by the plant in m^2.

The membrane injury to crop by herbicide and biotic stress measured as per cent proportion of ions leakage into an aqueous solution to total ions concentration of the stressed tissue as measured by electrical conductivity (EC) of the external medium. Sample of 200 mg of fresh leaf was kept in 20 ml test tube containing 10 ml distilled water for 5 hr at 27^{0}C. Then EC of this aqueous solution was measured by EC meter and represented as EC_1. Then same samples were kept in water bath at 100^{0}C for 50 min. After cooling, EC of solution was again measured and represented as EC_2. It was recorded at 60 and 90 DAS.

$$\text{Membrane injury index (MII) (\%)} = \frac{EC_1}{EC_2} \times 100$$

$$\text{Membrane stability index (MSI) (\%)} = \left(1 - \frac{EC_1}{EC_2}\right) \times 100$$

Total chlorophyll content (mg/g fresh weight) was estimated at 60 and 90 DAS. Sample of 50 mg of freshly harvested leaf tissue was placed in a test tube containing 5 ml of dimethyl sulfoxide (DMSO) at room temperature overnight till the tissue became colourless. The extracted chlorophyll in DMSO was assessed by recording its absorbance at the wavelength of 663 and 645 nm, respectively on Eppendorf BioSpectrometer® basic. DMSO was used as blank. It was calculated from the formula suggested by Hiscox and Israelstam 1979.

$$\text{Total Chlorophyll} = (20.2\ A_{645} + 8.02\ A_{663}) \times \text{dilution factor}$$

$$\text{Dilution factor} = \frac{V}{W \times 1000}$$

Where, V is volume of extract (ml) and W is fresh weight (FW) of sample (g)

Visual control of weeds (*P. minor* and broad-leaved weeds) was recorded 30, 90 and 120 DAS. It was evaluated on 0-100 per cent scale (0 means no control and 100 indicate complete control of weeds). The data of visual control from each treatment was estimated by comparing with the weedy check (control). Dry weight of weeds (biomass) was taken at 90 DAS from four randomly selected places from each plot using a quadrat. Individual weeds were first sundried followed by oven dried at 65±5 ^{0}C till a constant weight was achieved and finally biomass was expressed as g/m^2. The wheat grain yield (t/ha) was measured from net plot area using standard procedures. Marginal benefit-cost ratio (MBCR) was calculated by dividing marginal benefit to marginal cost incurred from different treatments over control (unweeded check).

$$MBCR = \frac{\text{Marginal benefit due to treatment over control (₹/ha)}}{\text{Marginal cost due to treatment over control (₹/ha)}}$$

The data were subjected to statistical analysis by Analysis of Variance (ANOVA) using OPSTAT software (Sheoran *et al*. 1998). The response of different treatments was similar during both the years and followed the homogeneity test; data were pooled for statistical analysis. The significance of the different treatment effects was tested with help of "F" (variance) test, least significant difference (LSD) was tested at 5% level of significance.

RESULTS AND DISCUSSION

Effect on wheat morpho-physiology

The metribuzin, as a component of herbicide combinations tested, caused visual phytotoxicity ranging from 5-9% at 15 DAS and 1.5-5.5% at 45 DAS (**Table 1**). Metribuzin PE caused higher visual phytotoxicity than TM combination with other herbicides and with the advancement of crop growth stage, visual symptoms on crop phytotoxicity got recovered as observed by Punia *et al*. (2017a). Significantly higher LAI of 5.03 and 3.12 at 90 and 120 DAS was recorded in weed-free check. This was at par with TM pendimethalin + pyroxasulfone PE *fb* mesosulfuron + iodosulfuron PoE in both the stages and it was statistically similar with most of the treatments except a few treatments including sole applied PE herbicides and its TM combinations. The effective weed control by sequentially applied herbicides resulted in the least crop weed competition producing more healthy leaves leading to higher LAI value (Sattar *et al*. 2010). CGR is the measure of dry matter accumulation by crop per unit leaf area per unit time. The CGR was low in the beginning, increased up to 90 DAS and decreased thereafter in all treatments. The significantly highest CGR value of 7.97, 24.73 and 15.46 g/m^2/day during 30-60, 60-90 and 90-120 DAS intervals, respectively was obtained in TM pendimethalin + pyroxasulfone (PE) *fb* mesosulfuron + iodosulfuron PoE, which were statistically similar to weed-free check. Lower CGR was observed in herbicides applied alone either as PE or PoE, when compared to their sequential application. The broad-spectrum weed control by sequentially applied herbicides helped in better crop growth, leading to higher dry matter accumulation and CGR. Similar findings were reported by Yadav and Choudhary (2015).

Ion's leakage from leaves was calculated as MII and MSI. Membrane injury index (MII) increased gradually from 60 to 90 DAS (**Table 1**). At 60 DAS, TM pendimethalin + pyroxasulfone PE *fb* pinoxaden PoE recorded significantly highest MII (66.8%). At 90 DAS, sulfosulfuron PI *fb* pinoxaden PoE recorded significantly higher MII (82.9%) that was statistically similar to almost all the treatments having pinoxaden and/or pyroxasulfone as a component herbicide. Whereas, significantly lowest MII was recorded in weed-free check (69.7%) at par with almost all PE treatments. The reverse was true for MSI. Stress caused by weed infestation and herbicide application with sequential application of higher dose of herbicides led to an increase in MII (Sairam *et al*. 2001). However, it declined with the advancement of crop age, while, stress-induced by weed infestation increased with an increase in weed density and dry biomass. The average increase in MII due to weeds infestation in weedy check was 21.1 and 13.5% higher than weed-free check at 60 and 90 DAS, respectively. Dhawan *et al*. (2010a) also stated that

Table 1. Effect of different treatments on physiological response of wheat crop at different growth stages (pooled data of two years)

Treatment	Phytotoxicity (%)		LAI		CGR (g/m^2/day)			MII (%)		MSI (%)		Total chlorophyll (mg/g FW)	
	15 DAS	45 DAS	90 DAS	120 DAS	30-60 DAS	60-90 DAS	90-120 DAS	60 DAS	90 DAS	60 DAS	90 DAS	60 DAS	90 DAS
Pendimethalin 1500 g/ha PE	0	0	4.42	2.78	6.71	20.93	11.78	56.9	70.2	43.1	29.8	2.60	2.73
Metribuzin 210 g/ha PE	9	4	4.30	2.69	6.44	20.38	11.82	58.7	72.3	41.3	27.7	2.57	2.63
Pendimethalin + metribuzin 1500 + 175 g/ha PE	7	2	4.47	2.82	7.14	21.93	12.68	54.8	73.8	45.2	26.2	2.92	2.92
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	5	1.5	4.55	2.93	7.18	22.49	12.90	54.3	73.6	45.7	26.4	2.84	3.00
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	5	1.5	4.79	3.11	6.74	23.54	13.99	51.6	80.1	48.4	19.9	3.13	3.42
Pendimethalin + pyroxasulfone 1500+102 g/ha	0	0	4.50	2.92	6.85	21.79	12.84	66.6	79.8	33.4	20.2	2.90	2.83
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	0	0	4.85	2.96	7.58	23.23	12.97	66.8	79.6	33.2	20.4	3.04	3.14
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	0	0	4.97	3.11	7.97	24.73	15.40	56.1	77.3	43.9	22.7	2.93	3.03
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	8	4	4.62	2.91	6.79	22.40	12.91	62.3	78.0	37.7	22.0	2.64	2.63
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	0	0	4.75	3.04	6.89	22.37	13.73	66.2	82.9	33.8	17.1	2.77	2.84
Pinoxaden 60 g/ha PoE	0	0	4.51	2.87	6.78	21.37	12.54	60.2	79.2	39.8	20.8	2.33	2.67
Pinoxaden + metribuzin 50+120 g/ha PoE	0	4.5	4.69	2.96	7.06	20.53	12.87	60.9	75.9	39.1	24.1	2.24	2.19
Pinoxaden + metribuzin 50+150 g/ha PoE	0	5.5	4.66	2.98	7.21	20.76	13.00	62.7	81.4	37.3	18.6	2.62	2.70
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	0	0	4.79	3.05	7.14	21.07	13.20	54.7	78.1	45.3	21.9	2.76	2.97
Weed-free check	0	0	5.03	3.12	7.71	24.55	15.46	46.9	69.7	53.1	30.3	3.02	3.10
Weedy check	0	0	4.06	2.57	6.26	19.38	10.45	56.8	79.1	43.2	20.9	2.29	2.50
LSD (p=0.05)	-	-	0.37	0.21	1.02	2.03	2.57	9.1	5.9	9.1	5.9	0.61	NS

PE = pre-emergence, PoE = post-emergence, PS = prior to sowing and PI = prior to irrigation, TM = tank mixed, RM = ready mix, LAI = Leaf area index, CGR = Crop growth rate, MII = Membrane injury index, MSI = Membrane stability index ions leakage from leaves after herbicide spray was relatively higher than unsprayed leaves and higher in ACCase herbicides. None of the treatments tested had a significant effect on total chlorophyll content of wheat at 90 DAS. Higher chlorophyll values were recorded in weed-free check followed by herbicidal treatments, whereas, lower value was recorded in weedy check and pinoxaden + metribuzin PoE. In spite of selectivity of herbicides to wheat, some of the herbicides may reduce the chlorophyll and carotenoids of wheat (Agostinetto *et al.* 2016). The decrease in chlorophyll content by different herbicides in wheat for a limited time was reported (Dhawan *et al.* 2010b, Kaur *et al.* 2016, Prinsa *et al.* 2018).

Effect on weeds

Visual control of weed (*P. minor* and BLW) was recorded at 30, 90 and 120 DAS on a 0-100 scale (**Table 2**). Pendimethalin and metribuzin PE, applied alone caused <80% control of *P. minor* at 30 DAS while tank-mixed (TM) application of pendimethalin with metribuzin or pyroxasulfone PE resulted in increased *P. minor* control efficiency up to 91%. The efficacy of pendimethalin + pyroxasulfone TM PE was better than pendimethalin + metribuzin (TM) PE. At 90 and 120 DAS, pendimethalin + metribuzin (TM) PE resulted in <70% control while its sequential application with pinoxaden or mesosulfuron + iodosulfuron PoE resulted in 90-93 and 100% control of *P. minor*, respectively. Similarly, pendimethalin + pyroxasulfone (TM) PE recorded <85% and its sequential application with pinoxaden or mesosulfuron + iodosulfuron PoE resulted in nearly complete control of *P. minor*. At 30 DAS, visual control of BLW indicated that pendimethalin, metribuzin, TM pendimethalin + pyroxasulfone PE and sulfosulfuron PI recorded 68, 63, 65-68 and 56% control, respectively. Whereas, pendimethalin + metribuzin (TM) PE at different doses resulted in 82-85% control of BLW. At 90 and 120 DAS, pendimethalin + metribuzin (TM) (PE) *fb* mesosulfuron + iodosulfuron PoE and pendimethalin + pyroxasulfone (TM) (PE) *fb* mesosulfuron + iodosulfuron PoE caused complete control of BLW. Similarly, maximum reduction in *P. minor* biomass (complete control) was caused by pendimethalin + pyroxasulfone PE *fb* mesosulfuron + iodosulfuron or pinoxaden PoE. Concerning BLW, among herbicidal treatments significant reduction in biomass accumulation was recorded under pendimethalin + pyroxasulfone (TM) (PE) *fb* mesosulfuron + iodosulfuron PoE (96.6%). Yadav *et al.* (2016) reported that sequential application of pendimethalin with PoE herbicides could effectively control weeds. Pinoxaden provided 90-100% control of resistant *P.*

Table 2. Effect of different treatments on visual control of weeds at different stages and their dry matter production at 90 DAS (pooled data of two years)

Treatment	*P. minor* (%)			BLW (%)			*P. minor* biomass (g/m^2)	BLW biomass (g/m^2)
	30 DAS	90 DAS	120 DAS	30 DAS	90 DAS	120 DAS	90 DAS	90 DAS
Pendimethalin 1500 g/ha PE	77	55	55	68	70	70	5.1(24.6)	2.8(6.7)
Metribuzin 210 g/ha PE	65	43	40	63	52	50	5.8(32.4)	3.6(11.9)
Pendimethalin + metribuzin 1500 + 175 g/ha PE	85	68	68	85	77	75	4.0(15.0)	2.3(4.3)
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	80	93	90	82	70	75	2.0(2.9)	2.6(5.8)
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	81	100	100	84	100	100	1.4(0.8)	1.3(0.6)
Pendimethalin + pyroxasulfone 1500+102 g/ha	91	85	83	68	70	77	2.6(5.9)	2.9(7.5)
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	89	100	99	69	72	77	1.2(0.4)	2.7(6.4)
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	90	100	100	65	100	100	1.0(0.0)	1.2(0.5)
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	80	95	96	86	70	75	1.7(1.8)	2.8(7.2)
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	46	88	94	56	81	86	1.4(0.9)	2.6(5.8)
Pinoxaden 60 g/ha PoE	0	77	72	0	22	25	1.9(2.7)	4.2(16.4)
Pinoxaden + metribuzin 50+120 g/ha PoE	0	83	80	0	83	89	2.0(3.0)	2.3(4.5)
Pinoxaden + metribuzin 50+150 g/ha PoE	0	86	83	0	90	93	1.9(2.5)	2.0(3.0)
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	0	90	91	0	93	95	1.7(1.8)	1.8(2.4)
Weed-free check	100	100	100	100	100	100	1.0(0.0)	1.0(0.0)
Weedy check	0	0	0	0	0	0	6.8(45.5)	4.8(21.7)
LSD (p=0.05)							0.3	0.3

PE: pre-emergence, PoE: post-emergence, PS: prior to sowing and PI : prior to irrigation, TM: tank mixed, RM: ready mix, BLW: Broad-leaved weeds; Data given in parentheses are original values, and outside are square-root transformed value *minor* population (Singh *et al*. 2010) and pyroxasulfone best suited against grassy weeds including resistant grassy weeds (Walsh *et al.* 2011). Punia *et al*. (2018) observed only <35% control of *P. minor* by pendimethalin or metribuzin PE, and their combination could not control second and further flushes of weeds.

Effect on wheat yield

The highest grain and biological yield were recorded in weed-free which was statistically at par with pendimethalin + pyroxasulfone (TM) PE *fb* mesosulfuron + iodosulfuron PoE, pendimethalin + metribuzin (TM) PE *fb* mesosulfuron + iodosulfuron PoE and mesosulfuron + iodosulfuron PoE and least in weedy check during both the years (**Table 3**). The beneficial effect of herbicide mixture and their sequential application for management of resistant *P. minor* and higher grain and biological yield comparable to weed-free have was reported by Yadav *et al*. (2016), Punia *et al*. (2020) and Soni *et al*. (2021).

Marginal benefit-cost ratio (MBCR)

The higher marginal benefit was recorded in weed-free (39,192 ₹/ha) which was closely followed by pendimethalin + pyroxasulfone (TM) PE *fb*

Table 3. Effect of different treatments on grain and biological yield

Treatment	Grain yield (t/ha)			Biological yield (t/ha)		
	2016-17	2019-20	Pooled	2016-17	2019-20	Pooled
Pendimethalin 1500 g/ha PE	4.98	4.47	4.72	10.60	9.67	10.13
Metribuzin 210 g/ha PE	4.58	4.27	4.43	10.15	9.39	9.77
Pendimethalin + metribuzin 1500 + 175 g/ha PE	5.28	4.74	5.01	11.30	10.28	10.79
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	5.56	4.93	5.25	11.89	10.57	11.23
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	6.15	5.37	5.76	12.80	11.22	12.01
Pendimethalin + pyroxasulfone 1500+102 g/ha	5.09	4.58	4.84	10.78	9.70	10.24
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	5.78	5.13	5.45	12.14	10.87	11.50
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	6.28	5.45	5.87	13.09	11.36	12.22
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	5.43	4.98	5.20	11.44	10.53	10.98
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	5.76	5.01	5.39	12.07	10.59	11.33
Pinoxaden 60 g/ha PoE	5.31	4.64	4.97	11.29	9.96	10.63
Pinoxaden + metribuzin 50+120 g/ha PoE	5.63	4.91	5.27	12.13	10.80	11.60
Pinoxaden + metribuzin 50+150 g/ha PoE	5.71	5.16	5.44	12.26	11.14	11.70
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	5.93	5.26	5.59	12.61	11.24	11.93
Weed-free check	6.32	5.57	5.95	13.13	11.58	12.36
Weedy check	4.14	3.91	4.02	9.26	8.76	9.01
LSD (p=0.05)	0.45	0.41	0.40	1.04	0.88	0.89

PE: pre-emergence, PoE: post-emergence, PS: prior to sowing and PI: prior to irrigation, TM: tank mixed, RM: ready mix, BLWs: Broad-leaved weeds; Data given in parentheses are original values, and outside are square-root transformed value

Table 4. Effect of different weed control treatments on marginal-benefit, cost and marginal BC ratio of wheat (pooled data of two years)

Treatment	Marginal benefit (₹/ha)	Marginal cost (₹/ha)	Marginal benefit-cost ratio
Pendimethalin 1500 g/ha PE	13,861	1,900	7.4
Metribuzin 210 g/ha PE	8,462	1,063	8.0
Pendimethalin + metribuzin 1500 + 175 g/ha PE	20,402	2,494	8.2
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* pinoxaden 60 g/ha PoE	25,231	4,312	5.9
Pendimethalin + metribuzin 1000 + 175 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	35,272	3,839	9.3
Pendimethalin + pyroxasulfone 1500+102 g/ha	15,802	3,900	4.1
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* pinoxaden 60 g/ha PoE	29,185	6,035	4.9
Pendimethalin + pyroxasulfone 1500+102 g/ha PE *fb* mesosulfuron + iodosulfuron 14.4 g/ha PoE	37,478	5,562	6.8
Pendimethalin + metribuzin 1500 + 175 g/ha PS *fb* pinoxaden 60 g/ha PoE	23,902	4,829	5.0
Sulfosulfuron PI 25 g/ha *fb* pinoxaden 60 g/ha PoE	27,474	3,302	8.4
Pinoxaden 60 g/ha PoE	19,058	2,335	8.2
Pinoxaden + metribuzin 50+120 g/ha PoE	26,484	2,412	11.1
Pinoxaden + metribuzin 50+150 g/ha PoE	29,841	2,513	11.9
Mesosulfuron + iodosulfuron 14.4 g/ha PoE	32,767	1,862	17.8
Weed-free check	39,192	22,750	1.8
Weedy check	-	-	-

PE: pre-emergence, PoE: post-emergence, PS: prior to sowing and PI: prior to irrigation, TM: tank mixed, RM: ready mix mesosulfuron + iodosulfuron PoE and pendimethalin + metribuzin (TM) PE *fb* mesosulfuron + iodosulfuron PoE (**Table 4**). While, higher marginal cost was with weed-free check (22,750 ₹/ha) followed by TM pendimethalin + pyroxasulfone PE *fb* pinoxaden PoE. MBCR was observed higher in mesosulfuron + iodosulfuron PoE (17.8) followed by pinoxaden + metribuzin PoE (50+150 g/ha). Whereas, the lowest MBCR was obtained in weedy free (1.8). Increase in MBCR due to sequential application of pre- and post-emergence herbicide has been reported by Khatri *et al.* (2020).

It was concluded that sequential application of tank-mixed pendimethalin + pyroxasulfone PE (or) pendimethalin + metribuzin PE *fb* pinoxaden (or) mesosulfuron + iodosulfuron PoE results in complete control of herbicide-resistant *P. minor* and BLW (except in pinoxaden) at all the wheat growth stages. It is advised to follow the rotation of herbicides of different mode of action, along with their sequential application for sustainable management of herbicide-resistant *P. minor* in wheat.

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RESEARCH ARTICLE

Weeds response and control efficiency, greengram productivity and resource-use efficiency under a conservation agriculture-based maize-wheat-greengram system

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ABSTRACT

There has been a growing trend for achieving sustainable crop intensification without jeopardizing land productivity through conservation agriculture (CA). The CA has paved the way for cultivation of pulses in diverse cropping systems. A field experiment was conducted at ICAR-Indian Agricultural Research Institute, New Delhi during 2018-19 and 2019-20 cropping cycle with summer greengram in maize-wheat system to assess the effects of CA on weed interference, crop productivity and resource use efficiency. Results showed that CA-based practices with residue retention resulted in a considerable reduction in weed density and biomass when compared to conventional tillage (CT). Greengram yield parameters in CA were higher than in CT. The permanent broad bed (PBB) with residue retention (R) and recommended 100% N application (100N) (~PBB+R+100N) gave ~56% higher greengram grain yield than CT with considerably higher water productivity, nutrient-use efficiency and net returns. The adoption of CA practice involving PBB+R in greengram led to higher weed control efficiency and was more productive, remunerative and irrigation water-use efficient. Thus, it could potentially boost up the greengram productivity, profitability and resource-use efficiency under maize-wheat-greengram system in north-western Indo-Gangetic Plains (IGP) of India.

Keywords: Conservation agriculture, Residue retention, Greengram, Weed control efficiency, Nutrient use efficiency, Water productivity

INTRODUCTION

Based on land suitability and water availability of the northern and north-western India, maize–wheat system has been considered ideal for replacing the rice-based cropping systems (Ladha *et al.* 2016, Das *et al.* 2018, Gonçalves *et al.* 2019). Recently, conservation agriculture (CA) is being recommended for improving productivity, profitability and resource-use efficiency of cereal-based cropping systems (Hobbs *et al.* 2008, Ghosh *et al.* 2019, Das *et al.* 2020a, 2021). Several CA-based component technologies, such as zero tillage (ZT), raised bed planting, crop residue retention, crop diversification have been evaluated as alternatives to conventional practices in the IGP (Das *et al.* 2014, Bhattacharyya *et al.* 2015, Jat *et al.* 2020). Generally, fields in the indo-gangetic plains (IGP) remain fallow for 70–80 days (~up to June) after wheat harvest that allows for crop diversification. Diversified crop rotation including a legume, brown manuring under CA can lead to improved soil fertility, reduced pests/diseases infestations, improved weed management and increased crop yield stability (Behera *et al.* 2019, Li *et al.* 2019, Page *et al.* 2020, Das *et al.* 2020b, Ghosh *et al.* 2021). Because of their lower C:N ratio, legume residues also promote rapid nutrient mineralization (Hazra *et al.* 2019). Greengram (*Vigna radiata* L. Wilczek), a nutritious (24-28% protein, 60% carbohydrate) warm season grain legume crop with a short growing season (60-70 days), is ideal for sustainable intensification of CA-based maize-wheat systems (Nath *et al.* 2017). Multiple tillage operations required for seed-bed preparation (ploughing, harrowing, planking, *etc*.) in maize, wheat, and greengram can stretch the crop calendar and delay greengram sowing by 15-20 days under conventional farming. As a result, delayed pod harvest of greengram until mid-June may coincide with the onset of monsoon (rains), resulting in significant crop damage and reduced greengram

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yield. However, under CA, greengram can be effectively sown under ZT conditions using ZT drills or happy turbo seeders in a single tractor operation, saving time and allowing for early greengram sowing and harvesting (Hazra *et al.* 2019).

However, weeds become the major biological constraints in CA in the early years of adoption (Chauhan *et al.* 2012, Das *et al.* 2021). Weed seed accumulation under ZT is nearer to soil surface, where they are more likely to germinate but also face greater mortality risks due to weather variability and predation (Nichols *et al.* 2015). Simultaneously, weed seed production can be reduced indirectly due to crop residues, limiting weed growth through light interception, physical barriers, and allelopathy (Franke *et al.* 2007). Also, crop rotation could be an effective weed management strategy due to changes in production processes caused by diverse cropping systems, and weed species proliferation could be avoided (Buhler *et al.* 2001, Kaur *et al.* 2015). Bitew *et al.* (2022) observed lower weeds, higher soil organic matter, total N, and available P, and better soil water infiltration in CA-based maize-legume cropping systems. However, information on the comparative performance of CA (narrow, broad, flat beds with residue retention) and CT on greengram crop is scant. Therefore, this study was designed to compare the effects of CT and CA-based crop establishment on productivity, resource-use efficiency (water, nutrient, and weed control), and economics of greengram under a maize-wheat-greengram system to find out best tillage and crop establishment practice for long-term crop intensification.

MATERIALS AND METHODS

A field experiment was conducted during the summer seasons of 2018-19 and 2019-20 at Division of Agronomy, ICAR-Indian Agricultural Research Institute, New Delhi. The soil of the experimental site was clayey loam with a pH of 8.2, 0.60% organic C, medium available N (285 kg/ha) and P (18 kg/ha), and a high K (329 kg/ha). The experiment was laid out in a randomized complete block design with ten treatments and three replications. Greengram was sown as a component crop in a maize-wheat-greengram system, initiated during *Kharif* (*i.e.* rainy season) 2018-19. The experiment was a part of a long-term CA system, initiated in 2010. Different CA-based practices such as zero till (ZT) permanent narrow, broad and flat beds with and without retention of crops (maize, wheat and greengram) residues and 75% and 100% of the recommended dose of N were compared with conventional tillage (CT) practice. The treatments comprised of: conventional tillage without residue with 100% N (CT) and nine CA based treatments : permanent narrow bed (PNB) without residue with 100% N (PNB), permanent narrow bed with residue (R) with 75% N (PNB+R+75N), permanent narrow bed with residue with 100% N (PNB+R+100N), permanent broad bed (PBB) without residue with 100% N (PBB), permanent broad bed with residue with 75% N (PBB+R+75N), permanent broad bed with residue with 100% N (PBB+R+100N), flat bed (FB) without residue with 100% N (FB), flat bed with residue with 75% N (FB+R+75N) and flat bed with residue with 100% N (FB+R+100N) were followed in maize-wheat-greengram system.

The CT plots were prepared with a tractor-drawn disc plough followed by planking. There was no ploughing in CA-based treatments. The PNB plots had the dimension of 40 cm bed and 30 cm furrow. The PBB plots had a bed of 110 cm and a furrow of 30 cm. Wheat residues were retained in CA-based residue retention plots. To ensure smooth germination of greengram, the entire field was pre-sown irrigated. Greengram variety '*SML 832*' was sown during summer season with a seed rate of 20 kg/ha and 20 cm row spacing. Sowing was done using a tractor-drawn seed-cum-fertilizer drill in CT, a bed planter in PNB, while a turbo seeder in PBB and FB. Recommended dose of 150 kg N, 26.2 kg P and 33.1 kg K/ha was applied to both maize and wheat crops under 100% N treatment in both CA and CT plots, while in CA-based plots with 75% N, 112.5 kg N was applied. Residual effects of both the N treatments were studied in greengram. The recommended dose of 18 kg N and 20.1 kg P/ha through 100 kg DAP was applied in greengram as basal in all treatments.

At 30 DAS, total weed population (~density) and dry weight (~biomass) were measured. An area of 0.25 m^2 was selected randomly at 3 places using a quadrat (0.5 m × 0.5 m) and weed species were counted from that area and collected. First, weed samples were sun-dried for three days and then, kept in an oven at 70^0C to achieve a constant weight. Before analysis of variance, data on weed density and biomass were transformed using the square-root $[(x+0.5)]^{1/2}$ method (Das 1999) to reduce inherent variation in weed data.

Weed control efficiency (WCE) and weed control index (WCI) were calculated considering CT and CA-based plots are control and treated plots, respectively (Das 2008).

WCE = [(Weed density in control plot - weed density in treated plot)/ weed density in control plot] × 100

WCI = [(Weed biomass (g) in control plot-weed biomass (g) in treated plot)/ weed biomass (g) in control plot] × 100

Root nodules number and their dry weight were measured at flowering stage (~6 weeks after sowing) of greengram. Five mature plants were randomly chosen, and their pods were counted. Twenty pods were randomly chosen and manually threshed to estimate number of grains per pod. Matured pods were hand-picked from a net plot area of 10 m^2 and sun-dried. Dried pods from each plot were manually threshed, grains separated, weighed, and grain yield recorded. Stover yield was calculated from the greengram plants of net plot area after picking of pods.

In greengram, the nutrient-use efficiency was estimated in terms of partial factor productivity of nutrients (N and P) by dividing crop yield (kg/ha) by the amount of N and P applied (kg/ha). Water productivity (kg grain/ha/mm of water) was determined as per Bhushan *et al.* (2007) and Das *et al.* (2018) given below.

Water productivity (kg grain/ha/mm of water) = [Grain yield (kg/ha)/ Total water applied (mm)]

The cost of cultivation of various treatments was calculated using current market prices of various inputs used in the treatments. To determine the statistical significance of treatment effects, data on weed density, weed biomass, crop productivity, gross returns, net returns, net benefit: cost, water productivity, and partial factor productivity of nutrients were analyzed using analysis of variance (ANOVA) for a randomized completed block design using R (version 4.0.5) statistical software (Anonymous 2013). The Tukey Multiple Comparison Test was used to test for treatment differences at 5% level of significance.

RESULTS AND DISCUSSION

Weed interference and control efficiency

Weed flora in greengram comprised of *Setaria viridis* (L.) P.Beauv., *Dinebra retroflexa* (Vahl) Panz., *Cynodon dactylon* (L.) Pers. among grassy weeds; *Commelina benghalensis* L., *Digera arvensis* Forsk., *Euphorbia hirta* L., *Euphorbia microphylla* Lam., *Trianthema portulacastrum* L., *Amaranthus viridis* L. among broad-leaved weeds and *Cyperus rotundus* L., *Cyperus esculentus* L. among sedges. Among the different tillage, residue and crop establishment practices, CT recorded significantly higher weed density than CA-based practices. The CT practice recorded 51.1% and 47.9% higher weed density than PBB+R+75N and FB+R+75N during 2018-19 and 2019-20, respectively. The CA-based practices caused significant reduction in total weed density and biomass during both the years (**Figures 1** and **2**). It was observed that PBB+R+75N and FB+R+75N significantly reduced total weed density during 2018-19 and 2019-20, respectively. The treatment PBB+R+75N significantly reduced total weed biomass during 2018-19 and was found comparable with PBB+R+100N and PNB+R+100N. Similarly, during 2019-20, PBB+R+100N significantly decreased weed biomass and was statistically at par with PBB+R+75N and PNB+R+100N. PBB+R+75N and FB+R+75N registered the highest weed control efficiency during 2018-19 and 2019-20, respectively (**Table 1**). PBB+R+75N and PBB+R+100N also recorded the highest weed control index during 2018-19 and 2019-20, respectively (**Table 1**). CA-based practices with residue retention significantly reduced total weed density and biomass, increased weed control efficiency and weed control index in greengram due to smothering effect of residues on weed emergence and growth (Ghosh *et al.* 2021) and enabled the crop to gain an advantage over weeds while also sustaining more productivity (Nath *et al.* 2016, Baghel *et al.* 2020). Zero tillage with crop residue retention can be a vital multi-tactic approach to managing weed population dynamics and successfully incorporating CA into crop rotations (Nath *et al.* 2017).

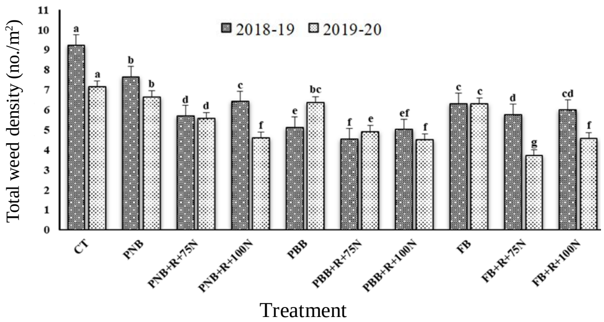

Figure 1. Total weed density in greengram as affected by tested treatments at 30 DAS

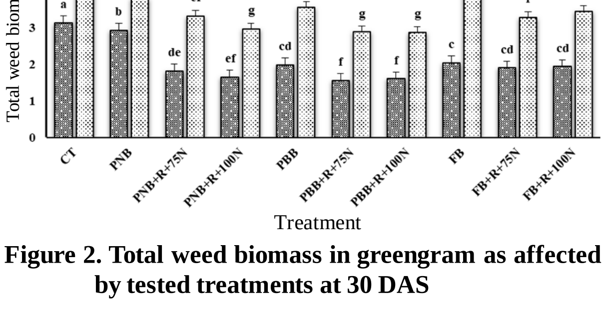

Figure 2. Total weed biomass in greengram as affected by tested treatments at 30 DAS

Table 1. Weed control efficiency and weed control index in greengram as affected by tested treatments

Treatment	Weed control efficiency (WCE) (%)		Weed control index (WCI) (%)	
	2018-19	2019-20	2018-19	2019-20
CT	0.0	0.0	0.0	0.0
PNB	16.3	5.6	6.7	19.5
PNB+R+75N	38.0	21.1	42.2	29.7
PNB+R+100N	30.4	35.2	47.3	37.2
PBB	44.6	9.9	36.7	24.8
PBB+R+75N	51.1	31.0	50.2	38.9
PBB+R+100N	45.7	36.6	48.9	39.1
FB	31.5	11.3	35.1	10.6
FB+R+75N	37.0	47.9	39.3	30.6
FB+R+100N	34.8	35.2	38.3	27.2

Refer materials and methods for treatment details

Effect on greengram nodules growth and yield variables

CA-based practices with residue retention influenced nodulation characteristics of greengram and had a greater influence on nodule growth of greengram (**Table 2**). Under PBB+R+100N, the number of nodules and nodule dry weight per plant were significantly higher during both the years. The numbers of pods per plant and test weight were found to be significantly higher under CA-based practices. During both the years, PBB+R+100N recorded significantly higher number of pods per plant (**Table 2**). In case of test weight, the treatment FB+R+100N recorded significantly higher test weight (42.03 g) than rest of the practices during 2018-19. But, it remained at par with the CA-based practices with residue retention. During 2019-20, PBB+R+100N recorded significantly higher test weight (42.16 g) and it was found to be statistically at par with FB+R+100N. However, the number of greengram seeds per pod did not vary significantly among the treatments during both the years. The conservation agriculture-based practices with residue retention contributed to greater number of pods per plant, more seeds per plant, and improved nodule growth in greengram, resulting in higher test weight in these practices.

Effect on greengram productivity

CA-based practices also increased greengram yield significantly (**Table 3**). The results revealed that among CA-based practices, treatments with residue retention resulted in higher greengram productivity than treatments with residue removal. During 2018-19, FB+R+100N, resulted in significantly higher grain yield (1.10 t/ha) and stover yield (3.24 t/ha) than rest of the practices. It recorded 46.7% and 16.9% higher grain and stover yield, respectively than CT practice. PBB+R+100N was observed to be the next best treatment. During 2019-20, PBB+R+100N significantly recorded the highest grain (1.17 t/ha) and stover (3.78 t/ha) yield and it was found to be statistically at par with FB+R+100N and PNB+R+100N treatments. The treatment PBB+R+100N achieved yield improvement to the tune of 69.6% and 42.6% in grain and stover yield, respectively as compared to CT. Greengram yield was significantly higher under CA-based practices with residue retention due to improved yield attributes under CA as compared to CT. Weed interference is inversely related to crop yield (Das and Yaduraju 2011). The weed suppression, increased soil water retention and availability, and stabilization of soil nutrients due to a long-term CA practice created a favourable environment for improving yield attributes, resulting in increased yield in greengram (Bhattacharyya *et al.* 2013, Das *et al.* 2018). The residual effects of previous crop nutrient

Table 2. Nodule characteristics and yield parameters of greengram as affected by tested treatments

Treatment	No. of nodules/ plant		Nodule dry weight/ plant (mg)		No. of pods/ plant		No. of seeds/ pod		Test weight (g)	
	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20	2018-19	2019-20
CT	27.7^{c}	29.3^{c}	66.73^{e}	67.13^{f}	19.7^{b}	21.1^{f}	7.6	7.3	38.36^{b}	37.91^{e}
PNB	28.3^{c}	32.7^{bc}	89.76^{bc}	89.64^{cd}	20.7^{b}	22.8^{ef}	8.4	8.1	39.97^{ab}	38.94^{d}
PNB+R+75N	30.3^{bc}	35.3^{ab}	90.42^{bc}	92.09^{bcd}	23.3^{ab}	24.9^{cdef}	8.6	8.3	40.41^{ab}	40.25^{bc}
PNB+R+100N	33.0^{ab}	36.3^{ab}	102.73^{a}	100.49^{abc}	27.1^{ab}	28.8^{abc}	8.7	8.5	41.39^{a}	41.04^{b}
PBB	29.7^{bc}	33.0^{bc}	81.56^{cd}	82.03^{de}	20.3^{b}	23.3^{def}	8.5	8.1	40.20^{ab}	39.64^{cd}
PBB+R+75N	31.3^{abc}	35.0^{ab}	97.21^{ab}	98.08^{abc}	26.7^{ab}	27.7^{abcd}	8.6	8.3	41.22^{a}	40.94^{b}
PBB+R+100N	35.7^{a}	37.3^{a}	105.76^{a}	106.92^{a}	29.0^{a}	30.3^{a}	8.9	9.0	41.81^{a}	42.16^{a}
FB	30.0^{bc}	33.0^{bc}	72.75^{de}	74.07^{ef}	22.3^{ab}	23.6^{def}	8.3	8.5	40.11^{ab}	40.19^{bc}
FB+R+75N	30.7^{bc}	34.3^{ab}	95.97^{ab}	96.18^{abc}	24.0^{ab}	25.6^{bcde}	8.6	8.6	41.13^{a}	40.72^{b}
FB+R+100N	32.0^{abc}	36.7^{ab}	100.15^{ab}	103.06^{ab}	28.6^{a}	29.6^{ab}	8.7	8.8	42.03^{a}	42.08^{a}

Refer materials and methods for treatment details management (maize and wheat) also aided in increasing greengram yield attributes as well as yield. Among all the CA-based practices, PBB+R+100N was found superior in significantly increasing greengram yield attributes, as a result higher productivity was observed in this practice. When compared to conventional or flat planting, bed planting techniques had various advantages in terms of higher productivity owing to a variety of factors, including lower weed density, less competition for resources, enhanced soil water regimes, better aeration, and nutrient use (Das *et al.* 2013).

Effect on economics of greengram cultivation

Tillage, residue and crop establishment practices had significant impacts on economics in greengram cultivation (**Table 4**). The CA-based practices with residue removal recorded 16.8% and 15.5% lesser cost of cultivation than CT during 2018-19 and 2019-20, respectively, while the CA-based practices with residue retention registered on an average 3.5% higher cost of cultivation than CT. During 2018-19, FB+R+100N significantly recorded higher gross returns (80.20 × 10^3 ₹/ha), net returns (51.35 × 10^3 ₹/ha) and net benefit: cost (B:C) ratio (1.78) and was found comparable with CA-based practices with residue retention. During 2019-20, PBB+R+100N was found to register significantly higher gross returns (86.27 × 10^3 ₹/ha), net returns (55.52 × 10^3 ₹/ha) and net B:C ratio (1.81). This treatment was found to be comparable with FB+R+100N and PNB+R+100N. The CA-based practices recorded 7-46.1% higher gross returns, 29-89.8% higher net returns and 40.2-83.5% higher net B: C ratio during 2018-19. CA-based residue removal practices resulted in lower cultivation costs due to less use of machinery, labour, and fuel. Due to the cost of residue application, CA-based practices with residue retention resulted in higher cultivation costs than CT. However, residue retention practices significantly increased greengram yield. Higher yields in residue-retained treatments offset the cost of residue retention, resulting in higher net returns and net B: C.

Table 3. Productivity of greengram as affected by tested treatments

Treatment	2018-19			2019-20		
	Grain yield (t/ha)	Stover yield (t/ha)	Harvest index (%)	Grain yield (t/ha)	Stover yield (t/ha)	Harvest index (%)
CT	0.75[d]	2.77[d]	21.3	0.69[f]	2.65[c]	20.9
PNB	0.81[d]	2.84[cd]	22.2	0.76[f]	2.78[c]	21.7
PNB+R+75N	0.93[bc]	3.01[abcd]	23.7	0.84[def]	2.95[bc]	22.2
PNB+R+100N	1.06[a]	3.20[ab]	24.9	1.02[abc]	3.41[ab]	23.2
PBB	0.82[cd]	2.86[bcd]	22.3	0.79[ef]	2.81[c]	21.8
PBB+R+75N	1.01[ab]	3.11[abc]	24.4	0.97[bcd]	3.37[ab]	22.3
PBB+R+100N	1.08[a]	3.19[ab]	25.3	1.17[a]	3.78[a]	23.6
FB	0.80[d]	2.80[cd]	22.3	0.80[ef]	3.00[bc]	21.1
FB+R+75N	1.02[ab]	3.10[abcd]	24.8	0.95[cde]	3.35[ab]	22.1
FB+R+100N	1.10[a]	3.24[a]	25.6	1.12[ab]	3.67[a]	23.5

Refer materials and methods for treatment details

Table 4. Greengram economics as affected by tested treatments

Treatment	2018-19				2019-20			
	Cost of cultivation (×10^3 ₹/ha)	Gross returns (×10^3 ₹/ha)	Net returns (×10^3 ₹/ha)	Net B:C	Cost of cultivation (×10^3 ₹/ha)	Gross returns (×10^3 ₹/ha)	Net returns (×10^3 ₹/ha)	Net B:C
CT	27.84	54.90[d]	27.05[d]	0.97[d]	29.74	51.29[f]	21.55[e]	0.72[e]
PNB	23.84	59.45[d]	35.61[c]	1.49[abc]	25.74	56.13[f]	30.38[de]	1.18[cd]
PNB+R+75N	28.84	67.99[bc]	39.15[bc]	1.36[c]	30.74	61.94[def]	31.19[de]	1.01[de]
PNB+R+100N	28.84	76.86[a]	48.01[a]	1.66[ab]	30.74	75.56[abc]	44.81[abc]	1.46[abc]
PBB	23.84	59.96[cd]	36.12[c]	1.51[abc]	25.74	58.27[f]	32.53[de]	1.26[bcd]
PBB+R+75N	28.84	73.30[ab]	44.46[ab]	1.54[abc]	30.74	71.52[bcd]	40.78[bcd]	1.33[bcd]
PBB+R+100N	28.84	78.52[a]	49.67[a]	1.72[ab]	30.74	86.27[a]	55.52[a]	1.81[a]
FB	23.84	58.74[d]	34.90[cd]	1.46[bc]	25.74	59.40[ef]	33.66[cd]	1.31[bcd]
FB+R+75N	28.84	74.17[ab]	45.33[ab]	1.57[abc]	30.74	70.33[cde]	39.58[cd]	1.29[bcd]
FB+R+100N	28.84	80.20a	51.35[a]	1.78[a]	30.74	82.63[ab]	51.89[ab]	1.69[ab]

Refer materials and methods for treatment details

Water productivity

Water consumption varied according to tillage, residue and crop establishment practices. Water productivity was found to be significantly higher in CA-based practices due to less water use in CA plots compared to CT plots (**Figures 3** and **4**). Among CA-based practices, PBB+R treatment consumed 30.3% and 29.9% less water than CT during 2018-19 and 2019-20, respectively. Water productivity increased as a consequence of both increased greengram yield and irrigation water savings under PBB+R+100N. Weeds, being ubiquitous in nature, intensely competitive, persistent, and hardy in comparison to cultivated crops, impede agricultural operations and reduce resource use efficiency (Das 2008, Kaur *et al.* 2018, Das *et al.* 2020b). The increased weed suppression under CA-based residue retained practices led to increased soil water conservation under these practices (Ghosh *et al.* 2021). Also, CA-based practices involving crop residue retention increased soil water storage by reducing soil evaporation (Nath *et al.* 2017, Parihar *et al.* 2017) which increased greengram yield and, as a result, both irrigation water productivity and total water productivity were significantly improved under these practices. When compared to PNB+R+100N, PBB+R+100N retained more residues due to more uniform distribution of residue on top of the broad beds. This resulted in improved infiltration and water conservation on beds (Das *et al.* 2018), reduced run-off and erosion, weed control, higher fertilizer usage efficiency, and higher productivity under PBB+R+100N as compared to other practices.

Partial factor productivity of N and P

The CT treatment had the lowest partial factor productivity of N and P during both years (**Figures 5** and **6**). Among CA-based practices with residue retention, FB+R+100N registered significantly higher PFP of N (61.3 kg grain/ kg N) during 2018-19 and was found comparable with PBB+R+100N, PNB+R+100N, PBB+R+75N and FB+R+75N. During 2019-20, PBB+R+100N registered significantly higher PFP of N (65 kg grain/ kg N) and was found to be statistically at par with FB+R+100N and PNB+R+100N. The same trend was observed in recording partial factor productivity of P also. Crop production requires a variety of agricultural inputs, including nutrients/fertilizers and water (Kaur *et al.* 2018). These resources are critical in crop-weed interactions. Fertilizer application may benefit weeds more than crops because weeds absorb nutrients faster and more efficiently than crop plants (Das 2008). The significant reduction in weed growth in

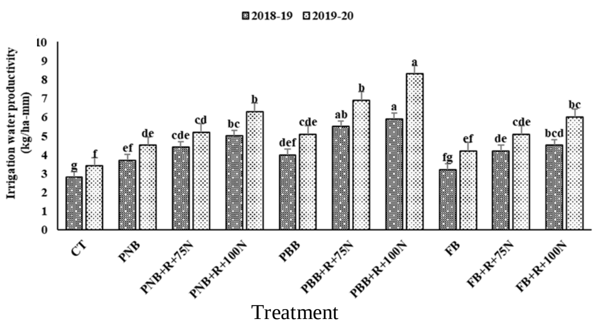

Figure 3. Irrigation water productivity in greengram as affected by tested treatments

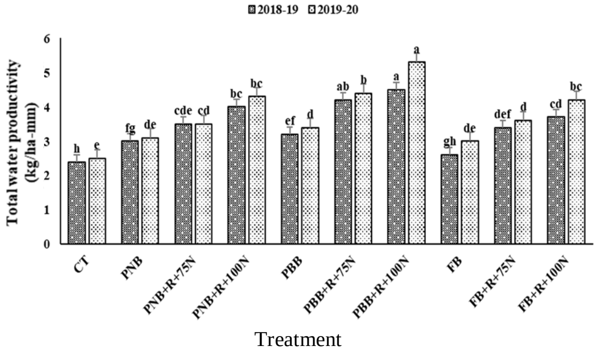

Figure 4. Total water productivity in greengram as affected by tested treatments

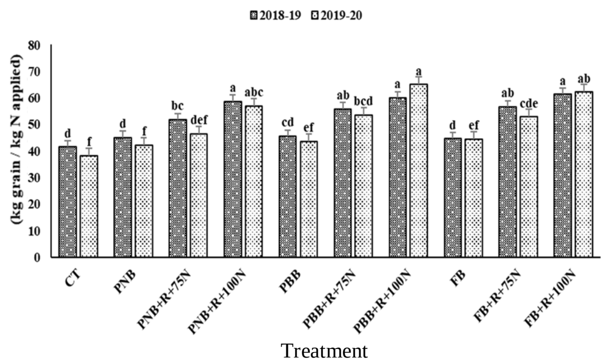

Figure 5. Partial factor productivity of N in greengram as affected by tested treatments

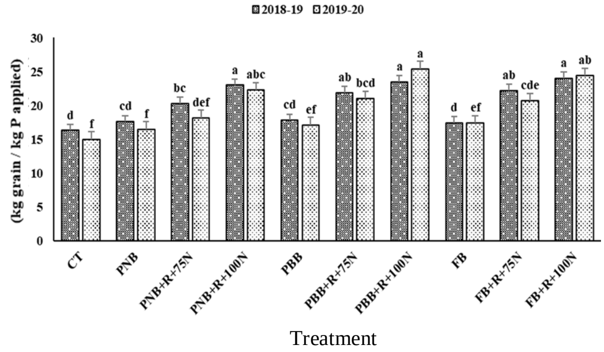

Figure 6. Partial factor productivity of P in greengram as affected by tested treatments

CA-based practices as well as the beneficial effects of crop residue retention on crop growth led to higher crop productivity per unit of nutrient application, which resulted in significantly higher PFP of nutrients in CA-based practices than CT indicating efficient utilization of N and P for greengram growth and productivity.

Thus, the conservation agriculture-based permanent broad bed with residue retention (PBB+R+100N) resulted in significant improvement in crop productivity, profitability, weed control efficiency, water productivity and nutrient use efficiency in greengram under the maize-wheat-greengram system. It can be recommended for sustainable greengram production in north-western Indo-Gangetic Plains of India under the maize-wheat-greengram sequence.

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RESEARCH ARTICLE

Long-term tillage and weed management effects on weed shifts, phyto-sociology and crops productivity

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ABSTRACT

The understanding of the diverse weed flora composition and weed shift in conservation agriculture production system is important to identify weed management component to increase agro-ecosystem sustainability. Hence, in this study, different tillage and weed management practices were assessed to evaluate their impact on diverse weed flora composition and shift in maize-wheat cropping system in North Western Himalaya from 2018-20 in an ongoing long-term experiment being conducted since 2013. Fifteen treatment combinations comprising of five tillage treatments, *viz.* conventional tillage (CT) in maize-CT in wheat; CT-zero tillage (ZT); ZT-ZT; ZT-zero tillage in combination with residue retention (ZTR) and ZTR-ZTR and three weed management treatments, *viz.* recommended herbicide (H) in maize-recommended herbicide (H) in wheat; integrated weed management (IWM)-IWM and hand weeding (HW)-HW were evaluated in a strip plot design. In CT, annual weed species were dominant, whereas, perennial weeds dominated in zero tillage (ZT). A shift in weed species with greater dominance of monocots and a marginal decrease in dicots was observed. *Parthenium hysterophorus*, an obnoxious weed, was observed in the experimental field in maize only during 2018. The monocot weed (*Echinochloa colona*) had higher relative density (RD), relative abundance (RA), relative frequency (RF) and important value index (IVI) compared to the dicot weeds in maize crop. In *Rabi* (winter) season, *Avena ludoviciana* (monocot grass) had higher RD, RF and IVI values, while, *Daucus carota* (perennial weed) had higher RA when compared to the other annual and biennial weeds. The grain yield of main and intercrop and system productivity were higher in conservation agriculture-based production systems in combination with recommended herbicide (ZTR+H-ZTR+H) in maize-wheat based cropping systems.

Keywords: Conservation agriculture, Conventional tillage, Integrated weed management, Weed phyto-sociology, Zero tillage

INTRODUCTION

Globally, modern agricultural production systems are extremely intensive and cause environmental degradation (Sial *et al.* 2021). The traditional agricultural method involving intensive tillage, inefficient pesticide applications, and excessive irrigation can lead to soil and water contamination and deterioration of natural resources negatively (Penescu *et al.* 2001, Pratibha *et al.* 2021). Thus, conservation agriculture (CA) with three interlinked principles, *viz.* (i) minimum or no mechanical soil disturbance (ii) permanent soil cover and (iii) diversification of cropping system either through sequences and/or rotations, along with good agronomic practices is a sustainable land management approach (FAO 2019, Bhattacharyya *et al.* 2019, Naeem *et al.* 2021). The main barriers to low adoption of CA are the lack of availability of CA machines, competing demands for crop residues for alternative uses, greater competition between crops and weeds, and weed management (Farooq *et al.* 2011). The zero tillage (ZT) has many environmental benefits such as reducing soil and water pollution, reducing run-off and soil degradation and stimulating soil macro and micro flora (Holland 2004). Recently, CA is being adopted and promoted for sustainable intensification of crops under various ecosystems (FAO 2011, Saad *et al.* 2016). Despite the low level of soil disturbance, weed seeds remain near or on the soil surface in ZT (Naeem *et al.* 2021), resulting in increased weeds problem which is preventing the adoption of ZT at a large scale among farmers (Yang *et al.* 2018). The benefits of CA systems may be counterbalanced by heavy weed infestations, weed community shifts either increase, decrease, or extinction of weed species (Yang *et al.* 2018, Zhang and Wu 2021), as there are many ecological and agronomic factors that influence weeds.

Farmers employ a variety of weed management strategies to reduce crop loss due to weeds (Zhang

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and Wu 2021). Presently, farmers are preferring herbicides use alone to manage diverse weed flora, which is leading to serious problems of resistance among weeds and eco-system damages (Annett *et al*. 2014, Gu *et al*. 2019). Crop residue retention is a potential weed control practice that reduces the penetration of light directly into the soil surface (Yang *et al*. 2018), which minimizes weed diversity, density and biomass accumulation (Campiglia *et al*. 2012, Yang *et al*. 2018). In the early competition between crops and weeds, the amount and type of covering material delay the germination of weeds (Teasdale and Mohler 2000, Chauhan and Mahajan 2012). Some researchers have found crop residues can release allelo-chemicals that reduce the germination and emergence of weed seeds (Duke 2015). However, mulch cover in CA makes hand-weeding and mechanical weed management strategies more difficult due to which dependency on chemical weed control measure increases. Furthermore, there has been a significant shift from easily controlled annual weeds to perennials that are difficult to control in crop lands (Armengot *et al*. 2016).

Weed community, diversity, and crop yields vary with tillage systems (Alarcon *et al*. 2018). It is therefore vital to understand the interactions among different components of CA to develop control measures that consistently minimize weed abundance. Generally, CA is criticized for its increased dependence on non-selective herbicides to control perennial weeds. The herbicides efficacy is determined by weather conditions; specifically, the timing and quantity of rainfall have a considerable impact on the efficacy of pre-emergence and post-emergence herbicides (Jursik *et al*. 2011). The over reliance and indiscriminate use of herbicides lead to weed shift and herbicide-resistant weed varieties (Farooq *et al*. 2011), ecological adversity (Owen *et al*. 2007) and human health risks. In CA, weed control and herbicide resistance to weeds are major challenges, therefore, Farooq *et al*. (2011) suggested a fourth pillar of CA to the IWM options with cautionary use of herbicides.

There are a limited research reports on influence of varied tillage intensities and residue management along with weed management strategies on weed shifts in CA systems (Han *et al*. 2013, Vanlauwe *et al*. 2014, Hosseini *et al*. 2016, Yang *et al*. 2018). Therefore, the objective of the present study was to monitor weed flora shifts over time in response to varied tillage (CT, ZT or ZTR) and residue levels in combination with weed management strategies in maize-wheat cropping system.

MATERIAL AND METHODS

Study area

The experiment was conducted at Research Farm (32°62 N, 76°32 E), Department of Agronomy, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur (H.P.), India. The results reported in this paper were collected during rainy (*Kharif*) 2018 to winter (*Rabi*) season 2019-20 in an ongoing experiment being conducted since 2013. The experimental location has a sub-temperate mid hill zone at 1290 m above mean sea level. Experimental site has silty clay loamy soil (21% clay, 43% silt and 36% sand), according to USDA classification (**Table 1**). The soil properties of the experimental site before the start of the experiment are in **Table 1**. The second year was relatively hotter and humid, whereas, first year received higher amount of rainfall (**Figure 1**). During 2018-19, ~20% higher rainfall was received than 2019-20. The crops were irrigated when ever needed with a good drainage system.

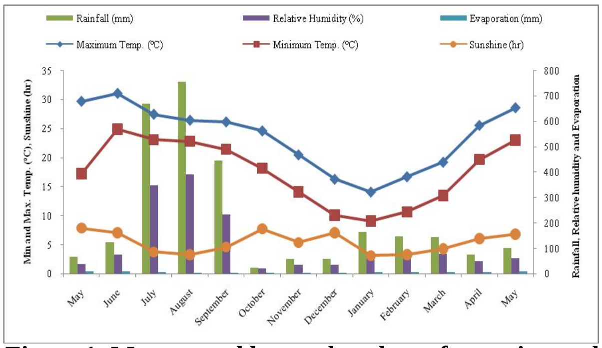

Figure 1. Mean monthly weather data of experimental site (2018-2020)

Table 1. The physic-chemical properties of 0-15 cm soil at the beginning of the experiment

Particulars	Sand (%)	Silt (%)	Clay (%)	BD (g/m^3)	SOC (g/kg)	Av. N (kg/ha)	Av. P (kg/ha)	Av. K (kg/ha)
Content	21	43	36	1.18	11.0	323.0	25.8	276.4
Analytical Method employed	International pipette method (Piper 1966)			Core Method (Singh 1980)	Walkley and Black' rapid titration method (Piper 1966)	Alkaline permanganate method (Subbiah and Asija 1956)	Olsen' method (Olsen *et al.* 1954)	Ammonium acetate extraction method (AOAC 1970)

SOC: Soil organic carbon; Av. N: Available Nitrogen; Av. P: Available Phosphorus; Av. K: Available Potassium

Experimental details

The details of the experimental treatments are given in **Table 2**. Maize crop was sown in *Kharif* (rainy) and wheat in *Rabi* (winter) season. Pre sowing irrigation at depth 5 cm was given during both *Kharif* and *Rabi* seasons of both the years. Except for ZT treatment, the plots were prepared with the help of a rotary power tiller. During seedbed preparation, crop stubble and weeds were removed to facilitate the planting operations in conventional tilled plots. The left-over weeds were removed and the plots were leveled to have uniform sowing and germination thereof. The conventional tillage (CT) plots were ploughed to a fine tilth before the start of experiment through single ploughing, harrowing twice and then leveling. The seeds of maize variety '*Kanchan 51 hybrid*' were sown in rows 60 cm apart in the first week of June and harvested in the mid to end of September every year. Sowing was done with hand plough by the kera (dropping of seeds by hand into the burrows, which have been opened by the local plough) method. Common dosage of 120 kg N, 60 kg P, and 40 kg K/ha respectively, was supplied through urea (46% N), IFFCO (12:32:16), and MOP (60% K). Intercrop of soybean, grown in additive series with maize, was not given any additional fertilizer dose. The net plot size was 2.7 m × 4.5 m. The crops water requirement was fulfilled according to the prevailing climatic conditions. Wheat crop variety '*HPW 368*' was sown during the first fortnight of November at a spacing of 20 cm using a seed rate of 120 kg/ha. The crop was fertilized with 120 kg N, 60 kg P, and 30 kg K/ha. Half N and whole P and K were applied at the time of sowing. Four irrigations were given in order to avoid drought stress. The remaining nitrogen was top-dressed in two equal splits at tillering and earing stage. The crop was harvested by the mid of May each year.

In both crops, all other production practices, except tillage and weed control treatments were followed as per recommendations in the package of practices. All the crops (main crops and intercrops) were harvested manually.

System productivity

In order to calculate the productivity of the maize-wheat cropping system, the equivalent yield of maize cob was calculated by using the following formula:

Maize cob equivalent yield (MEY) = Maize cob yield (kg/ha) + soybean seed yield (kg/ha) × price of soybean seed (₹/kg)/price of maize cob/(₹/kg) + wheat grain yield (kg/ha) × price of wheat grain (₹/kg)/price of wheat seed/(₹/kg) + mustard seed yield (kg/ha) × price of mustard seed (₹/kg)/price of maize cob/(₹/kg)

Data analysis

In both crops, weeds were counted at monthly interval from 0.5 × 0.5 m quadrat placed randomly at 2 places in each experimental treatment plots and then mean value of two was calculated. Individual weed species population was added to calculate the total weed density in a particular treatment. Statistical analysis of system productivity was performed with ANOVA techniques (Gomez and Gomez 1984) for the strip-plot design and the treatment means were tested with LSD at (p=0.05) at a 5% level of significance to interpret the treatment differences.

Weed phyto-sociology

Importance value index (IVI) of each of the weed species was calculated by using the following formulae:

$$\text{Density} = \frac{\text{Total number of individuals of a species in all quadrats}}{\text{Total number of quadrates studied}}$$

$$\text{Frequency (\%)} = \frac{\text{Total number of quadrates in which the species occurred}}{\text{Total number of quadrats studied}}$$

$$\text{Abundance} = \frac{\text{Total number of individuals of a species in all quadrats}}{\text{Total number of quadrats in which the species occurred}}$$

IVI = Relative density + Relative frequency + Relative abundance

Table 2. Treatments adopted in the experiment

Maize crop	Wheat crop	Notation
Tillage and residue management		
T_1 - Conventional tillage (CT)	T_1 - Conventional tillage (CT)	CT-CT
T_2 - Conventional tillage (CT)	T_2 - Zero tillage (ZT)	CT-ZT
T_3 - Zero tillage (ZT)	T_3 - Zero tillage (ZT)	ZT-ZT
T_4 - Zero tillage (ZT)	T_4 - Zero tillage + residue (ZTR)	ZT-ZTR
T_5 - Zero tillage + residue (ZTR)	T_5 - Zero tillage + residue (ZTR)	ZTR-ZTR
Weed management treatment		
W_1 - Recommended herbicides (atrazine *fb* 2,4-D)	W_1 - Recommended herbicides (isoproturon *fb* 2,4-D)	H-H
W_2 - IWM (intercropping* + pendimethalin spray + one HW)	W_2 - IWM (intercropping** + isoproturon spray + HW)	IWM-IWM
W_3 - Hand weeding (hand hoeing) twice	W_3 - Hand weeding (hand hoeing) twice	HW-HW

*Intercropping of soybean in maize crop; **Intercropping of mustard in wheat crop; HW: Hand weeding

RESULTS AND DISCUSSION

Weed flora shift

There were changes in weed flora in maize-wheat cropping system as per observations taken during *Kharif* 2018 to *Rabi* 2019-20 from those taken at the initiation of the experiment during *Rabi* 2013-14 and at the mid of experiment (Anonymous 2014) (**Table 3)**. Ball and Miller (1990) also reported that tillage practices (minimum or zero tillage) cause changes in the abundance and diversity of weed species in cropping systems.

Weed flora shift during *Kharif* (rainy) season

In *Kharif* (rainy) season maize, *Echinochloa colona* and *Panicum dichotomiflorum* were observed in *Kharif* 2014, 2018, 2019 and were not recorded during *Kharif* 2016. Per cent population of *Ageratum conyzoides*, *Echinochloa colona* and *Commelina benghalensis* were 33, 30 and 15%, respectively, of the total weed flora during 2014. Whereas, during *Kharif* 2016, the relative density of *Ageratum conyzoides* and *Commelina benghalensis* increased to 47 and 23%, respectively. *Digitaria sanguinalis*, *Panicum dichotomiflorum* and *Cyperus iria* constituted 10, 9 and 3%, respectively, of the total weed flora in maize during 2014. *Cynodon dactylon* was the new invasion in the experimental field during 2016. *Cyperus iria*, *Digitaria sanguinalis* and *Cynodon dactylon* constituted 11, 10 and 9%, respectively, of the total weed flora of maize in 2016. During *Kharif* 2018, *A. conyzoides* and *C. benghalensis* were the major weeds constituting 23.8 and 21.4%, respectively of the total weed flora. Occurrence of *Parthenium hysterophorus* and *Bidens pilosa* was also seen during *Kharif* 2018 constituting around 2.0 and 6.3% of the total population, respectively, which were otherwise not present earlier and during *Kharif* 2019. *Polygonum alatum* which was observed only during *Kharif* 2019 with relative density of about 11% (**Figure 2**). Bajwa (2014) reported that small seeded and perennial weeds are more abundant in CA. Surface residue retention caused limited germination and growth of small-seeded annuals because of restricted light availability, physical growth barriers and potential allelopathic effects (Nichols *et al*. 2015).

Weed flora shift in wheat crop: During 2013-14, *Avena ludoviciana, Coronopus didymus* and *Phalaris minor* were major weeds with relative density of 41, 20 and 18%, respectively. *Lolium temulentum* and *Vicia sativa* constituted 11 and 10% of total weed density, respectively, in wheat during 2013-14. Among these weeds, *Phalaris*, *Avena* and *Lolium* were not recorded during 2016-17, which were further present during *Rabi* 2018-19 and 2019-20. *Erodium cicutarium*, *Euphorbia hirta* and *Oxalis corniculata* were observed only during 2016-17 with higher relative density of 38, 17 and 17%, respectively of the total weed flora. *Vicia sativa* constituted 11% of the weed flora in wheat in 2016-17. *Avena ludoviciana* and *Daucus carota* were the dominant weeds constituting 26.4 and 25.1% relative density during 2018-19 and 25.2and 24.4% during 2019-20, respectively.

Lolium temulentum, *Poa annua*, *Vicia sativa* and *Phalaris minor* constituting about 15.55, 13.8, 9.6 and 5.8% during *Rabi* 2018-19 and about 15.9, 12.6, 10.5 and 5.8% during *Rabi* 2019-20. *Poa annua* and *Daucus carota* were seen only during the last years of experiment which were however not visible during earlier years of research trial. Nichols *et al*. (2015) reported that minimum tillage may shift weed communities from annual dicots to grassy annuals and perennials. A weed shift is 'the change in the

Table 3. Weeds occurred in the experimental field from 2013-14 to 2019-20

Weed species	Year								
	Maize					Wheat			
	2014	2016	2018	2019		2013-14	2016-17	2018-19	2019-20
Cyperus iria	+	+	+	+	*Coronopus didymus*	+	-	+	+
Commelina benghalensis	+	+	+	+	*Vicia sativa*	+	+	+	+
Digitaria sanguinalis	+	+	+	+	*Lolium temulentum*	+	-	+	+
Ageratum conyzoides	+	+	+	+	*Phalaris minor*	+	-	+	+
Cynodon dactylon	+	-	-	-	*Avena ludoviciana*	+	-	+	+
Bidens pilosa	-	-	+	-	*Anagallis arvensis*	-	+	-	-
Echinochloa colona	+	-	+	+	*Euphorbia hirta* (L.)	-	+	-	-
Panicum dichotomiflorum	+	-	+	+	*Oxalis corniculata* (L.)	-	+	-	-
Parthenium hysterophorus	-	-	+	-	*Erodium cicutarium* (L.)	-	+	-	-
Polygonum alatum	-	-	-	+	*Poa annua*	-	-	+	+
					Daucus carota	-	-	+	+

+: Presence of the weed; -: Absence of the weed composition, abundance or relative frequencies of weeds in a weed population or community in response to natural or man-influenced changes' (Rana *et al.* 2020). Weedy and invasive species can easily adapt to changes in production practices in order to take advantage of the available niches (Rana and Rana 2015).

Weed phyto-sociology in maize

Studies of weed phyto-sociology are useful in identifying the species that are most important during distinct periods of crop growth. Phyto-sociological attributes, *viz*. relative density (RD), relative abundance (RA) relative frequency (RF) and important value index (IVI) were estimated based on seasonal observations and pooled values of both the years (**Table 4** and **5)**. A total of eight annual weed species were identified in the experimental area. The overall RD, RA and RF were higher for *Echinochloa colona* followed by *Commelina benghalensis* and *Ageratum conyzoides*. Mekonnen and Markos (2016) also found that *Ageratum conyzoides* were higher in abundance in maize-based cropping system in CT-based cropping system. Among different treatments combinations, CT+H-ZT+H had higher RD, RA and RF for *Cyperus iria* in maize crop. ZTR+IWM-ZTR+IWM resulted in higher RD, RA and RF for *Commelina benghalensis*. For *Digitaria sanguinalis*, higher RD was recorded in ZT+H-ZT+H, while its RA and RF were higher in ZTR+H-ZTR+H. Froud-Williams (1988) also found that *Digitaria sanguinalis* population was higher under zero tilled plots. Higher RD of *Ageratum conyzoides* was in CT+IWM-CT+IWM, whereas, its RA and RF was higher in CT+IWM-ZT+IWM. Mekonnen and Markos (2016) also reported that *Ageratum conyzoides* was most abundant in CT in maize-cowpea intercropping system. However, RD, RA and RF of *Digitaria* sp. were higher in CT+HW-CT+HW in maize crop. The CT+HW-CT+HW resulted in higher RD, RA and RF of *Bidens pilosa*. *Echinochloa colona* had higher RD, RA and RF per cent in ZT+HW-ZT+HW. CT+HW-CT+HW had maximum RD of *Parthenium hysterophorus* and *Polygonum alatum*. However, CT+IWM-CT+IWM have RA and RF of *Parthenium hysterophorus* and *Polygonum alatum*.

Phyto-sociology of weeds showed the trend of variation in weed populations within a crop and variations are interlinked to production practices adopted, which further used to support varied weed management strategies (Concenço *et al.* 2017). Weeds IVI varied with tillage and weed management treatments and the dominant weed species would have high important value index (**Table 5**). Maximum averaged IVI among all the weeds was recorded for *Echinochloa colona* (55.90%) followed by *Commelina benghalensis* (54.83%) and *Ageratum conyzoides* (50.28%).

Amongst all the weeds, highest IVI of *Echinochloa colona* was found in ZTR+H-ZTR+H followed by ZT+HW-ZT+HW. However, higher IVI of *Commelina benghalensis* was recorded in ZT+H-ZTR+H followed by ZT+IWM-ZTR+IWM. Among all weeds, lowest averaged IVI was of *Parthenium hysterophorus* (4.10%), while its IVI was higher in CT+HW-ZT+HW during *Kharif* season. Rana *et al.* (2019) also reported that *Ageratum conyzoides*, *Echinochloa colona* and *Commelina benghalensis*

Table 4. Effect of treatments on relative density (RD) and relative abundance (RA) of associated weed species in maize crop

Treatment	Weed species																	
	Cyperus iria		*Commelina benghalensis*		*Digitaria sanguinalis*		*Ageratum conyzoides*		*Bides pilosa*		*Panicum dichotomiflorum*		*Echinochloa colona*		*Parthenium hysterophorus*		*Polygonum alatum*	
	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA
CT+H-CT+H	20.08	20.06	17.52	14.26	15.61	13.31	22.60	21.84	2.90	5.42	3.54	7.29	16.02	13.76	0.00	0.00	1.74	4.09
CT+IWM-CT+IWM	7.90	9.35	21.61	17.19	8.20	8.26	32.56	29.40	4.76	4.55	3.68	8.52	12.41	13.73	1.91	3.64	6.98	5.38
CT+HW-CT+HW	14.70	13.85	15.67	14.95	12.28	11.38	14.69	17.04	10.00	9.83	5.83	5.27	16.65	17.58	0.00	0.00	10.20	9.22
CT+H-ZT+H	25.45	24.75	12.65	11.99	8.81	10.42	17.48	17.22	3.55	6.70	9.46	4.19	15.96	18.85	0.00	0.00	6.67	5.89
CT+IWM-ZT+IWM	1.96	7.96	20.98	14.84	11.84	11.14	34.06	32.27	3.41	9.31	6.05	5.94	12.92	12.08	0.00	0.00	8.79	6.48
CT+HW-ZT+HW	13.93	15.46	19.10	15.60	7.26	10.25	8.68	15.74	1.02	2.78	8.65	7.50	21.80	21.92	7.15	0.00	12.43	10.78
ZT+H-ZT+H	8.90	10.90	21.46	16.37	19.97	14.95	14.00	28.33	4.27	6.51	4.93	1.66	20.96	15.89	1.94	0.00	3.59	5.40
ZT+IWM-ZT+IWM	9.24	9.36	18.89	13.31	15.75	14.57	28.32	28.20	3.95	6.13	0.95	5.53	12.75	19.16	5.70	0.00	4.48	3.75
ZT+HW-ZT+HW	18.63	15.35	11.55	11.55	11.67	10.56	10.63	15.89	5.14	6.48	6.02	4.90	32.85	30.11	0.00	0.00	3.53	5.17
ZT+H-ZTR+H	17.46	15.12	24.15	18.30	8.95	8.83	17.05	28.18	3.47	4.58	5.94	4.73	22.99	20.28	0.00	0.00	0.00	0.00
ZT+IWM-ZTR+IWM	5.19	10.23	25.52	16.56	17.24	16.84	18.04	21.26	8.62	9.08	0.00	0.00	17.21	19.13	0.00	0.00	8.21	6.91
ZT+HW-ZTR+HW	13.27	10.96	14.96	18.02	15.83	13.48	15.28	22.86	6.85	7.71	7.20	3.45	24.90	19.56	0.00	0.00	1.74	3.98
ZTR+H-ZTR+H	12.09	16.16	20.54	19.57	18.40	22.34	7.15	15.65	0.45	2.94	8.04	0.00	29.33	23.36	4.02	0.00	0.00	0.00
ZTR+IWM-ZTR+IWM	21.95	18.08	28.16	19.04	9.36	18.06	6.08	13.70	1.60	5.25	7.18	8.54	21.44	17.34	4.26	0.00	0.00	0.00
ZTR+HW-ZTR+HW	11.28	12.99	15.61	14.14	17.53	18.19	15.04	15.63	3.75	5.71	7.18	6.23	21.18	20.50	0.84	0.00	7.63	6.62
Overall	14.32	14.04	20.27	15.71	14.16	13.51	18.27	21.55	4.25	6.20	6.28	4.92	21.26	18.88	1.72	0.25	5.75	4.91

RD, Relative density; RA, Relative abundance; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

Table 5. Effect of treatments on relative frequency (RF) and important value index (IVI) of associated weed species in maize crop

Treatment	Weed species																	
	Cyperus iria		*Commelina benghalensis*		*Digitaria sanguinalis*		*Ageratum conyzoides*		*Bides pilosa*		*Panicum dichotomiflorum*		*Echinochloa colona*		*Parthenium hysterophorus*		*Polygonum alatum*	
	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI
CT+H-CT+H	20.06	55.90	14.26	50.75	13.31	46.80	21.84	60.20	5.42	12.50	7.29	18.20	13.76	46.65	0.00	0.0	4.09	9.0
CT+IWM-CT+IWM	9.35	30.55	17.19	57.10	8.26	27.35	29.40	78.15	4.55	16.80	8.52	19.15	13.73	39.65	3.64	9.30	5.38	21.95
CT+HW-CT+HW	13.85	44.95	14.95	47.05	11.38	40.05	17.04	44.60	9.83	28.35	5.27	19.00	17.58	48.70	0.00	0.0	9.22	27.30
CT+H-ZT+H	24.75	66.25	11.99	39.90	10.42	32.35	17.22	50.65	6.70	14.50	4.19	27.80	18.85	47.55	0.00	0.0	5.89	21.05
CT+IWM-ZT+IWM	7.96	14.40	14.84	58.95	11.14	39.35	32.27	83.70	9.31	15.95	5.94	19.65	12.08	42.35	0.00	0.0	6.48	25.55
CT+HW-ZT+HW	15.46	42.85	15.60	55.45	10.25	29.80	15.74	28.85	2.78	6.75	7.50	26.60	21.92	60.05	0.00	15.95	10.78	33.65
ZT+H-ZT+H	10.90	32.50	16.37	58.20	14.95	55.25	28.33	49.95	6.51	16.00	1.66	13.00	15.89	56.15	0.00	5.05	5.40	13.85
ZT+IWM-ZT+IWM	9.36	33.60	13.31	53.50	14.57	46.50	28.20	71.55	6.13	15.20	5.53	7.70	19.16	43.05	0.00	12.10	3.75	16.75
ZT+HW-ZT+HW	15.35	53.25	11.55	39.70	10.56	39.35	15.89	35.15	6.48	18.00	4.90	20.90	30.11	79.40	0.00	0.0	5.17	14.25
ZT+H-ZTR+H	15.12	51.10	18.30	63.45	8.83	34.10	28.18	54.65	4.58	14.15	4.73	22.00	20.28	60.60	0.00	0.0	0.00	0.0
ZT+IWM-ZTR+IWM	10.23	24.00	16.56	67.85	16.84	50.85	21.26	53.60	9.08	25.75	0.00	0.0	19.13	52.80	0.00	0.0	6.91	25.10
ZT+HW-ZTR+HW	10.96	41.55	18.02	46.80	13.48	46.50	22.86	47.90	7.71	21.20	3.45	24.45	19.56	62.70	0.00	0.0	3.98	8.85
ZTR+H-ZTR+H	16.16	42.35	19.57	62.90	22.34	58.65	15.65	26.45	2.94	4.60	0.00	17.80	23.36	79.55	0.00	7.70	0.00	0.0
ZTR+IWM-ZTR+IWM	18.08	61.45	19.04	73.50	18.06	35.35	13.70	27.40	5.25	9.60	8.54	23.35	17.34	60.90	0.00	8.40	0.00	0.0
ZTR+HW-ZTR+HW	12.99	37.90	14.14	47.40	18.19	51.40	15.63	41.35	5.71	14.90	6.23	22.40	20.50	58.40	0.00	3.0	6.62	23.25
Overall	14.04	42.17	15.71	54.83	13.51	42.24	21.55	50.28	6.20	15.62	4.92	18.80	18.88	55.90	0.25	4.10	4.91	16.04

RF, Relative frequency; IVI, Important value index; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

were the most important weeds in the maize field during survey in 2008 as well as in 2018 in the North Western Indian Himalaya. Pala *et al.* (2020) reported that change in IVI values might be due to change in climate, nature of soil and management factors. However, Pala and Mennan (2018) also reported that *Avena fatua* with a high important value index in wheat crop. Due to the abundance of weed seeds in soil, *A. conyzoides* and *D. absynicum* tend to dominate most cropping systems and tillage practices (Thomas and Frick 1993).

Weed phyto-sociology in wheat crop

Relative density (RD), relative abundance (RA) relative frequency (RF) and important value index (IVI) of weeds in wheat crop indicated that among seven (six annual and one perennial) weed species during *Rabi* season in wheat crop, overall percent RD and RF was higher for *Avena ludoviciana*, whereas, RA was higher for *Daucus carota* (**Table 6** and **7)**. Among tillage and weed treatments combination, CT+IWM-CT+IWM had higher RD of *Lolium temulentum*, *A. ludoviciana*, *P. minor*, *D. carota* and *V. sativa*, whereas, ZT+HW-ZT+HW had higher RD for *Poa annua*. Thomas and Frick (1993) also found that in no-till systems, broad leaf perennials are less abundant. CT+IWM-ZT+IWM had higher RD value for *Lolium temulentum*, whereas, ZT+H-ZT+H had higher RF percent value. CT+H-CT+H had higher RA value, whereas, ZT+H-ZT+H resulted in higher value of RF for *L. temulentum*. ZTR+H-ZTR+H had high percent value of *A. ludoviciana*, whereas, CT+H-CT+H resulted in higher RF. CT+IWM-CT+IWM resulted in higher RA per cent value of *P. minor* and *C. didymus* in wheat crop, whereas, CT+H-CT+H had higher value of RF of these weeds. CT+H-ZT+H had higher value of RF for *Daucus carota*, however, ZTR+IWM-ZTR+IWM had higher RF for *Vicia sativa.* ZT+IWM-ZTR+IWM resulted in higher RA for *D. carota*. Kells and Meggitt (1985) also reported that no-tillage systems favored perennial weeds. Froud-Williams (1988) and Kells and Meggitt (1985) also found that no-till systems tend to favor annual grass species over annual broadleaf species. Highest averaged overall IVI value was reported for *A. ludoviciana* (76.99%) followed by *Poa annua* (58.55%) and *L. temulentum* (47.69%) (**Table 7**). Among all the weeds, *Coronopus didymus* (15.66%) had lowest averaged IVI. Among different treatment combinations, highest IVI for *A. ludoviciana* was recorded in CT+H-CT+H followed by ZTR+H-ZTR+H.

Lolium temulentum had higher IVI in CT+H-CT+H followed by CT+IWM-ZT+IWM. *P. minor* had higher IVI value in CT+H-ZT+H followed by ZT+H-ZT+H. ZT+IWM-ZTR+IWM followed by ZT+HW-ZTR+HW had highest IVI value for *D. carota* among all the treatments combinations. However, *Vicia sativa*, a annual broad-leave weed had higher IVI value in ZT+IWM-ZT+IWM followed by ZTR+HW-ZTR+HW and ZTR+IWM-ZTR+IWM.

System productivity

In a maize-wheat cropping system, tillage and weed control treatments made significant contributions to the grain yield of main and intercrop

Table 6. Effect of treatments on relative density of associated weed species in wheat crop

Treatment	*Lolium temulentum*		*Avena ludoviciana*		*Phalaris minor*		*Coronopus didymus*		*Daucus carota*		*Poa annua*		*Vicia sativa*	
	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA	RD	RA
CT+H-CT+H	5.56	12.58	72.74	40.92	11.91	20.22	0.00	0.00	2.39	16.18	7.42	10.11	0.00	0.00
CT+IWM-CT+IWM	57.50	15.58	94.67	22.63	62.72	22.95	18.14	4.65	70.04	19.55	12.91	7.27	46.77	7.39
CT+HW-CT+HW	24.98	29.99	22.46	25.72	8.03	17.36	19.18	0.00	8.23	13.29	10.49	6.37	6.65	7.28
CT+H-ZT+H	13.95	25.99	23.51	20.88	23.91	18.48	0.00	0.00	20.31	18.61	12.36	5.71	5.98	10.35
CT+IWM-ZT+IWM	32.14	34.48	19.50	19.69	1.52	3.77	0.00	0.00	26.53	28.72	13.40	5.52	6.92	7.82
CT+HW-ZT+HW	7.22	20.97	18.23	22.54	8.94	10.41	13.13	0.00	31.93	33.32	19.81	8.68	0.75	4.10
ZT+H-ZT+H	19.55	20.04	49.98	29.18	17.71	17.42	0.40	0.00	3.90	16.11	1.54	6.06	6.93	11.21
ZT+IWM-ZT+IWM	26.51	31.05	23.58	20.05	7.07	9.37	0.00	0.00	15.83	25.86	18.06	7.44	8.95	6.25
ZT+HW-ZT+HW	1.58	15.88	10.27	13.79	13.52	9.51	5.22	0.00	34.38	39.40	28.04	13.17	7.01	8.26
ZT+H-ZTR+H	17.29	20.80	14.80	16.11	2.84	6.35	0.00	0.00	34.78	34.93	20.20	9.67	10.10	12.15
ZT+IWM-ZTR+IWM	3.24	8.91	12.68	13.11	4.29	5.20	3.84	0.00	64.72	59.43	3.40	5.35	7.84	8.01
ZT+HW-ZTR+HW	6.44	30.14	28.81	22.11	11.33	11.22	8.12	0.00	30.13	25.86	11.84	5.39	3.36	5.29
ZTR+H-ZTR+H	8.77	19.51	41.52	38.02	8.37	6.80	10.04	0.00	19.50	24.02	1.85	3.89	9.97	7.78
ZTR+IWM-ZTR+IWM	13.81	19.49	26.97	31.96	6.31	6.06	4.27	0.00	21.41	25.63	8.04	4.64	19.22	21.56
ZTR+HW-ZTR+HW	3.62	16.03	16.00	11.91	9.05	6.64	5.12	0.00	33.79	33.27	20.22	10.01	12.22	8.56
Overall	16.15	21.43	31.71	24.15	13.17	11.45	5.83	0.31	27.86	27.61	12.64	7.28	10.18	8.40

Weed species: columns 2–15.

RD, Relative density; RA, Relative abundance; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

Table 7. Effect of treatments on relative frequency (RF) and important value index (IVI) of associated weed species in wheat crop

Treatment	*Lolium temulentum*		*Avena ludoviciana*		*Phalaris minor*		*Coronopus didymus*		*Daucus carota*		*Poa annua*		*Vicia sativa*	
	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI	RF	IVI
CT+H-CT+H	13.04	31.20	52.17	165.85	17.39	21.80	0.00	27.75	4.35	9.65	13.04	34.50	0.00	9.30
CT+IWM-CT+IWM	17.21	61.25	20.65	72.90	14.92	50.25	8.04	11.70	16.60	48.20	9.97	30.80	12.62	24.90
CT+HW-CT+HW	20.74	67.85	22.21	70.30	4.41	41.35	9.74	26.95	17.15	17.90	16.81	56.25	8.96	19.45
CT+H-ZT+H	12.02	63.00	25.00	64.15	12.02	54.60	0.00	2.70	25.00	28.25	18.91	64.40	7.05	22.95
CT+IWM-ZT+IWM	20.02	66.75	21.26	61.35	3.75	11.35	0.00	8.70	20.00	50.65	21.24	70.75	13.74	30.50
CT+HW-ZT+HW	8.12	47.00	18.95	90.50	8.12	37.95	19.60	31.05	22.96	42.25	19.60	46.45	2.66	4.75
ZT+H-ZT+H	24.62	72.60	43.49	96.40	11.60	51.25	1.47	6.70	7.23	8.45	2.90	38.35	8.70	26.30
ZT+IWM-ZT+IWM	17.88	47.90	24.84	55.10	6.90	35.15	0.00	12.90	13.12	34.90	20.03	77.35	17.24	36.80
ZT+HW-ZT+HW	2.30	36.75	17.25	45.55	13.22	46.25	13.80	12.60	20.11	43.45	20.69	85.25	12.65	30.15
ZT+H-ZTR+H	19.25	39.45	21.52	51.35	4.62	29.20	0.00	7.80	23.09	49.90	20.76	106.65	10.78	15.75
ZT+IWM-ZTR+IWM	9.45	33.90	25.20	62.15	10.23	22.35	4.73	13.85	28.35	88.65	7.88	53.35	14.18	25.75
ZT+HW-ZTR+HW	4.17	37.85	25.01	86.70	9.73	42.95	13.17	18.30	22.93	53.60	18.06	51.30	6.95	9.40
ZTR+H-ZTR+H	9.26	37.55	22.23	101.80	11.12	36.75	22.23	25.15	16.67	46.15	3.67	36.20	14.82	16.40
ZTR+IWM-ZTR+IWM	14.68	47.95	17.39	76.35	9.77	46.75	6.52	12.30	17.39	35.30	15.22	50.70	19.02	30.60
ZTR+HW-ZTR+HW	4.68	24.30	12.86	54.40	12.28	41.60	10.53	16.40	21.06	51.30	19.89	75.90	18.71	36.15
Overall	13.16	47.69	24.67	76.99	10.00	37.97	7.32	15.66	18.40	40.57	15.24	58.55	11.20	22.61

Weed species: columns 2–15.

RF, Relative frequency; IVI, Important value index; CT, conventional tillage; ZT, zero tillage; ZTR, zero tillage in combination with residue; H, recommended herbicides; IWM, integrated weed management; HW, hand weeding; CT+H-CT+H, Conventional tillage in maize in combination with recommended herbicides in maize-wheat

along with system productivity in terms of MEY (maize cob equivalent yield) (**Table 8**). In ZTR-ZTR, higher grain yield of maize and wheat crop was recorded which was statistically similar to the CT-CT and CT-ZT. Consequently, higher MEY was recorded in ZTR-ZTR (13.12 t/ha) which remained statistically (p=0.05) alike with CT-CT (12.60 t/ha) and CT-ZT (12.47 t/ha). In case of weed management treatments, application of recommended herbicides (H-H) resulted in higher maize and maize cob equivalent yield; whereas, HW-HW had higher wheat grain yield. Prasai *et al.* (2018) also reported that

Table 8. Effect of tillage and weed management treatments on grain yield of maize, wheat and intercrop (soybean, mustard) and maize equivalent yield (MEY) (t/ha) (mean of 2 year's)

	Maize cob yield (t/ha)	Soybean grain yield (t/ha)	Wheat grain yield (t/ha)	Mustard grain yield (t/ha)	MEY (t/ha)
Tillage					
CT-CT	7.47[ab]	0.15[a]	5.45[ab]	0.04[bc]	12.60[a]
CT-ZT	7.26[bc]	0.10[b]	5.75[a]	0.03[c]	12.47[a]
ZT-ZT	6.93[c]	0.07[c]	4.72[c]	0.03[c]	11.17[b]
ZT-ZTR	7.00[c]	0.06[c]	5.01[bc]	0.05[b]	11.51[b]
ZTR-ZTR	7.74[a]	0.08[bc]	5.92[a]	0.07[a]	13.12[a]
LSD (p=0.05)	0.35		0.64		0.70
Weed management					
H-H	7.57[a]	0.00	6.28	0.00	12.81[a]
IWM-IWM	7.57[a]	0.27	3.32	0.14	11.60[b]
HW-HW	6.69[b]	0.00	6.51	0.00	12.11[ab]
LSD (p=0.05)	0.46	0.11	0.83	0.04	0.84

CT, conventional tillage; ZT, zero tillage; R, residues; H, herbicide; IWM-IWM, integrated weed management; HW, hand weeding; MEY, wheat grain equivalent yield; figures with the same sign as superscript mean statistically (p=0.05) similar

conservation agriculture resulted in higher system productivity compared to the conventional till plots.

Weed control is a major challenge for the adoption of CA-based production systems. Conservation production system (ZTR-ZTR) had higher system productivity compared to the conventional tilled plots and zero tilled plots in maize-wheat cropping system. Different tillage operations and weed management practices influenced the weed shifts and weeds phyto-sociology, but consistent relationship between weed species dominance with tillage and weed management system was not observed which indicate that aside from tillage, residues incorporation and the weed management practices could play a role in influencing weed shifts and weed population diversity. Although, CA in combination with recommended herbicides had higher system productivity, it is necessary to continuously identify economically feasible weed management practices to effectively manage the weeds shifts over time in CA.

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RESEARCH ARTICLE

Evaluation of weed management efficacy of post-emergence herbicides in blackgram under semi-arid Alfisols

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ABSTRACT

The efficacy of a post-emergence herbicides in managing weeds in blackgram was evaluated during summer and rainy *(Kharif)* seasons of 2016 at University of Agricultural Sciences (UAS), GKVK, Bangalore, India. The experiments were laid in RCBD with three replications comprising of nine treatments. Major weed species observed were: *Cyperus rotundus, Eleuisine indica, Dactyloctenium aegyptium, Borreria articularis, Echinochloa colona, Commelina benghalensis, Euphorbia geniculata, Phyllanthus niruri.* The post-emergence application (PoE) of sodium acifluorfen 16.5% + clodinafop-propargyl 8% EC (206.25 + 100 g/ha) has attained significantly higher seed and haulm yield of blackgram (1305 and 2088 kg/ha, respectively) in summer 2016 and (1519 and 2253 kg/ha, respectively) in *Kharif* 2016, followed by sodium acifluorfen 16.5% + clodinafop-propargyl 8% EC (165 + 80 and 123.75 + 60 g/ha) (1192 and 1808 kg/ha, respectively) in summer 2016 and (1425 and 2095 kg/ha, respectively) in *Kharif* 2016. Similarly the weed control efficiency in summer and kharif 2016 was higher with sodium acifluorfen + clodinafop-propargyl (330 + 160 g/ha) PoE (93.20 and 91.0%, respectively) and it was followed by sodium acifluorfen + clodinafop-propargyl (206.25 + 100 g/ha) PoE (89.51 and 90.24%, respectively) when compared to weedy check. The increased yield was mainly due to a significant reduction in weed density and biomass, without any phytotoxicity to succeeding finger millet crop under semi-arid Alfisols.

Keywords: Blackgram, Bio-efficacy, Clodinafop-propargyl, Economics, Sodium acifluorfen, Weed management

INTRODUCTION

The pulses contribute significantly to the dietary protein in different regions in India. The pulses also maintain soil fertility through the process of biological nitrogen fixation (BNF) in the soil, while being a rich source of protein to the human population. Thus, the pulses play a vital role in furthering sustainable agriculture under rainfed condition. Among different pulses, blackgram which is also known as urd bean, is a rich source of protein and carbohydrates. Blackgram is grown as a subsidiary crop because of less inputs and lower management given to the crop at all soil and agro-climatic conditions. However, the weeds are severe threat to the blackgram crop growth as they compete with crop for the limited resources like water, nutrient, light and space leading to a significant reduction in growth and seed yield of blackgram (Upasani *et al*. 2017), which range from 43.2 to 64.1% during *Kharif* (Chand *et al*. 2004, Rathi *et al*. 2004) and 46.0 to 53.0 % during summer season (Bhandari *et al*. 2004, Kumar and Tewari 2004).

Weed management with conventional hand weeding was observed to be highly expensive among different weed control methods due to the non-availability and increased cost of labour at some of the most important and critical stages of the crop weed competition. In addition, the unusual and incessant rains make it difficult to enter into the fields for hand weeding. Hence, the timely control of weeds in blackgram using herbicides would be preferable and the use of post-emergent herbicides could be better option for the control of weeds during the early stages of the crop growth. The present study was undertaken to evaluate the efficacy of different post-emergent herbicides for efficient management of weeds in blackgram for attaining profitable yields under semi-arid Alfisols.

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MATERIALS AND METHODS

Field experiments were conducted during rainy *(Kharif)* 2016 and summer 2016 seasons at the University of Agricultural Sciences, GKVK, Bangalore. Blackgram (Rashmi variety) was sown at a spacing of 30 × 10 cm in both summer and *Kharif* seasons. The summer crop was sown on 1st February and harvested on 28th April 2016. The *Kharif* crop was sown on 20th July and harvested on 20th October 2016. The post-emergence application (PoE) of herbicides was done at 22 days after seeding (DAS) using 500 litres of water per ha with flat fan nozzle attached to the knapsack sprayer. The study was conducted with 9 treatments arranged in a Randomized block design with 3 replications. The nine treatments include: sodium acifluorfen 16.5% + clodinafop-propargyl 8% EC (sodium acifluorfen + clodinafop-propargyl) 330 + 160 g /ha PoE; sodium acifluorfen + clodinafop-propargyl 206.25+100 g/ha PoE; sodium acifluorfen + clodinafop-propargyl 165 + 80 g/ha PoE; sodium acifluorfen + clodinafop-propargyl 123.75 + 60 g/ha PoE; sodium acifluorfen 165 g/ha PoE; clodinafop-propargyl 80 g/ha PoE; propaquizafop 100 g/ha PoE; hand weeding twice 20 and 45 DAS and weedy check (untreated).

The observations on weed density (no./m^2) of different species were collected in a quadrat of 50 × 50 cm on 20, 45, 65 DAS and at harvest. The weeds collected were used for determining weed dry weight (biomass) per m^2 at 20, 45, 60 DAS and at harvest. The measurements on herbicide efficiency index (HEI) and weed control index (WCI) were calculated at the harvest of blackgram. The observations collected in each of the season on the weed density and biomass have been transformed using the square-root transformation. The weed control efficiency (WCE) at harvest was calculated. The observations on seed yield (kg/ha) and haulm yield (kg/ha) were recorded at harvest in each of the treatment during summer and kharif seasons of this study.

Herbicide efficiency index (HEI) and Weed control efficiency (WCE) of different treatments were also calculated as per the formula suggested by Krishnamurthy *et al.* (1975) and Walia (2003), respectively.

$$\text{HEI} = \frac{\text{Yield of treated plot} - \text{Yield in Control}}{\text{Yield in Control}}$$

$$\text{WCE} = \frac{\text{Weed dry weight in control} - \text{Weed dry weight in treated}}{\text{Weed dry weight in control}} \times 100$$

After the harvest of the greengram crop, the residual crop finger millet was grown to know the phytotoxicity effect on succeeding crop.

The differences between 9 treatments in influencing the seed yield were tested based on the Analysis of Variance (ANOVA) in each year and also pooled over years. The treatments were compared for superiority based on the Duncan's Multiple Range Test (DMRT) at $p < 0.05$ and $p < 0.01$ level of significance (Gomez and Gomez 1984)

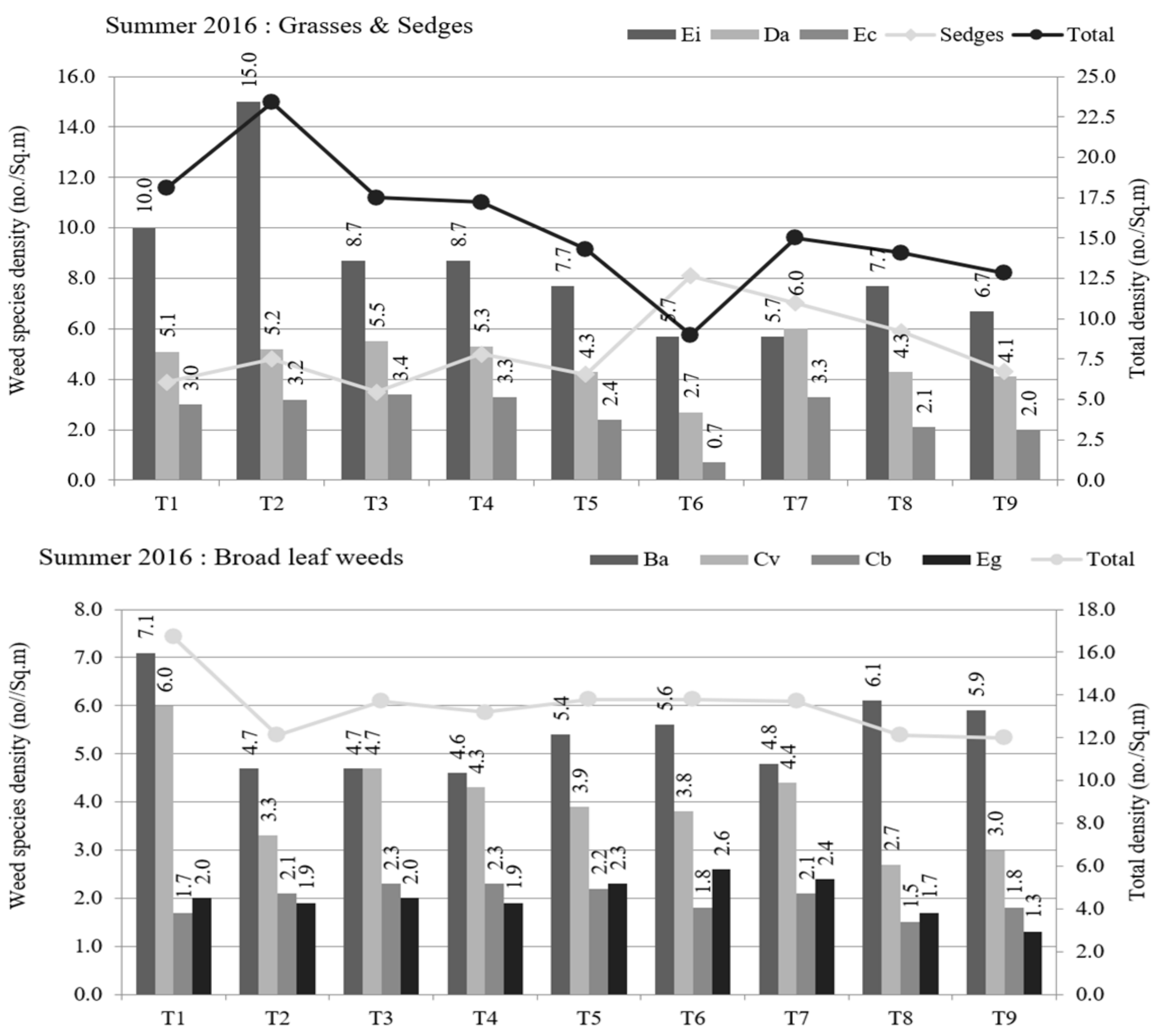
RESULTS AND DISCUSSION

Weed flora

The weed flora observed in this study comprised of: *Cyperus rotundus,* the sedge; *Eleusine indica, Dactyloctenium aegyptium, Echinochloa colona* amongst grasses, *Borreria articularis, Cleome viscosa, Phyllanthus niruri, Commelina benghalensis, Euphorbia geniculata, Alternenthara* spp., *etc.* among broad-leaved weeds. A few other weeds observed in lesser numbers were *Amaranthus viridis, Cleome monophylla* and *Acanthospermum hispidum.*

During summer 2016, the sedges density ranged from 3.5 to 8.1 per m^2 with mean of 5.2/m^2. Among different grasses, *E. indica* density ranged from 5.7 to 15.0/m^2 with mean of 8.4/m^2, while *D. aegyptium* density ranged from 2.7 to 6.0/m^2 with mean of 4.7/m^2. *E. colona* density ranged from 0.7 to 3.4/m^2 with mean of 2.6/m^2, while the total weed species density of all the 3 grasses ranged from 9.0 to 23.4/m^2 with mean of 15.7/m^2 (**Figure 1**). Among broad-leaved weeds, *B. articularis* ranged from 4.6 to 7.1/m^2 with mean of 5.4/m^2, while *C. viscose* ranged from 2.7 to 6.0/m^2 with mean of 4.0/m^2. *C. benghalensis* ranged from 1.5 to 2.3/m^2 with mean of 2.0 per, while *E. geniculata* ranged from 1.3 to 2.6/m^2 with mean of 2.0/m^2. The total of all broad-leaved weeds ranged from 12.0 to 16.7/m^2 with mean of 13.5/m^2, while the grand total of all sedges, grasses and broad-leaved weeds ranged from 30.1 to 40.3/m^2 with mean of 34.5 /m^2. (**Figure 1**).

During *Kharif* 2016, the sedges density ranged from 4.8 to 9.1/m^2 with mean of 6.8/m^2 (**Figure 2**). Among grasses, *E. indica* density ranged from 12.3 to 17.3/m^2 with mean of 14.6/m^2, while *D. aegyptium* density ranged from 5.1 to 8.2/m^2 with mean of 7.1/m^2. *E. colona* density ranged from 2.9 to 5.0/m^2 with mean of 3.8/m^2, while the total grasses weed species density ranged from 20.8 to 29.9/m^2 with mean of 25.5/m^2. Among broad-leaved weeds, *B. articularis* density ranged from 6.5 to 10.7/m^2 with mean of 8.0/m^2, while *C. viscose* density ranged from 4.2 to 6.0/m^2 with mean of 4.9/m^2. *P. niruri* density ranged from 2.0 to 2.8/m^2 with mean of 2.2/m^2, while *C.*



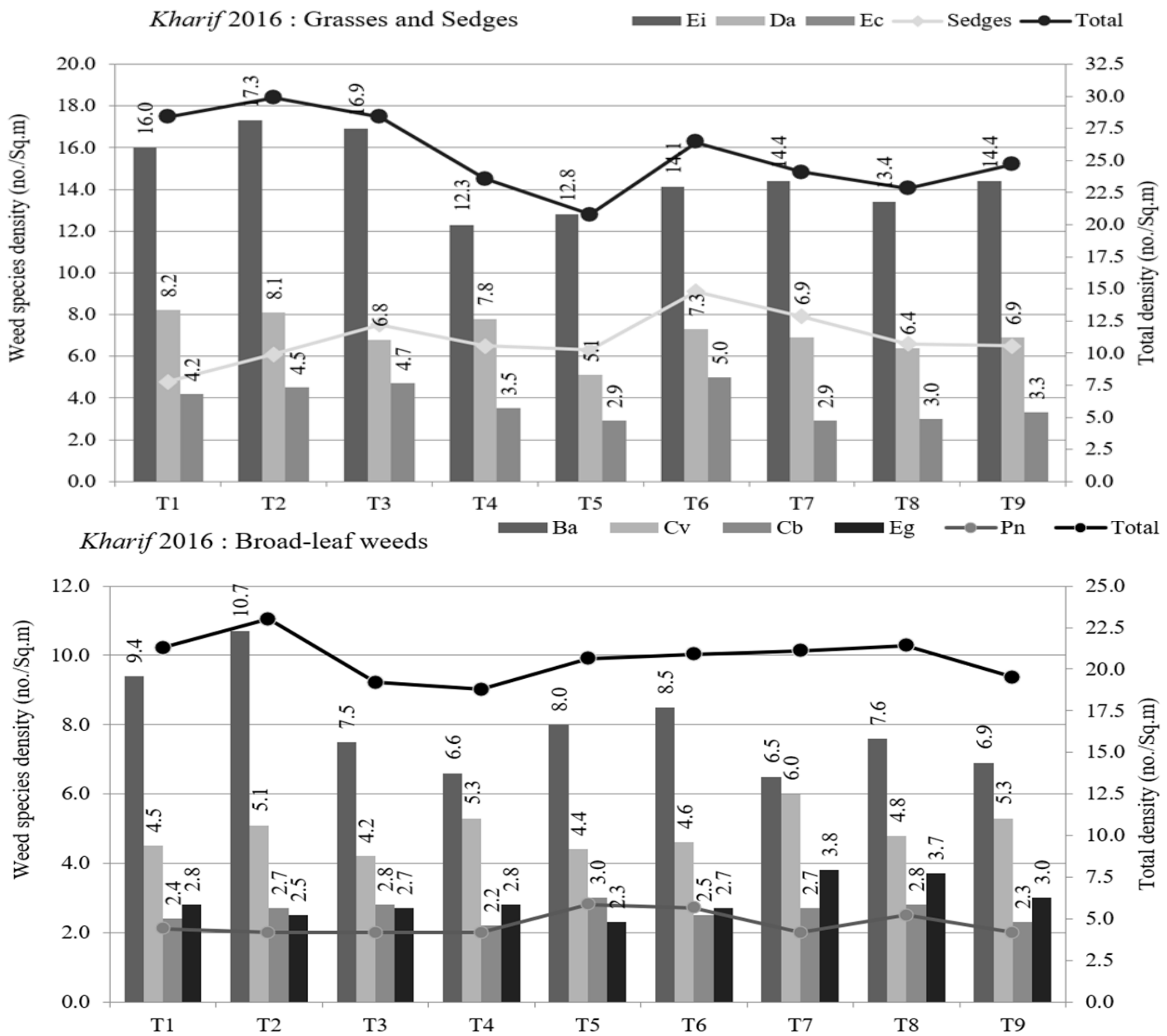
T$_1$: Sodium acifluorfen + clodinafop-propargyl (123.75 + 60 g/ha); T$_2$: Sodium acifluorfen + clodinafop-propargyl (165 + 80 g/ha); T$_3$: Sodium acifluorfen + clodinafop-propargyl (206.25 + 100 g/ha); T$_4$: Sodium acifluorfen (165 g/ha); T$_5$: Clodinafop-propargyl (80 g/ha); T$_6$: Propaquizafop; T$_7$: Hand weeding twice at 20 and 45 DAS; T$_8$: Weedy check (untreated); and T$_9$: Sodium acifluorfen + clodinafop-propargyl (330+160 g/ha); EI = *Eleusine indica*; DA = *Dactyloctenium aegyptium*; EC = *Echinochloa colona*; BA = *Borreria articularis*; CV = *Cleome viscosa*; CB = *Commelina benghalensis*; EG = *Euphorbia geniculate*; PN = *Phyllanthus niruri*

Figure 1. The density of grasses, sedges and broad-leaf weeds under different treatments in blackgram during summer 2016

benghalensis density ranged from 2.2 to 3.0/m^2 with mean of 2.6/m^2 and *E. geniculate* density ranged from 2.3 to 3.8/m^2 with mean of 2.9/m^2. The total broad-leaved weeds density ranged from 18.8 to 23.0/m^2 with mean of 20.6/m^2, while the total of all sedges, grasses and broad-leaved weeds density ranged from 47.6 to 59.0/m^2 with mean of 52.9/m^2 (**Figure 2**).

Effect on weed density

During summer 2016, the total weed density ranged from 5.49 to 6.34/m^2 with mean of 5.86/m^2 at 20 DAS; 3.99 to 7.65/m^2 with mean of 5.25/m^2 at 45 DAS 3.15 to 8.34/m^2 with mean of 4.88/m^2 at 65 DAS and 2.73 to 10.05/m^2 with mean of 5.15/m^2 at harvest of the crop (**Table 1**). During *Kharif* 2016, the weed density ranged from 6.90 to 7.68/m^2 with mean of 7.27/m^2 at 20 DAS; from 5.31 to 8.59/m^2 with mean of 6.40/m^2 at 45 DAS; from 3.49 to 9.67/m^2 with mean of 5.42/m^2 at 65 DAS and from 3.04 to 10.57/m^2 with mean of 5.40/m^2 at harvest of the crop. Based on F-test, the treatments were found to be significantly different at 20, 45, 65 DAS and at harvest in influencing the weed density during both summer 2016 and *Kharif* 2016.



T_1: Sodium acifluorfen + clodinafop-propargyl (123.75 + 60 g/ha); T_2: Sodium acifluorfen + clodinafop-propargyl (165 + 80 g/ha); T_3: Sodium acifluorfen + clodinafop-propargyl (206.25 + 100 g/ha); T_4: Sodium acifluorfen (165 g/ha); T_5: Clodinafop-propargyl (80 g/ha); T_6: Propaquizafop; T_7: Hand weeding twice at 20 and 45 DAS; T_8: Weedy check (untreated); and T_9: Sodium acifluorfen + clodinafop-propargyl (330+160 g/ha); EI = *Eleusine indica*; DA = *Dactyloctenium aegyptium*; EC = *Echinochloa colona*; BA = *Borreria articularis*; CV = *Cleome viscosa*; CB = *Commelina benghalensis*; EG = *Euphorbia geniculate*; PN = *Phyllanthus niruri*

Figure 2. The density of grasses, sedges and broad-leaved weeds under different treatments in blackgram during *Kharif* 2016

At 45 DAS, sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE recorded a significantly lower weed density (24.9 no./m^2), followed by its application rate of 165 + 80 g/ha and 123.75 + 60 g/ha (29.4 and 29.2 no./m^2). A similar trend of the weed density was observed at 65 DAS and harvest. The significantly lower weed density was found to be due to the combined application of sodium acifluorfen and clodinafop-propargyl, since the sodium acifluorfen was found to effectively control the broad-leaved weeds by inhibiting the enzyme protoporphyrinogen oxidase (PPG) in the weed species and clodinafop-propargyl efficacy was due to its inhibitory action on the enzyme Acetyl co-A carboxylase (Accase) which was found to effectively control the grassy weeds and provided a lower weed density (Rao 2011).

Effect on weed biomass

During summer 2016, the weed biomass ranged from 2.59 to 2.95 g/m^2 with mean of 2.76 g/m^2 at 20 DAS; from 2.28 to 4.02 g/m^2 with mean of 2.85 g/m^2 at 45 DAS; from 1.92 to 4.47 g/m^2 with mean of 2.72 g/m^2 at 65 DAS and from 1.78 to 5.42 g/m^2 with mean of 2.87 g/m^2 at harvest of blackgram crop (**Table 2**). During *Kharif* 2016, the weed biomass ranged from

3.19 to 3.52 g/m² with mean of 3.35 g/m² at 20 DAS; 2.72 to 4.34 g/m² with mean of 3.30 g/m² at 45 DAS; from 2.01 to 4.94 g/m² with mean of 2.93 g/m² at 65 DAS and from 2.14 to 6.36 g/m² with mean of 3.39 g/m² at harvest of the crop. The treatments were found to be significantly different at 45 and 65 DAS and harvest in summer 2016, while they were significantly different at 20, 45, 65 DAS and harvest in influencing the weed biomass.

At 20 DAS, the weed biomass was found to be lower in the control (7.98 g/m²) *i.e.*, before actually imposing the treatments. At 45 DAS, lower weed biomass was found with sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE (6.88 g/m²). This was followed by its application rate of 123.75 + 60 g/ha and 165 + 80 g/ha (7.09 and 7.26 g/m²). At 60 DAS and at harvest of the crop also similar trend was found. The decreased weed biomass with the sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE was mainly because of its effective control of grasses and broad-leaved weeds throughout the crop growth. Similar results were observed by Choudhary *et al*. (2017) and Biswal (2017) in groundnut.

Table 1. Effect of post-emergence application (PoE) of herbicides and other weed control treatments on total weed density (no./m²) at different days after sowing (DAS) in blackgram during summer 2016 and *Kharif* 2016

Treatment	20 DAS		45 DAS		65 DAS		At Harvest	
	Summer	*Kharif*	Summer	*Kharif*	Summer	*Kharif*	Summer	*Kharif*
Sodium acifluorfen + clodinafop-propargyl 123.75 + 60 g/ha PoE	6.21(38.8)	7.38(54.4)	5.18(26.8)	6.09(37.1)	3.75(14.1)	4.37 (18.9)	3.21 (10.3)	3.69 (13.6)
Sodium acifluorfen + clodinafop-propargyl 165 + 80 g/ha PoE	6.34(40.3)	7.68(59.0)	4.66(21.7)	5.53(30.6)	3.45(11.9)	3.99 (15.9)	3.29 (10.8)	3.44 (11.8)
Sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE	5.88(34.7)	7.42(55.1)	4.23(17.9)	5.15(26.5)	3.3(10.9)	3.65 (13.3)	3.11(9.7)	3.24 (10.5)
Sodium acifluorfen 165 g/ha PoE	5.95(35.4)	6.99(48.9)	6.38(40.7)	7.44(55.3)	6.70(44.9)	7.10 (50.4)	7.57 (57.3)	7.70 (59.3)
Clodinafop-propargyl 80 g /ha PoE	5.68(32.3)	6.90(47.6)	5.83(34.0)	6.76(45.7)	5.48(30.1)	6.08 (37.0)	6.11 (37.3)	6.74 (45.4)
Propaquizafop 100 g/ha PoE	5.55(30.9)	7.51(56.5)	5.79(33.6)	7.16(51.3)	6.04(36.4)	6.60 (43.6)	6.54 (42.8)	6.97 (48.6)
Hand weeding twice 20 and 45 DAS	5.97(35.6)	7.29(53.1)	3.99(15.2)	4.46(20.00)	3.68(13.5)	3.49 (12.2)	4.56 (20.8)	3.04(9.2)
Weedy check	5.66(32.1)	7.13(50.8)	7.65(58.5)	8.59(73.8)	8.34(70.0)	9.67 (93.6)	10.05(101.2)	10.57 (111.7)
Sodium acifluorfen + clodinafop-propargyl 330 + 160 g/ha PoE	5.49(29.1)	7.11(49.6)	4.16(16.3)	5.31(27.2)	3.15(8.9)	3.63(12.2)	2.73(6.5)	3.28(9.8)
LSD (p=0.05)	0.53	0.54	0.34	0.27	0.49	0.24	0.52	0.30
Minimum	5.49	6.90	3.99	4.46	3.15	3.49	2.73	3.04
Maximum	6.34	7.68	7.65	8.59	8.34	9.67	10.05	10.57
Mean	5.86	7.27	5.25	6.26	4.88	5.40	5.15	5.40
SD	0.29	0.26	1.17	1.09	1.84	2.11	2.55	2.68

Data averaged over three replications; Data analyzed using transformation= Square root of (x+1); Data within parentheses are original values

Table 2. Effect of post-emergence application (PoE) of herbicides and other weed control treatments on weed biomass (g/m²) observed on different days after sowing (DAS) in blackgram during summer 2016 and *Kharif* 2016

Treatment	20 DAS		45 DAS		65 DAS		At Harvest	
	Summer	*Kharif*	Summer	*Kharif*	Summer	*Kharif*	Summer	*Kharif*
Sodium acifluorfen + clodinafop-propargyl 123.75 + 60 g/ha PoE	2.95(7.7)	3.40(10.5)	2.64(5.97)	3.08(9.1	2.60(5.7)	2.53(5.4)	2.67(6.1)	2.96(7.7)
Sodium acifluorfen + clodinafop-propargyl 165 + 80 g/ha PoE	2.92(7.5)	3.52(11.4)	2.66(4.70)	3.03(8.2)	2.08(3.3)	2.25(4.1)	2.14(3.6)	2.30(4.3)
Sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE	2.79(6.8)	3.42(10.7)	2.62(4.25)	2.98(7.9)	2.06(3.2)	2.19(3.8)	2.00(3.0)	2.20(3.8)
Sodium acifluorfen 165 g/ha PoE	2.59(5.7)	3.29(9.8)	2.28(4.20)	2.80(6.8)	1.92(2.7)	2.07(3.3)	1.78(2.2)	2.14(3.6)
Clodinafop-propargyl 80 g /ha PoE	2.79(6.8)	3.23(9.5)	3.44(10.9)	3.68(12.6)	3.59(11.8)	3.73(12.9)	3.92(14.3)	4.68(21.0)
Propaquizafop 100 g/ha PoE	2.71(6.4)	3.19(9.2)	2.70(6.3)	3.39(10.5)	2.70(6.3)	3.20(9.3)	2.84(7.1)	3.30(9.9)
Hand weeding twice 20 and 45 DAS	2.64(6.0)	3.45(10.9)	2.79(6.9)	3.66(12.4)	2.86(7.2)	3.45(10.9)	2.98(7.9)	4.26(17.2)
Weedy check	2.79(6.8)	3.36(10.3)	2.48(3.9)	2.72(6.4)	2.23(4.0)	2.01(3.05)	2.09(6.0)	2.33(4.4)
Sodium acifluorfen + clodinafop-propargyl 330+160 g/ha PoE	2.67(6.1)	3.29(9.8)	4.02(15.2)	4.34(17.8)	4.47(19.0)	4.94(23.4)	5.42(28.4)	6.36(39.4)
LSD (p=0.05)	NS	0.16	0.35	0.40	0.32	0.19	0.32	0.20
Minimum	2.59	3.19	2.28	2.72	1.92	2.01	1.78	2.14
Maximum	2.95	3.52	4.02	4.34	4.47	4.94	5.42	6.36
Mean	2.76	3.35	2.85	3.30	2.72	2.93	2.87	3.39
SD	0.12	0.11	0.54	0.52	0.94	1.00	1.33	1.50

Data averaged over three replications; Data analyzed using transformation= Square root of (x+1); Data within parentheses are original values

Herbicide efficiency index

The herbicide efficiency index (HEI) would indicate about the potential of the herbicide for killing the weeds in the field (Krishnamurthy *et al.* 1975). Maximum herbicide efficiency index was observed with sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE (5.92%), followed by its application rate of 123.75 + 60 g/ha and 165 + 80 g/ha (4.38 and 3.94%) (**Table 3**). Higher herbicide efficiency index was observed due to the broad spectrum of weed control by the PoE herbicides in blackgram which have resulted in a significantly lower weed biomass in those treatments.

Weed index

The weed index is an index which is indicative of the weed's competition effect on the grain yield. The weedy check treatment was found to attain a significantly higher weed index of 58.41%. The weed index ranged from 10.90 to 58.41% with mean of 31.10% during summer 2016, while it ranged from 5.3 to 56.50% with mean of 27.0% during *Kharif* 2016. Lower weed index was found with sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha (8.59%) PoE, followed by its application of 165 + 80 g/ha 123.75 + 60 g/ha (15.34 and 35.63%, respectively) (**Table 3**). The lower weed index was due to satisfactory control of all the weeds resulting in a significant reduction in the crop and weed competition. This has also enabled the crop to efficiently utilize all the available resources like light, nutrients, moisture and space (Gupta by *et al.* 2013).

Weed control efficiency

The weed control efficiency at harvest stage ranged from 46.86 to 93.2% with mean of 68.40% in summer 2016 and from 48.18 to 91.0% with mean of 69.10% in *Kharif* 2016 (**Table 3**). Among different herbicides, a significantly higher weed control efficiency at the harvest stage was observed with sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha (89.88%), followed by its application at 165 + 80 g/ha and 123.25 + 60 g/ha (88.27 and 79.43%, respectively). The higher weed control efficiency was associated with a minimum weed density and biomass at the subsequent stages due to the herbicide efficacy for a longer period (Jagadesh *et al.* 2019 and Marimuthu *et al.* 2016). The combined application of sodium acifluorfen and clodinafop-propargyl was found to be beneficial and has controlled both the grassy and broad-leaved weeds resulted in a higher weed control efficiency as observed by Jha *et al.* (2014).

Effect of treatments on seed and haulm yield

The seed yield ranged from 616 to 1320 kg/ha with mean of 1021 kg/ha during summer 2016, while it ranged from 705 to 1519 kg/ha with mean of 1176 kg/ha during *Kharif* 2016. The haulm yield ranged from 928 to 2265 kg/ha with mean of 1637 kg/ha during summer 2016, while it ranged from 1148 to 2440 kg/ha with mean of 1860 kg/ha during *Kharif* 2016 (**Table 4**).

The blackgram seed yield (1412 kg/ha) and haulm yield (2171 kg/ha) were significantly higher with sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha and was at par with the hand weeding at 20 and 45 DAS (1543 kg/ha and 2353 kg/ha, respectively). A significantly higher seed yield attained in these treatments was due to an efficient control of all categories of weeds, reduced weed index, higher weed control index and higher

Table 3. Effect of treatments on weed index and weed control efficiency at harvest of blackgram during summer 2016 and *Kharif* 2016

Treatment	Weed index (%)			Weed control efficiency (%) at harvest			Herbicide efficiency index (%)
	Summer	*Kharif*	Pooled	Summer	*Kharif*	Pooled	Pooled
Sodium acifluorfen + clodinafop-propargyl 123.75 + 60 g/ha PoE	36.73	34.53	35.63	78.5	80.35	79.425	4.38
Sodium acifluorfen + clodinafop-propargyl 165 + 80 g/ha PoE	19.51	11.16	15.34	87.47	89.07	88.27	3.94
Sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE	11.88	5.3	8.59	89.51	90.24	89.88	5.92
Sodium acifluorfen + clodinafop-propargyl 330 + 160 g/ha PoE	10.90	9.90	11.00	93.20	91.0	92.1	-
Sodium acifluorfen 165 g/ha	49.97	42.39	46.18	46.86	48.18	46.86	0.44
Clodinafop-propargyl 80 g/ha PoE	45.1	39.03	42.07	74.9	75.03	74.90	0.95
Propaquizafop (100 g/ha) PoE	47.33	44.2	45.77	56.44	64.38	56.44	0.73
Hand weeding twice 20 and 45 DAS	0	0	0	88.74	83.74	88.74	-
Weedy check	58.41	56.50	57.45	0	0	0	-
Minimum	10.90	5.30	8.59	46.86	48.18	46.86	0.44
Maximum	58.41	56.50	57.45	93.20	91.00	92.10	5.92
Mean	31.1	27.0	29.1	68.4	69.1	68.5	2.73
SD	19.0	17.4	18.1	21.4	18.5	19.2	2.31

herbicide efficiency in controlling the weeds to a great extent confirming the findings made by Hemraj *et al.* (2009) in cluster bean and Nishant and Tigga (2018) in blackgram.

Effect of on economics

The cost of cultivation ranged from ₹ 21500/ha to ₹ 31500/ha with mean of ₹ 23988/ha while the gross returns has ranged from ₹ 24400/ha to ₹ 61720/ha with mean of ₹ 43107/ha (**Table 5**). The net returns ranged from ₹ 2900/ha to ₹ 32542/ha with mean of ₹ 19119/ha while the benefit-cost ratio has ranged from 1.13 to 2.36 with mean of 1.78 Minimum cost of cultivation, gross, net return and benefit-cost ratio were recorded with weedy check, while maximum cost of cultivation and gross return was observed with hand weeding twice 20 and 45 DAS. The maximum net returns and benefit-cost ratio was attained by sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE.

Effect on succeeding finger millet crop

The germination percentage of succeeding finger millet was not affected by acifluorfen + clodinafop-propargyl 165 + 80 g/ha and 330 + 160 g/ha PoE and up to 30 days stage of the finger millet crop, yellowing, stunting, wilting and deformities *i.e.*, epinasty, hyponasty and necrosis *etc*. were not noticed (**Table 6**). This was in accordance with Sathya Priya and Chinnusamy (2020).

Conclusion

It can be concluded from this study that post-emergence application of sodium acifluorfen 16.5% + clodinafop-propargyl 8% EC 206.25 + 100 g/ha at 22 DAS results in efficient control of both the grassy and broad-leaved weeds in blackgram with significant improvement in the growth, yield and economics of blackgram crop and it was non phyto-toxic to the succeeding finger millet crop.

Table 4. Effect of treatments on seed yield and haulm yield of blackgram during summer 2016 and *Kharif* 2016

Treatment	Seed yield (kg/ha)			Haulm yield (kg/ha)		
	Summer	*Kharif*	Mean	Summer	*Kharif*	Mean
Sodium acifluorfen + clodinafop-propargyl 123.75 + 60 g/ha PoE	937	1050	994	1587	1784	1686
Sodium acifluorfen + clodinafop-propargyl 165 + 80 g/ha PoE	1192	1425	1309	1808	2095	1952
Sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE	1305	1519	1412	2088	2253	2171
Sodium acifluorfen + clodinafop-propargyl 330 + 160 g/ha PoE	1320	1485	1402	2080	2420	2250
Sodium acifluorfen 165 g/ha	741	924	833	1407	1615	1511
Clodinafop-propargyl 80 g/ha PoE	813	978	896	1308	1523	1416
Propaquizafop (100 g/ha) PoE	780	895	838	1263	1458	1361
Hand weeding twice 20 and 45 DAS	1481	1604	1543	2265	2440	2353
Weedy check	616	705	661	928	1148	1038
SEM	59.38	68.53	46.53	65.32	69.04	62.34
LSD (p=0.05)	178.01	205.59	139.59	195.3	200.22	187.02
Minimum	616	705	66	928	1148	1038
Maximum	1320	1519	1543	2265	2440	2353
Mean	1021	1176	1099	1637	1860	1749
SD	320	317	317	451	457	454

Table 5. Cost of cultivation, gross and net returns and benefit-cost ratio of different treatments in blackgram

Treatment	Cost of cultivation (Rs/ha)	Gross returns (Rs/ha)	Net returns (Rs/ha)	Benefit-cost ratio
Sodium acifluorfen + clodinafop-propargyl 123.75 + 60 g/ha PoE	22963	45200	22237	1.97
Sodium acifluorfen + clodinafop-propargyl 165 + 80 g/ha PoE	23450	41400	17950	1.77
Sodium acifluorfen + clodinafop-propargyl 206.25 + 100 g/ha PoE	23938	56480	32542	2.36
Sodium acifluorfen + clodinafop-propargyl 330 + 160 g/ha PoE	24590	56080	31490	2.28
Sodium acifluorfen 165 g/ha	22738	33320	10582	1.47
Clodinafop-propargyl 80 g/ha PoE	22560	35840	13280	1.59
Propaquizafop (100 g/ha) PoE	22650	33520	10870	1.48
Hand weeding twice 20 and 45 DAS	31500	61720	30220	1.96
Weedy check	21500	24400	2900	1.13
Minimum	21500	24400	2900	1.13
Maximum	31500	61720	32542	2.36
Mean	23988	43107	19119	1.78
SD	2952	12705	10640	0.40

Table 6. Residual effect of Sodium acifluorfen + clodinafop-propargyl on succeeding finger millet crop

Treatment	Germination (%)	Yellowing			Stunting			Wilting			Deformities**		
		7 DAS	15 DAS	30 DAS	7 DAS	15 DAS	30 DAS	7 DAS	15 DAS	30 DAS	7 DAS	15 DAS	30 DAS
Sodium acifluorfen + clodinafop-propargyl (165 + 80 g/ha)	93.0	0	0	0	0	0	0	0	0	0	0	0	0
Sodium acifluorfen + clodinafop-propargyl (330 + 160 g/ha)	90.0	0	0	0	0	0	0	0	0	0	0	0	0
Weedy check (untreated)	94.0	0	0	0	0	0	0	0	0	0	0	0	0

*Mean of three replications, ** Deformities consists epinasty, hyponasty and necrosis, NS=Non significant, DAS: Days After Sowing

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RESEARCH ARTICLE

Effect of herbicides on weeds, yield and economics of chickpea

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ABSTRACT

A filed experiment was conducted at Mahatma Gandhi Chitrakoot Gramodaya Vishwavidyalaya, Chitrakoot, Satna, Madhya Pradesh during winter (*Rabi*) season of 2019-20 and 2020-21 to assess the efficacy of herbicides on production and profitability of chickpea (*Cicer arietinum* L.). The experiment was laid out in a randomized block design with ten treatments and three replications. The crop was sown as per the package of practices recommended for zone Kymore Plateau of Madhya Pradesh. The major monocot weed was *Cynodon dactylon* and dominant dicot weed was *Chenopodium album* at 30 days after sowing (DAS). At 30 DAS, significantly lower weed density (7.75/m^2) and biomass (2.70 g/m^2) were recorded with post-emergence application (PoE) of fomesafen (11.1% W/W) 220 g + fluazifop-p-butyl (11.1% W/W) 220 g/ha PoE at 20 DAS, followed by imazethapyr (35%) + imazamox (35%) 100 g/ha PoE at 20 DAS. The lowest weed index was noted with imazethapyr 55 g/ha PoE followed by pre-emergence application (PE) of pendimethalin 0.75 kg/ha and fomesafen 220 g + fluazifop-p-butyl 220 g/ha PoE at 30 DAS. Higher weed control efficiency (WCE) at 30 DAS was recorded with fomesafen 220 g + fluazifop-p-butyl 220 g/ha (70.6%) followed by hand weeding at 20 and 40 DAS (57.1%). However, fomesafen 220 g + fluazifop-p-butyl 220 g/ha PoE at 20 DAS and imazethapyr + imazamox 100 g/ha PoE at 20 DAS caused severe injury to chickpea plants and even mortality of a few plants. Significantly higher 1000 seed weight (183.0 g) and grain yield (1.79 t/ha) were observed with imazethapyr 55 g/ha PoE which was statistically at par with weed free check. Significantly higher net returns (₹ 70746/ha) and B:C ratio (3.97) were recorded with imazethapyr 55 g/ha PoE (₹ 70746/ha), followed by pendimethalin 0.75 kg/ha PE. The monetary efficiency (₹ 589.5/ha/day) of imazethapyr 55 g/ha PoE was statistically at par with weed free (₹ 541.3/ha/day) and was significantly higher than all other treatments.

Keywords: Chickpea, Economics, Fomesafen + fluazifop-p-butyl, Herbicides, Imazethapyr, Imazethapyr + imazamox, Weed control efficiency

INTRODUCTION

Chickpea (*Cicer arietinum* L.) is the third most important pulse crop in the world after French bean and field peas (FAO 2019). Chickpea occupies about 38% of area under pulses and contributes about 50% of the total pulse production of India. In India, it was grown in an area of 10.17 million ha and producing 11.35 million tons with productivity of 1116 kg/ha (Anonymous 2021). Madhya Pradesh is ranked first amongst chickpea growing states of the India covering an area of about 1.93 million ha with production of 2.48 million tons and productivity 1288 kg/ha (Anonymous 2021).

The poor productivity of chickpea is due to biological and physical constraints of which weed menace is a prominent one. Early and heavy flushes of weeds are recognized as a major bottleneck in realizing the full yield potential of chickpea (Dubey *et al.* 2018) as chickpea is a short statured crop with slow initial growth and heavily infested with wide spectrum of weeds. The early emergence and fast-growing weeds cause severe crop – weed competition for light, moisture, nutrients and space, which culminates in heavy reduction in growth and 40-75% yield of chickpea and lessens the profitability (Chopra *et al.* 2003, Chaudhary *et al.* 2005, Ratnam *et al.* 2011). Hence, weed management is one of the critical input essential for improving the chickpea productivity which necessitates the development of an effective weed management program in chickpea. Thus, the present study was conducted to identify suitable herbicides for effective weed management while assessing their influence on weed flora, yield and economics of chickpea under Kymore Plateau of Madhya Pradesh.

MATERIALS AND METHODS

The field experiment was conducted during winter (*Rabi*) seasons of 2019-20 and 2020-21 at Agriculture Farm of Mahatma Gandhi Chitrakoot

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Gramodaya Vishwavidyalaya, Chitrakoot, Satna Madhya Pradesh (M.P.). The soil of the experimental field was sandy loam in texture having soil in neutral pH (6.5 and 6.8), low in organic carbon (0.49% and 0.43%), available nitrogen (235.6 kg/ha and 228.3 kg/ha), high in available phosphorus (42.76 kg/ha and 26.5 kg/ha) and medium in available potassium (245.2 kg/ha and 247.1 kg/ha) during two consecutive years.

The mean annual rainfall of Chitrakoot is 950 mm while, the crop received 264 mm and 38 mm rainfall during crop season *i.e.* October to March in two respective years. Ten treatments were tested, *viz.* weedy check, weed free, hand weeding twice at 20 and 40 days after seeding (DAS), pre-emergence application (PE) of pendimethalin 0.75 kg/ha, post-emergence application (PoE) of imazethapyr 55 g/ha at 20 DAS, fluazifop-p-butyl 250g/ha PoE, propaquizafop 2.5% 33.3 g/ha + imazethapyr 3.7% 50 g/ha PoE, acifluorfen-sodium 16.5% 140 g + clodinafop-propargyl 8% 70 g/ha PoE, fomesafen 11.1% W/W 220g + fluazifop-p-butyl 11.1% W/W 220 g/ha PoE and imazethapyr 35 % + imazamox 35% 100 g/ha PoE. A randomized block design was used with three replications.

Chickpea seeds were treated with carrier-based *Rhizobium* 20 g/kg and PSB 40 g/kg seed and mixed well to ensure the inoculums to stick on to the surface of the seeds. The chickpea (*RVG-203*) was sown on 20th October 2019 and 10th November 2020 at a row spacing of 30 cm using 100 kg seed/ha and was harvested on 10th March 2020 and 14th March 2021. The crop was fertilized 20 kg N, 40 kg P and 20 kg K/ha through DAP and MOP as basal. The PoE herbicides alone or in combination were applied at 20 DAS with knapsack sprayer fitted with flat-fan nozzle using 600-litter water/ha. Crop was irrigated at pre-flowering and pod development stage.

The data on density (no./m^2) and biomass (g/m^2) of weeds was recorded at 30 DAS with the help of quadrat of one meter square. Yield attributes and grain and straw yields were recorded as per standard procedures and economics was computed using the prevailing market price for inputs and outputs (grain and straw). The data on total weed density and biomass were subjected to square root transformation ($\sqrt{x+1}$) before subjecting to statistically analysis. Monetary efficiency was calculated by dividing the total net returns with the duration of the crop as follows:

$$\text{Monetary efficiency (₹/ha/day)} = \frac{\text{Net returns (₹/ha)}}{\text{Duration of the crop (days)}}$$

The Experimental data related to each character was then statistically analysed as per procedure of analysis of variance and significance tested by "F" test (Gomez and Gomez 1984).

RESULTS AND DISCUSSION

Weed flora

The weeds species (weed flora) recorded in weedy check plots were *Cynodon dactylon, Cyperus rotundus, Chenopodium album, Anagallis arvensis, Convolvulus arvensis, Medicago hispida, Argemone mexicana* and *Parthenium hysterophorus.* The major monocot/sedge weed was *Cynodon dactylon* (7.33/m^2) while, dominant dicot weed was *Chenopodium album* (134.33/m^2) at 30 DAS. However, relative density of monocot/sedge was higher for *Cynodon dactylon* (4.05 %) and it was 74.36 % for *Chenopodium album* (**Table 1**). Similar weeds in winter season chickpea were also reported earlier (Goud *et al.* 2013 and Kumar *et al.* 2014).

Weed density and biomass

At 30 DAS, significantly lower weed density was recorded in fomesafen 220 g + fluazifop-p-butyl 220 g/ha (7.75/m^2) and imazethapyr + imazamox 100g /ha (9.20/m^2). Similar observations were made by Singh and Jain (2017) and Ashu and Menon (2021). The weed biomass at 30 DAS was also significantly lower in fomesafen 220 g + fluazifop-p-butyl 220g/ha (2.70 g/m^2). Hand weeding twice at 20 and 40 DAS, pendimethalin 0.75 kg/ha PE, imazethapyr 55 g/ha PoE, fluazifop-p-butyl 250 g/ha PoE, propaquizafop 33.3 g + imazethapyr 50 g/ha PoE, acifluorfen-sodium 140 g + clodinafop

Table 1. Weed density and relative density (%) in weedy check at 30 days after seeding (DAS)

Weed species	Weed density (no./m^2)	Relative density (%)
Monocot / Sedge		
Cynodon dactylon	7.33	4.05
Cyperus rotundus	3.6	1.99
Total	10.99	6.08
Dicot		
Chenopodium album	134.33	74.36
Anagallis arvensis	6	3.32
Convolvulus arvensis	5.33	2.95
Medicago hispida	12	6.64
Argemone Mexicana	9.66	5.34
Parthenium hysterophorus	2.33	1.28
Total	169.65	93.91
Grand total	180.64	100

propargyl 70 g/ha, fomesafen 220 g + fluazifop-p-butyl 220 g/ha and imazethapyr + imazamox 100 g/ha reduced the weed biomass by 44.9, 40.2, 34.7, 33.0, 27.6, 34.7, 50.3 and 41.7%, respectively (**Table 2**). The post-emergence application of the efficacy of imazethapyr PoE in effectively controlling weeds was also reported earlier in soybean (Ram and Singh 2011) and blackgram (Singh *et al.* 2013, Nirala *et al.* 2012).

Weed index and weed control efficiency at 30 DAS

Weed index (WI) at 30 DAS was highest under weedy check and the lowest in imazethapyr 55 g/ha PoE (5.57) followed by pendimethalin 0.75 kg/ha PE (15.38) and fomesafen 220 g + fluazifop-p-butyl 220 g/ha (15.90) treated plots. Fomesafen 220 g + fluazifop-p-butyl 220 g/ha recorded highest weed control efficiency (70.6%) followed by hand weeding (57.1%) and imazethapyr 55 g/ha (55%), while, it was the lowest in propaquizafop 33.3 g/ha + imazethapyr 50 g/ha (14.4%). However, imazethapyr 35% + imazamox 35% 100 g/ha was observed to cause higher toxicity to chickpea crop. These results are in conformity with those of Ratnam *et.al* (2011), Singh *et al*. (2014), Kumar and Chinnamuthu (2014).

Effect on crop

Nodulation: The number of nodules at chickpea flower initiation stage were significantly higher under hand weeding (4.22) followed by pendimethalin 0.75 kg/ha PE (4.10), imazethapyr 55 g/ha PoE (3.98). However, dry weight of nodules per plant at flower initiation stage was significantly superior in pendimethalin 0.75 kg/ha PE (0.11 g) followed by weed free (0.10 g) and hand weeding twice at 20 and 40 DAS (0.10 g) (**Table 3**). This might be due to more space availed by roots of crop which could have resulted into greater number of nodules per plant in those treatments

Table 2. Effect of treatments tested on weed density and biomass, weed index and weed control efficiency in chickpea at 30 days after seeding

Treatment	Weed density (no./m^2)	Weed biomass (g/m^2)	Weed index	Weed control efficiency (%)
Pendimethalin 0.75 kg/ha (PE)	9.54(73)	3.26(5.15)	15.38	48.08
Imazethapyr 10 % SL 55g/ha at 20-25 DAS	11.24(105)	3.52(6.40)	5.57	55
Fluazifop-p-butyl 13.4 % W/W 250 g/ha at 20-25 DAS	11.72(115)	3.63(6.93)	28.99	30.14
Propaquizafop 2.5% 33.3 g + imazethapyr 3.7% 50 g/ha at 20-25 DAS	11.26(105.33)	3.91(8.50)	20.61	14.43
Acifluorfen-sodium 16.5% 140 g + clodinafop propargyl 8% 70g/ha at 20-25 DAS	9.66(75)	3.52(6.37)	39.14	35.78
Fomesafen 11.1%W/W 220g + fluazifop-p-butyl 11.1%W/W 220 g/ha at 20-25 DAS	7.75(45.66)	2.70(2.92)	15.90	70.56
Imazethapyr 35% + imazamox 35% 100 g/ha at 20–25 DAS	9.20(67.33)	3.14(4.60)	47.19	53.62
HW at 20 and 40 DAS	10.30(86.66)	3.72(7.40)	31.98	57.15
Weed free	1.00(0.00)	1.00(0.00)	-	100
Weedy check	14.49(182) *	4.14(9.92)*	48.25	-
LSD (p=0.05)	2.79	0.63	-	-

*Original data given in parentheses were subjected to square root transformation $\sqrt{X+1}$ before statistically analysis

Table 3. Effect of treatments tested on nodulation, yield attributes and yield of chickpea

Treatment	No of nodules/plant at 60 DAS	Nodules dry weight/plant (g) at 60 DAS	Pods/ plant	Seeds/ pod	Grain weight / plant (g)	1000 seed weight (g)	Yield (t/ha)	
							Grain	Stover
Pendimethalin 0.75 kg/ha (PE)	4.10	0.11	26.60	1.53	18.93	178.4	1.61	1.96
Imazethapyr 10 % SL 55g/ha at 20-25 DAS	3.98	0.09	24.27	1.55	19.33	183.0	1.79	2.33
Fluazifop-p-butyl 13.4 % W/W 250 g/ha at 20-25 DAS	3.75	0.08	27.00	1.38	17.40	175.6	1.35	2.05
Propaquizafop 2.5% 33.3 g + imazethapyr 3.7% 50 g/ha at 20-25 DAS	3.97	0.09	27.13	1.52	18.00	174.7	1.51	1.97
Acifluorfen-sodium 16.5% 140 g + clodinafop propargyl 8% 70 g/ha at 20-25 DAS	3.55	0.07	27.47	1.50	19.07	164.8	1.15	1.72
Fomesafen 11.1%W/W 220g + fluazifop-p-butyl 11.1%W/W 220 g/ha at 20-25 DAS	3.22	0.07	26.73	1.47	20.53	177.4	1.60	1.90
Imazethapyr 35% + imazamox 35% 100 g/ha at 20–25 DAS	2.63	0.05	18.00	1.58	15.07	162.4	1.00	0.91
HW at 20 and 40 DAS	4.22	0.10	26.27	1.48	20.07	179.6	1.29	1.90
Weed free	3.53	0.10	41.93	1.52	22.93	185.2	1.90	2.78
Weedy check	3.11	0.08	26.27	1.46	20.87	171.0	0.98	1.35
LSD (p=0.05)	0.93	0.04	4.81	NS	3.93	12.3	189	616

Table 4. Effect of treatments tested on returns and monetary efficiency of chickpea

Treatment	Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	Benefit: cost ratio	Monetary efficiency (₹/ha/day)
Pendimethalin 0.75 kg/ha (PE)	24735	84509	59773	3.42	498.10
Imazethapyr 10 % SL 55g/ha at 20-25 DAS	23856	94602	70746	3.97	589.55
Fluazifop-p-butyl 13.4 % W/W 250 g/ha at 20-25 DAS	26499	71725	45225	2.71	376.87
Propaquizafop 2.5% 33.3 g + imazethapyr 3.7% 50 g/ha at 20-25 DAS	24243	79560	55316	3.28	460.72
Acifluorfen-sodium 16.5% 140 g + clodinafop propargyl 8% 70 g/ha at 20-25 DAS	24824	61392	36567	2.47	304.72
Fomesafen 11.1%W/W 220g + fluazifop-p-butyl 11.1%W/W 220 g/ha at 20-25 DAS	26930	83901	56970	3.12	474.75
Imazethapyr 35% + imazamox 35% 100 g/ha at 20–25 DAS	23699	52124	28424	2.20	236.86
HW at 20 and 40 DAS	27308	68582	41274	2.51	343.95
Weed free	35848	100805	64957	2.81	541.30
Weedy check	23038	51996	28958	2.25	241.31
LSD (p=0.05)	-	9631	9631	0.38	-

Yield attributes

Higher number of pods/plant (27.47) were recorded under acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha PoE and it was statically at par with rest of weed control treatments except imazethapyr + imazamox 100 g/ha PoE. Number of seeds/pod was numerically higher under imazethapyr + imazamox 100 g/ha PoE (1.58) followed by propaquizafop 33.3 g/ha + imazethapyr 50 g/ha PoE (1.52) and acifluorfen-sodium 140 g + clodinafop-propargyl 70g/ha PoE (1.50). Seed weight/plant (20.53 g) was found significantly greater under fomesafen 220 g + fluazifop-p-butyl 220g/ha PoE and it was statistically at par with all weed control treatments except imazethapyr + imazamox 100 g/ha PoE. The 1000-seed weight was higher with imazethapyr 55 g/ha (183 g), and it was statistically at par with HW twice at 20 and 40 DAS, pendimethalin 0.75 kg/ha PE, fluazifop-p-butyl 250 g/ha PoE, propaquizafop 33.3 g + imazethapyr 50 g/ha PoE, fomesafen 220 g + fluazifop-p-butyl 220 g/ha PoE and weedy check. Goud *et al.* (2013) also reported highest growth and yield attributing parameters of chickpea with the application of imazethapyr 75 g/ha PoE. Weed free treatment producing higher values of yield attributes in chickpea was reported earlier by Khope *et al.* (2011), Singh *et al.* (2014) and Rupareliya *et al.* (2018).

Yield

Seed yield was higher with weed free check (1.90 t/ha) and was statistically at par with imazethapyr 55 g/ha PoE (1.79 t/ha) and pendimethalin 0.75 kg/ha PE (1.61 t/ha). Stover yield also followed the similar trend (**Table 3**). Khope *et al.* (2011) also reported higher chickpea yield with imazethapyr. Similar results have also been reported by Goud *et al.* (2013).

Economics

The maximum cost of production was incurred in weed free treatment (₹ 35848 /ha) followed by hand weeding twice wat 20 and 40 DAS (₹ 27308/ha) due to greater number of labor involved. Gross return was maximum under weed free (₹ 100805 /ha) but statistically at par to imazethapyr 55g/ha PoE (₹ 94602/ha). The higher gross returns were mainly due to higher seed yield, obtained due to higher weed control efficiency. While, net return was significantly higher in imazethapyr 55 g/ha PoE (₹ 70746 /ha) and weed free (₹ 64957/ha), which were statistically at par. Higher B:C ratio was with imazethapyr 55 g/ha PoE (3.97) followed by pendimethalin 0.75 kg/ha PE (3.42) due to higher gross returns along with lesser cost of cultivation, particularly less weed management cost as observed by Rathod *et al.* (2017), Dubey *et al.* (2018) and Sethi *et al.* (2021).

Monetary efficiency

The monetary efficiency of imazethapyr 55 g/ha PoE (₹ 589.55/ha/day) was statistically at par with weed free (₹ 541.30/ha/day) and was significantly higher than rest of the treatments (**Table 4**). Thus, it was concluded that imazethapyr 55 g/ha applied at 20 DAS could be used for attaining satisfactory weed control in chickpea along with higher productivity and farm income in Kymore Plateau region of Madhya Pradesh.

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RESEARCH ARTICLE

Integration of raised beds, mulching and stem training for weed management in tomato under mid-hill conditions of Himachal Pradesh

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ABSTRACT

A field experiment was conducted at the Research Farm of Vegetable Science, DR YSPUHF, Nauni, Solan (HP), India to evaluate the effect of polythene mulches, planting methods and training systems on weed control and yield response of tomato crop. The experiment was laid out in factorial randomized block design with twelve treatments and replicated thrice. The consortium effect of raised bed (RB) + black polythene mulch (BPM) + two stem training have recorded less weed density (142.00/m^2), greater weed control efficiency (64.64%), less fresh (82.00 g/m^2) and dry weed biomass (13.00 g/m^2) and higher yield (100.12 t/ha). The dominance of *Cyperus rotundus*, *Echinochloa crus-galli* and *Galinsoga parviflora* weed species was also less with the integration of raised bed, black polythene mulch and two stem training system. This practice helps in the tomato production with better water conservation; weed management and improved tomato yield under mid-hill conditions of Himachal Pradesh.

Keywords: Black polythene mulch, Mulching, Raised bed system, Stem training, Tomato, Weed control efficiency

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is considered both as a vegetable and a fruit and has a number of uses. Weed management has always been an important component of tomato production (Bhullar *et al.* 2015). The negative implications of weeds in term of yield losses (45 to 60% in tomato) and the cost of its control are often ignored by farmers (Kaur *et al.* 2015). Weeds compete with crops for water, nutrients, space, light and oxygen resulting into a delay in maturity and low yield. The transplanted tomato's initial growth is slow and thus weeds pose a great problem during its initial slow growth stage of transplanted tomato and the weed competition during critical growth period could lead to tomato yield reduction up to 54.9% (Ved and Srivastava 2006)) and also reduces the quality and market value (Brown *et al.* 2019). Thus, weed control has always been an important constituent of tomato production (Bhullar *et al.* 2015).

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The manual weeding is becoming costly due to increasing cost of labour and reduced availability of labour. Controlling weeds with herbicides is possible but, overuse of herbicides causes environmental concerns because herbicides have negative effects on beneficial organisms also, may pollute the food and groundwater with their residue, and cause toxicity in mammalians (Sharma *et al.* 2019). Therefore, environment friendly, efficient and cost-effective weed management is essential. Growing of tomatoes on raised beds, black polythene mulch, along with a two stem has been identified as an alternative method that can increase not only the yield but also to manage weeds (Chaudhari *et al.* 2019, Hussain *et al.* 2016 and Alam *et al.* 2016). This study was conducted with an objective to evolve a cost-effective weed management method by integrating the cultural practices like planting bed systems, mulching and training systems for managing weeds in tomato.

MATERIALS AND METHODS

The field trial was conducted during *Kharif* (rainy) season of 2017-18 and 2018-19 at Dr Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (Himachal Pradesh), Vegetable Experimental Farm [35^{0}5'N latitude and 77^{0}11'E longitude at an elevation of 1270 m (above MSL)]. Tomato cultivar '*Solan Lalima*' was taken as experimental material. Treatments comprised of combinations of two different planting techniques: raised bed and flat-bed, three mulch treatments: black polythene, silver/black polythene, and no mulch, and two training systems; two stem and three stem training (**Table 1**). Two stem method was achieved by planting one seedling in a plot and allowing the sucker at the bottom to grow as the second main stem, which resulted in the growth of double leader stems. Three stem training method was achieved by planting one seedling and then allowing the two suckers at the bottom to grow as the three stem, which resulted in the growth of three stems trained plants.

The soil of experimental site was sandy loam, having pH 6.6, organic carbon 6.78 mg/L of soil, available nitrogen 312.56 kg/ha, phosphorus 22.15 kg/ha and potassium 154.5 kg/ha. Farm Yard Manure and fertilizers were applied as per package of practices for vegetable crops (RDF: 100 N: 75 P: 55 K kg/ha). The fertilizers were applied manually at the time of preparation of the experimental filed and nitrogen was given in three split doses. The experiment was laid out in randomized block design (factorial) with three replications, consisting of 12 treatments: raised bed + black mulch + two stem training, raised bed + black mulch + three stem training, raised bed + silver/black mulch + two stem training, raised bed + silver/black mulch + three stem training, raised bed + no mulch + two stem training, raised bed + no mulch + three stem training, flat bed + black mulch + two stem training, flat bed + black mulch + three stem training, flat bed + silver/black mulch + two stem training, flat bed + silver/black mulch + three stem training, flat bed + no mulch + two stem training, flat bed + no mulch + three stem training. The height of raised beds was 15 cm and each bed was separated at a 45 cm distance. Black polyethylene mulch and silver/black mulch of 50µ (200-gauge thickness) were applied according to the treatment combinations. Black mulch and grey or black mulch used in the experiment were procured from the open market. Mulches of 50µ (200-gauge thickness) were applied in plots according to the treatment combinations. Mulches were applied one week prior of transplanting of the crop.

Weed density

Weed density was collected from each plot with the help of a quadrat of 1×1 m (1m^2) by placing the quadrat randomly in each plot. For this, the quadrate was placed randomly in each plot and the total number of weeds growing within the quadrate was counted.

Weed control efficiency

WCE was calculated at harvest as per the formula given below (Kondap and Upadhyay 1985). Lesser the weed index, better is the efficiency of the herbicide. It is expressed in percentage and was determined with the help of following formula: 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.

$$WCE = \frac{DMC - DMT}{DMC} \times 100$$

Where,

WCE= Weed control efficiency (percent)

DMC= Dry matter production of weeds in control (weedy check) plots

DMT= Dry matter production of weeds in treatments.

Fresh and dry weight (biomass) of weeds

Observations on the fresh and dry weight (biomass) (g/m^2) of weeds were recorded from an area of 1×1 m in each plot. Fresh weight was recorded just after the collection of weeds from the field while dry weight was recorded after drying of weeds in an oven at 70°C and expressed as gram/m^2. Number of harvests varied within the treatment combinations. Yield per plot was calculated by pooling the weight of the all the tomato fruits harvested over all the pickings in a given plot/ treatment. On the basis of yield obtained from each plot in kilogram, yield per hectare was calculated in quintals. The results were similar during both the years. Hence, the data was pooled to show the results in a single table.

Statistical analysis

The data recorded was statistically analysed for interpretation (Panse and Sukhatme 2000). Yes pooled analysis of data for two years has been done. Statistical analysis of data was done manually on MS Excel sheet.

Post hoc test: Post hoc (“after this” in Latin) tests are used to uncover specific differences between three or more group means when an analysis of variance (ANOVA) F test is significant. The level of significance is 0.05. Probability is a branch of mathematics that deals with the occurrence of a random event.

RESULTS AND DISCUSSION

Effect of bed configuration, mulch and training systems on weeds and yield of tomato

Bidens Pilosa, *Commelina benghalensis*, *Echinochloa crus-galli*, *Galinsoga parviflora*, *Nicandra physalodes* and *Cyperus rotundus* were the predominant weeds in the experimental field.

The planting technique, mulch application and training had significant effect on weed density, weed control efficiency, fresh and dry biomass of weeds and tomato yield (t/ha) (**Table 2**). The raised bed planting method recorded less number of weeds (467.89/m^2), highest weed control efficiency (40.24%), least weeds fresh biomass (213.28 g/m^2), least weeds dry biomass (34.28 g/m^2) of weeds and produced more (90.29 t/ha) yield as compared to flat bed system. Regarding the effects of mulches, covering with black plastic mulch resulted in lesser weed density (207.42/m^2), greater weed control efficiency (52.62%), lower fresh weed biomass (113.25 g/m^2) and dry weed biomass (22.58 g/m^2) and higher tomato yield (916.58 g/ha) as compared to silver/black polythene mulched and non-mulched beds. In the case of training system, the two-stem training system had less weeds density (472.94/m^2), higher weed control efficiency (37.61%), least fresh weed biomass (245.11 g/m^2), least dry weed biomass (36.50 g/m^2) and higher yield (88.20 t/ha). The weed density and biomass were higher in the silver-coloured mulch as it allowed more solar radiation passed through it and was made available to weeds (Ramakrishna *et al.* 2006) in tomato.

Raised bed planting technique, black polythene mulch and plants trained to two stem training system recorded minimum weed density and greater weed control efficiency. In the raised beds, it could be due to less tillage and maintenance of the raised bed since, once the soil in a raised bed is stabilized, compaction is almost non-existent, so the need for tillage is minimal. Therefore, the weed population decreased over time in a raised bed which are well cared and managed. Black mulch prevented the weed seeds to germinate (Hussain *et al.* 2016) and created partially anaerobic conditions for the survival of weed species and thus resulted low weed density. Mulching enhances the soil moisture retention and improves the soil temperature which helps boost crop performance making the crop more competitive against the associated weeds. Reduced number of weeds under the two-stem training system might be due to unavailability of visible light spectrum resulting into reduced photosynthetic activity and therefore less number of weeds. Greater the competition for light lesser will be the absorbance of radiations resulting into reduced emergence of weeds along together with poor growth of germinated seeds (Brown *et al.* 2019). There was complete elimination of weeds under black polyethylene mulch. Similar findings were also reported by Ramakrishna *et al.* (2006) in tomato.

Consortium effect on weeds and yield of tomato

Interaction effect of planting technique + mulching + training (**Table 3**) caused less weeds density (142.0/m^2), higher weed control efficiency (62.24%), low fresh (82.00 g/m^2) and dry (13.00 g/m^2) biomass of weeds and higher tomato yield (100.12 t/ha) with raised bed + black polythene mulch + two stem training system.

Weed control efficiency (%) was positively correlated with tomato yield. The probable reason of

Table 1. Effect of planting methods, mulches and training systems on weed density, biomass and yield (pooled data for two years)

Treatment	Weed density (no./m^2)	Weed control efficiency (%)	Fresh weight of weeds (g/m^2)	Dry weight of weeds (g/m^2)	Yield (t/ha)
Planting method					
Raised bed	467.89	42.53 (40.24)	213.28	34.28	90.30
Flat bed	541.17	28.04 (28.68)	303.50	43.17	81.46
LSD (p=0.05)	41.43	2.20	9.79	1.77	1.15
Mulches					
Black polythene mulch	207.42	62.74 (52.62)	113.25	22.58	91.66
Silver polythene mulch	301.67	33.08 (34.92)	130.58	39.92	89.47
No mulch	1004.50	10.03 (15.84)	531.33	53.67	76.51
LSD (p=0.05)	50.74	2.69	11.99	2.17	1.41
Training system					
Two stem training systems	472.94	38.83 (37.61)	245.11	36.50	88.20
Three stem training system	536.11	31.74 (31.31)	271.67	40.94	83.55
LSD (p=0.05)	41.43	2.20	9.79	1.77	1.15

*Figures in parentheses represent angular transformation maximum weed control efficiency using black polythene mulch could be due to conservation of moisture and reduction of temperature in the top soil which suppressed the weed growth. This is due to the fact that solar radiations transmittance is more in case of silver plastic mulch compared to black mulch as explained by Shylla *et al.* (2005). The present findings are in conformity with the report of Awodoyin *et al.* (2007) who reported that plastic mulches improve the performance of tomato due to less crop weed competition. Another reason could be less moisture depletion resulting into more water stress to the weeds vis-à-vis better availability of water to the economic part *i.e.* tomato plant. In the present studies, minimum fresh and dry weight of weeds was recorded in the plots mulched with black polythene. This may be due to lower weed density and short time of weed crop association to accumulate dry weight by weeds. Appearance of minimum number of the weeds through the holes and 100% (weed count) control of the weeds could be the reason for reduced fresh weight and consequently minimum dry weight of the weeds in okra (Muhammed *et al.* 2015), in tomato (Rajablariani *et al.* 2012) and in aonla (Iqbal *et al.* 2016). Raised beds with mulch cover gaining more and more importance in India, because tomato production in an open field can maintain its profitability in the long term just in case of using intensive production technology. It might be due to the reason that the soil in a raised bed is more stabilized and therefore compaction is almost non-existent so the need for seasonal tilling is minimal (Berle and Westerfield 2013). Another reason could be proper drainage facility which allows the plant roots to breathe properly as compared to the weeds, quick warming up of the soil, allowing the longer growing season and better growing conditions for the plants in the raised beds as compared to the flat beds (Locher *et al.* 2003).

Table 2. Interaction effect on weed density, weed biomass and yield of tomato

Consortium	Weed density (no./m^2)	Weed control efficiency (%)	Fresh biomass of weeds (g/m^2)	Dry biomass of weeds (g/m^2)	Yield (t/ha)
Raised bed + black polythene mulch+ two stem training system	142.00	78.26 (62.24)	82.00	13.00	100.12
Raised bed + black polythene mulch + three stem training system	209.33	64.68 (52.61)	89.33	21.00	94.31
Raised bed + silver/black polythene mulch + + two stem training system	265.33	41.93 (40.35)	98.33	34.67	97.71
Raised bed + silver/black colored polythene mulch + three stem training system	305.00	38.52 (38.35)	112.33	36.67	92.32
Raised bed + No mulch + + two stem training system	860.00	16.15 (23.64)	402.00	50.00	79.93
Raised bed + No mulch three stem training system	1025.67	15.62 (23.24)	495.67	50.33	77.32
Flat bed + Black polythene mulch + two stem training system	221.00	58.12 (49.68)	139.00	25.00	89.18
Flat bed + black polythene mulch + three stem training system	257.33	49.89 (44.94)	142.67	31.33	83.00
Flat bed + silver/black colored polythene mulch + two stem training system	310.00	30.14 (33.29)	152.67	41.67	87.02
Flat bed + silver/black colored polythene mulch + three stem training system	310.00	30.14 (33.29)	152.67	41.67	87.02
Flat bed + No mulch + two stem training system	326.33	21.71 (27.69)	159.00	46.67	80.81
Flat bed + No mulch + three stem training system	1093.00	1.00 (1.00)	631.00	59.67	73.54
LSD (p=0.05)	NS	5.39	23.97	3.88	NS

*Figures in parentheses represent angular transformation

Table 3. Effect of different treatments on economics of tomato

Treatment	Yield (t/ha)			*Gross return (`/ha)	Cost of cultivation (`/ha)	Net return (`/ha)	B: C ratio
	2017-18	2018-19	Pooled				
Raised bed + black mulch + two stem	99.27	99.84	100.12	1501875	307591	1194284	3.88
Raised bed + black mulch + three stem	91.95	94.90	94.31	1414605	315991	1098614	3.48
Raised bed + silver/black mulch + two stem	102.40	94.19	97.71	1465605	315591	1150014	3.64
Raised bed + silver/black mulch + three stem	96.66	91.23	92.32	1384875	323991	1060884	3.27
Raised bed + No mulch + two stem	79.71	80.81	79.93	1198995	254804	944190	3.71
Raised bed + No mulch + three stem	77.01	77.40	77.32	1159740	263204	896535	3.41
Flat bed + black mulch + two stem	90.78	88.78	89.18	1337715	299191	1038523	3.47
Flat bed + black mulch + three stem	82.75	83.19	83.00	1244955	307591	937363	3.05
Flat bed + silver/black mulch + two stem	87.39	88.13	87.02	1305285	307191	998093	3.25
Flat bed + silver/black mulch + three stem	88.32	86.04	87.02	1305285	315591	989693	3.14
Flat bed + No mulch + two stem	78.81	80.14	80.81	1212210	246404	965805	3.92
Flat bed + No mulch + three stem	72.99	73.36	73.54	1103175	254804	848370	3.33

Effect on economics

The highest cost of cultivation ₹ 323991/ha was with raised bed + silver/black mulch and three stem training system which was followed by raised bed + black mulch + three stem training system (₹ 315991/ha), whereas lowest cost of cultivation (₹ 246404/ha) was observed in flat bed + no mulch + two stem training system (**Table 3**). The raised bed + black mulch + two stem training system recorded both highest net return of ₹ 1181364/ha and highest benefit: cost ratio of 3.88.

It was concluded that by integrating the raised bed planting with black polythene mulching and two stem training system, higher weed control efficiency, net returns and B:C ratio can be obtained in transplanted tomato crop cultivation under mid-hill conditions of Himachal Pradesh.

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RESEARCH ARTICLE

Invasive weed *Lantana* utilization for textile finishes

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ABSTRACT

Herbal extract application on textile substrates is in great demand around the globe. In this study, a natural dye extracted from *Lantana camara* L. leaves' extract was tested to assess the ultra-violet protective properties on cotton fabric using direct dip dyeing technique. Extraction of phytochemicals was carried out using ethanol and aqueous solvents. Total phenolic content (TPC) quantification revealed that TPC of *L. camara* leaves' extracts were highest in ethanolic extraction as compared to aqueous extracts. The ultra violet protection factor (UVF) values ranged between good to excellent for the cotton fabrics. A cotton fabric treated in a solution containing cross linking agent showed a shade of light yellowish green. The colour fastness against light, washing, rubbing and perspiration of cotton fabric treated in extracted dye solution as well as treated with citric acid as cross-linking agent showed good to very good colour fastness properties (4–5). The results confirmed that natural dye from *Lantana camara* extract have potential for application in fabric dyeing and also helpful in producing UV protective fabric.

Keywords: *Lantana camara*, Dyeing, Fabric, UV protection, Weed utilization

INTRODUCTION

Clothing is a basic human need that traditionally is viewed as a means of satisfying the aesthetic needs of fashion, but today's need for fashion has been combined with a critical need for function. Human exposure to ultraviolet (UV) radiation has increased in recent years due to altered leisure habits and to higher overall level of UV radiations caused by the decreased ozone content of the atmosphere. UV radiations amounts to about 6 per cent of solar radiation and consists of UV-A (330-400 nm), UV-B (290-320 nm) and UV-C radiation (220-280 nm). Exposer to UV rays can cause not only sunburn but also premature skin aging. One of the most important elements in preventing skin cancer is the use of comfortable UV-protective clothing. Therefore, there is strong demand for means of providing UV protection and textiles play an important role as it is directly applied to the skin, when the UV radiation hits the textile materials, different types of interaction occur depending upon the substrate and its conditions. The UV protection by textiles materials and apparels is a function of the chemical characteristics, physico-chemical type of fibre, presence of UV absorber, fabric construction, thickness, porosity, extension of the fabric, moisture content of the fabric, colour and the finishing given to the fabric (Ashour and Ahmed 2016). Fabrics when dyed, can absorb significant amount of UV radiation and have a protective effect (Deepti *et al.* 2005). The degree of ultraviolet radiation protection of textile material is measured by the ultraviolet protection factor (UPF). The UPF is the measure of ultraviolet (UV) radiation blocked by the fabrics and indicates the amount of ultraviolet protection provided to skin by the fabric. Higher UPF value is indicative of more blocking of UV radiation.

Dyes often provide a good blocking effect against ultraviolet light transmittance and the protection level rises with an increase in dye concentration (Omer *et al.* 2015). The dyes used to colour textiles can have a considerable influence on their permeability to ultraviolet radiation. Any type of dye can provide the UV protection properties to the fabric but at present in the field of textiles, the application of natural dyes is on the rise because of the growing interest of the consumers towards the environmental sustainability. The fabric dyed with natural dyes have good ultraviolet protective properties and could absorb about 80 per cent of the ultra violet rays (Deepti *et al.* 2015). There are several plants which are available in abundance and have not yet been given any commercial importance; *Lantana camara* is one of them. Hence, keeping in mind it was decided to investigate the UV protection offered by *Lantana camara* dye on cotton fabric.

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Lantana is easy to grow anywhere in well-drained soil (Saravanan *et al.* 2014). The plant is an aromatic straggling shrub with prickly stem and strong unpleasant smell. It blooms all year long. It is considered as poisonous plant in nature but the leaves are used in traditional medicine. Chief constituents present in lantana are iridoid glycosides, flavonoids, sesquiterpenes, triterpenes, lantadene, lantanolic and lantic acid. Lantana is abundantly available in hilly and plain areas of Himachal Pradesh and throughout India.

Most of the plant materials used for the extraction of dyes are credited with medicinal properties. The tannins and other phenolic compounds present in plant kingdom are believed to provide a chemical defence against predators and ultraviolet radiation to the plant (Svobodova *et al.* 2003). A great attention for application of natural colourants is survived due to their availability. Moreover, natural dyeing practices can create employment avenues in rural area which can also help in promoting rural entrepreneurship. Some interested practitioners are using natural dyes for exclusive dyeing of handicrafts and handloom textiles at small scale in an attempt to produce green textiles (Babita and Anita 2018). Eventhough, synthetic colourants produce different shades and are available in low price, they cause environment pollution and hence, natural dyes are good alternative for textile colouration (Gawish *et al.* 2016). Plants have their own self defence mechanism and protect themselves from UV rays and microbes due to the presence of substances known as phytochemicals. These phytochemicals are divided into primary and secondary metabolite. Primary metabolites are the compounds involved in the metabolic pathway, which are common to all living organisms (Dewick 2009). Secondary metabolites extracted from plants such as phenols, flavonoids and anthrax-Quinone have been considered as sunscreen agents because of their ultraviolet absorption property (Ramu *et al.* 2012). Although, many plants rich in antibacterial and UV protective agents are reported, the work on the exploration of *Lantana camara* leaves extract and its application on textiles is not yet documented. Thus, the present study was planned to enhance the dyeing properties of cotton fabric using *Lantana camara* dye extract to impart functional properties into the dyed substrate as UV radiation protection.

MATERIALS AND METHODS

Fabric

Cotton fabric with plain weave, 120 GSM, 76 ends/inch and 60 pics/inch having 0.33 mm thickness was used for the study.

Scouring of fabric

In order to remove the impurities from the fabric, samples were treated in solution containing 2 g/litre of sodium hydroxide and 2 g/litre of detergent at material liquor ratio of 1:40 by raising the temperature of entire bath upto 40-60 ^{o}C and was maintained for one hour. After kneading and squeezing, fabric was rinsed in tap water and sundried (Sumithra and Raaja 2013).

Dye material collection

Lantana camara leaves selected as dye source were collected from Palampur region because of their availability in abundance and dried in shade until crispy. The dried leaves were pulverized and were sieved through a 0.5 mm size mesh to obtain uniform sample in the form of powder. The resulting powder was kept separately in glass container with screw cap and stored at room temperature prior to use (Maribet and Aurea 2008).

Dye extraction

Extract preparation from *Lantana camera* leaves was carried out in aqueous (100%) as well as ethanol (70%). In Aqueous extraction; 10 g of leaves were dissolved in 100 ml of distilled water and kept for overnight. After incubation for 24 hours, the extract was centrifuged and the amount of extract was measured. The final extract obtained was filtered using Whatman filter paper number 40 (125 mm), measured, stored in screw caped labelled sample bottles, refrigerated and used for further analysis. In ethanolic extraction 10 g leaves were macerated for 24 h in 70% v/v ethanol. After that vortex for 30 minutes and filtered through Whatman filter paper no. 40 (125 mm). The final extract obtained was filtered using Whatman filter paper no. 40 (125 mm), supernatant was measured, stored in screw caped labelled sample bottles, refrigerated and used for analysis. Further the aqueous as well as ethanol extract was used for the application on cotton fabric.

Before studying the UV protective properties of *L. camara* dyed cotton fabric, qualitative as well as quantitative screening of phyto-chemicals in leaves was carried out.

Qualitative phyto-chemical analysis

Qualitative phyto-chemical analysis of plant extracts was performed for the identification of various classes of active chemical constituents like alkaloids, flavonoids, phenolic compounds, tannins, saponins and terpenoids using different methods (Raman 2006).

Quantitative analysis - Total Phenolic Contents

Total phenolic content of the extract was determined by the Folin-Ciocalteu method and the result was expressed as mg of gallic acid equivalent per g dry weight (Kaur and Kapoor 2002).

Dyeing of cotton fabric

In case of control samples, scoured cotton fabric was immersed in previously prepared aqueous stock solution at 40°C and slowly the temperature was raised upto 90°C. Dyeing was carried out for one hour at neutral pH with adequate movement of dye liquor. The dye bath was allowed to cool for 15 minutes. The dyed samples were then removed, squeezed gently, washed thoroughly and shade dried (Anjali *et al.* 2013) whereas, in case of treated samples, after removing the samples from dye bath dyed samples were treated in stock solution containing 6% crosslinking agent *i.e.*, citric acid for one hour and after that cured the treated fabrics in oven for 30 sec. and then shade dried.

Ultra violet protection factor (UPF) of treated fabric samples was measured as per AATCC 183 test method.

Measurement of colour fastness properties

Colour fastness is the resistance of a material to change any of its colour characteristics or extent of transfer of its colorants to adjacent white materials in touch. The colour fastness is usually rated using greyscale either by loss of depth of colour in original sample or by staining adjacent white material. However, among all types of colour fastness, light fastness, wash fastness and rub fastness are considered most important for any textiles; perspiration fastness is more useful for apparels only (Samanta and Agarwal 2009). After dyeing samples were subjected to colour fastness test to light, washing, crocking or rubbing using the laboratory equipment like DIGI-Light, DIGI-Wash, crock-o-meter and perspire-o-meter, respectively as per the methods given in ISI Hand book of Textile Testing (1982). The fastness rating was given visually, according to Gray scale (AATCC Technical manual 1968) standards.

Physical properties of treated fabric

Thickness (mm), fabric count (no.), GSM, strength (Kgf) and per cent elongation were studied using standard method.

Thickness

Fabric thickness is the distance between the upper and lower surface of the fabric and was measured by a precision thickness gauge known as shirley's thickness tester by using ISI (IS:7702-1975) method. The fabric is kept on a flat anvil and a circular pressure foot is pressed on the fabric and is measured at several places keeping the fabric flat and under no tension. The width of the fabric is the average of the readings taken.

Fabric count

The fabric count of samples was determined by using digiTRA (Digital Traverse Thread Counter). Ten observations were made and average was calculated. The fabric count was expressed in ends/ inch and also picks/inch.

GSM

Gram per square meter (GSM) of dyes samples was measured using GSM cutters and then weighing the samples using digital weighing balance in the laboratory.

Strength (kgf) and % elongation

Tensile strength and per cent elongation of dyed samples was studied using tensile strength tester. Sample size of 25 cm × 5 cm was taken out in both warp and weft directions. The specimen was gripped centrally in between the clamps of tensile strength testing machine, with the longitudinal threads parallel to the direction of application of load. The required test parameters were applied to the instrument due to which continual increasing load was applied longitudinally to the specimen by moving one of the clamps until the specimen was ruptured. Finally, values of breaking strength were taken. A weight was used to ensure that the same amount of tension was put on each of the samples while securing the clamps. The peak load and breaking elongation of the fabric samples were measured. Average fabric tensile strength data was observed. Elongation- the average increase in length of the sample at its break (rupture) point.

RESULTS AND DISCUSSION

Extract yield from *Lantana camara* was measured as 21 ml per 50 ml in aqueous solution whereas it was 25 ml per 50 ml in solvent *i.e.* ethanol.

Not much variation in extract yield was observed. The presence of alkaloids, flavonoids, phenolic compounds and tannins, saponins and terpenoids was observed in *Lantana camera* leave's extract, extracted in aqueous as well as in ethanolic solvent (**Table 1**).

There are several types of solvents that can be used for extraction of plant extract such as methanol,

Table 1. Phyto-chemical analysis of *Lantana camera* Leaves

Phyto-chemical tests	Aqueous solution	Ethanol
Alkaloids		
Dragendorff's reagent	-	+
Wagner's reagent	+	-
Flavonoids		
Ammonia test	+	-
Sodium Hydroxide test	+	+
Phenolic compounds and tannins		
Ferric chloride reagent	+	+
Gelatin reagent	-	+
Lead acetate reagent	-	+
Saponins		
Foam test	+	-
Terpenoids		
Salkowski test	+	+

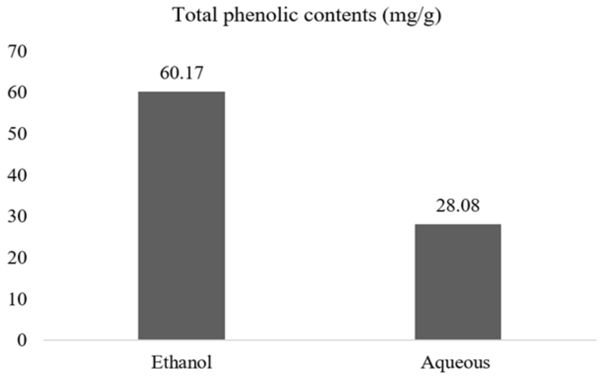

Figure 1. Total phenolic Content (TPC) in ethanol and aqueous extracts of lantana leaves

water, ethanol, acetone, *etc*. In present study ethanol and aqueous solvents were used for extract preparation in which maximum phenolic content was found in ethanolic extraction (60.17 mg/g), as compared to aqueous extraction (**Figure 1**).

The mean UVA per cent transmission of control (unfinished) cotton fabric was 7.70 whereas mean UVB per cent transmission was 8.57 and the mean UPF value was 10.9, providing no protection. Ultra violet protection factor (UPF) values varied from 11.0 (control-directly dyed) to 33.3 (treated) samples (**Table 2**). Per cent UV-A transmission and UV-B transmission was observed as higher (8.17 to 8.99) in control as compared to the treated samples (3.55 to 3.07). Not much variation in percent blocking UV-A and UV-B was observed in both control as well as treated samples. UPF rating of *L. camara* dyed control as well as treated samples varied from moderate to very good.

Beautiful tints and shades of green were obtained on the samples after dyeing with *L. camara* leaves whereas good to very good colour fastness properties were also observed in directly dip dyed control as well as citric acid as cross-linking treated cotton fabric samples. Grey scale rating for all the dyed samples were observed between 3 (moderate) to 5 (very good) (**Table 3**). During testing more colour staining was observed in cotton samples as compared to the woollen samples.

Fabric application of selected herbal finish was carried out using direct dip method. Performance of fabric treated with selected herbal finishing was observed using standard methods. Slight increase in thickness, fabric count, GSM, strength and elongation was observed when compared with white cotton fabric and which varied from 0.35 mm, 98 ends / inch / and 70 picks / inch, 1.205, 13.6 Kgf and 13.0% in control samples where samples were dyed directly in *L. camara* dye extract to 0.37 mm, 94 ends / inch and 70 picks / inch, 1.266, 15.70 Kgf and 17.0 per cent in treated samples (**Table 4**), where citric acid was used as cross-linking agent.

Conclusion

This study revealed that the colour obtained from *L. camara* leaves dye ranged from light yellowish green to dark green and *L. camara* leaves can be successfully used because of having good UV

Table 2. Evaluation of UV Protective properties of *Lantana camara* dyed samples

Dyed samples	UPF	Transmission (UV-A) %	Transmission (UV-B) %	Blocking (UV-A) %	Blocking (UV-B) %
Control (directly dyed)	11.0	8.17	8.99	91.83	91.01
Treated – (citric acid)	33.3	3.55	3.07	96.45	96.93

Table 3. Colour fastness of samples dyed using natural sources used for functional finishes

Plant source	Colour fastness grades													
	light	Washing			Rubbing				Perspiration					
		Colour change	Colour stain		Dry		Wet		Acidic			Alkaline		
			Wool	Cotton	Colour change	CW	Colour change	Cotton	Colour change	CW Wool	CW Cotton	Colour change	CW Wool	CW Cotton
Lantana camara														
Control (directly dyed)	3	4	5	4/5	4	4/5	3/4	4	4	4/5	4	4	5	4
Treated – (citric acid)	4	4	5	4/5	3/4	4	3	4	4/5	4/5	4/5	4/5	5	4/5

Table 4. Physical properties of fabric treated with herbal finish

Name of the plant source	Parameters Direct dip method				
Lantana camara	Thickness (mm)	Count (no.)	GSM	Strength (Kgf)	Elongation (%)
Control (directly dyed)	0.35	98 ends / inch 70 picks / inch	1.205	13.6	13.0
Treated – (citric acid)	0.37	94 ends / inch 70 picks / inch	1.266	15.7	17.0

protective as well as colour fastness properties. As *Lantana camara* whole plant has great potential due to its protective properties, further studies are needed for practical utilisation of the findings of this study.

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RESEARCH NOTE

Maize establishment methods and weed management effect on weeds, maize productivity and economics

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ABSTRACT

A field experiment was conducted during rainy *(Kharif)* season of 2019 at N.E.B. Crop Research Centre of GBPUA&T, Pantnagar with an objective to identify the best establishment method and weed management treatment for maize to attain higher maize growth, yield and economic returns. The experiment was conducted in split-plot design with three replications comprising of three establishment methods as main plot factor and seven weed management treatments as sub-plot factor, replicated thrice. Among the establishment methods, raised bed system was found most effective in reducing weed growth. The highest weed control efficiency of 85.7% was recorded with pre-emergence application (PE) of atrazine 1000 g/ha *fb* post-emergence application (PoE) of tembotrione 120 g/ha which was followed by rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE and tembotrione 120 g/ha PoE alone. Raised bed system resulted in 8.0% higher maize grain yield over zero till system and highest net return and B:C ratio. Among the weed management treatments, highest maize grain yield, net return and B:C ratio were recorded with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE.

Keywords: Atrazine, Maize establishment, Rice straw mulch, Tembotrione, Weed management

Maize is the third most important cereal crop in the world after wheat and rice. It is cultivated in nearly 190 Mha area all over the world. In India, maize is cultivated in 9.5 mha area and holds an important position in the Indian economy (DAC&FW 2018). In India, maize is mostly grown in the rainy *(Kharif)* season which is characterized by heavy downpours, high relative humidity, low sunshine hours. The prevailing weather conditions favor higher weed growth. The slower initial growth of maize allows weeds to grow abundantly at initial stage necessitating adoption of suitable weed management practices for attaining higher maize production. Proper maize establishment method may provide maize a significant competitive advantage over weeds with a head start to manage weeds problem while providing the crop with better resources availability and improved water and nutrient use efficiency (Kaur *et al.* 2020). A better establishment method coupled with a strategically planned weed management can result in better maize yields, resource use efficiency and better returns. Thus, the current experiment was conducted with an objective to identify the best establishment method and weed management treatment for maize to attain higher maize growth, yield and economic returns.

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The current experiment was conducted in the rainy *(Kharif)* season of 2019 at the N. E. Borlaug Crop Research Centre of G. B. Pant University of Agriculture and Technology, Pantnagar. The soil of the experimental site was clay loam in texture having a near neutral pH of 6.75, medium organic carbon (0.72%), 282.1 kg/ha available nitrogen, 25 kg/ha available phosphorus and 184.0 kg/ha available potassium. During the experimentation period (June to September), total rainfall was received 1119.4 mm with average maximum and minimum temperatures of 33.99^{o}C and 25.08^{o}C and relative humidity of 81.98% and 61.13%, respectively. The experiment was conducted in split-plot arrangement with three replications comprising of three levels of main plot factor (flatbed method, raised bed method and zero till method) and seven weed management treatments in the sub-plots include: pre-emergence application (PE) of atrazine 1000 g/ha, atrazine 1000 g/ha PE + rice straw mulching 5 t/ha; post emergence application (PoE) of tembotrione 120 g/ha; atrazine 1000 g/ha PE followed by (*fb*) tembotrione 120 g/ha PoE; rice straw mulching 5 t/ha *fb* tembotrione 120 g/ha PoE; weed free and weedy check. The treatment's gross plot size was 5.0 × 3.6 m, and the net plot size is 5.0 m x 1.2 m. Except for zero till planted plots, plots were prepared by one ploughing *fb* two cross harrowing. For raised bed planting, land shaping was done using tractor drawn bed maker.

Sowing in zero till system was done with tractor drawn zero till drill. Pre-emergence application of herbicides was done using knapsack sprayer (flat fan nozzle with triple boom) with 600 litre/ha water at one day after sowing (DAS) whereas post-emergence application was done using knapsack sprayer (flat fan nozzle) with 500 litre/ha water at 17 DAS. Maize variety '*P-1899*' was sown on 17th June, 2019 and harvested on 21st September, 2019. Maize plant dry matter accumulation, height, yield and yield attributing characters were recorded at harvest. Weed dry matter accumulation (biomass) and density were recorded using a 0.25 m^2 quadrat at 50% tasseling (60 DAS) of the crop. Benefit-cost (B:C) ratio was calculated by dividing net returns with cost of cultivation. Data for the weed biomass and density were subjected to $\sqrt{(x+1)}$ transformation for appropriate normalization before conducting analysis of variance. Analysis of variance of the data was done according to Fisher's Least Significant Difference method at p=0.05 using SPSS v.23 (IBM Corp 2017).

Effect on weeds

The dominant weeds (based on relative density at 60 DAS given in parenthesis) in the weedy check were: *Echinochloa colona* (9.5%), *Eleusine indica* (8.3%) among grasses, *Celosia argentea* (32.4%), *Trianthema monogyna* (8.3%) among broad-leaved weeds and *Cyperus iria* (21.4%) the sedge. Among the establishment methods, raised bed planting resulted in lowest weed density for all the weed species at 60 DAS whereas zero-tillage resulted in the highest weed density (**Table 1**). The raised bed system resulted in 27.7 and 49.7% reduction in density of grassy weeds like *Echinochloa colona* and *Eleusine indica*, respectively. The density of broad-leaved weeds *Celosia argentea* and *Trianthema monogyna* was also lower by 16.7 and 53.7%, respectively in raised bed system compared to zero tilled plots. However, density of *Celosia argentea* was statistically at par in all the establishment treatments. Both the flat bed method and raised bed methods were effective in reducing the density of *Cyperus iria* at 60 DAS. The total weed density was highest in zero tilled plots (93.5 no./m^2) which was at par with flatbed method and followed by raised bed methods. Higher weed density in the zero-tillage system in initial years with the dominance of annual weeds in initial years and greater dominance of perennial weeds in later years was also reported by Khedwal *et al.* (2017). Among weed management treatments, atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE caused the lowest density of *Echinochloa colona* and *Eleusine indica* compared to other weed management treatments. The lowest density of *Celosia argentea* was recorded with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE and it was at par with tembotione 120 g/ha PoE alone as well as rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE. Atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE was also found effective in reducing the density of *Cyperus iria* amongst all the weed management treatments. Total weed density at 60 DAS was also lowest with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE which was closely followed by rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE (**Table 1**). Interaction effects of establishment methods and weeds management treatments on weed density at 60 DAS were found statistically non-significant.

The biomass of grassy weeds, *viz. Echinochloa colona* and *Eleusine indica* was significantly lower in raised bed system than both the zero tilled and flatbed

Table 1. Effect of maize establishment methods and weed management treatments on different weeds density at 60 days after sowing (DAS)

Treatment	Weed density at 60 DAS (no./m^2)					
	Echinochloa colona	*Eleusine indica*	*Celosia argentea*	*Trianthema monogyna*	*Cyperus iria*	Total
Establishment method						
Flat bed	2.9(9.9)	3.0(10.5)	3.4(21.5)	2.7(8.4)	3.5(16.2)	8.0(89.7)
Raised bed	2.4(8.1)	2.5(7.4)	3.1(17.9)	2.1(5.7)	3.0(12.9)	7.7(64.1)
Zero till	3.2(11.2)	3.7(15.2)	3.7(21.5)	3.3(12.2)	3.8(19.5)	8.2(93.5)
LSD (p=0.05)	0.30	0.38	NS	0.54	0.26	0.38
Weed management						
Atrazine 1000 g/ha PE	4.2(16.9)	4.3(17.8)	4.5(19.6)	3.2(9.3)	3.4(10.7)	11.6(132.9)
Atrazine 1000 g/ha + rice straw mulch 5 t/ha	3.6(12.2)	3.2(10.2)	2.8(7.1)	2.8(7.6)	3.4(8.4)	8.0(63.1)
Tembotrione 120 g/ha PoE	3.0(8.0)	2.7(7.1)	1.9(3.2)	2.2(4.9)	3.1(11.1)	7.2(50.4)
Atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE	1.9(3.1)	1.9(3.6)	1.4(1.3)	1.8(2.7)	1.7(2.7)	4.5(19.1)
Rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE	2.6(5.6)	2.5(5.8)	1.9(3.1)	2.0(3.6)	3.0(9.3)	5.4(28.4)
Weed free	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)
Weedy check	5.6(31.1)	5.8(32.9)	10.3(105.8)	5.8(33.3)	8.5(71.1)	18.2(329.8)
LSD (p=0.05)	0.45	0.58	0.61	0.44	0.55	0.20
Interaction	NS	NS	NS	NS	NS	NS

Data are subjected to $\sqrt{x+1}$ transformation before analysis. Original values are given in parentheses. PE: Pre-emergence; PoE: Post-emergence systems (**Table 2**). *Celosia argentea* biomass did not significantly vary amongst different establishment methods at 60 DAS. Biomass of *Trianthema monogyna* was also lowest and was 44.8% lower with raised bed system than the zero till system. Similar trend was also recorded for biomass of *Cyperus iria*. The total biomass was also lowest in raised bed system which was 18.1 and 3.9% lower than the zero tilled and flatbed system, respectively at 60 DAS (**Table 2**). Lower weed density and higher crop vigour due to better nutrient and water availability to maize in raised bed system was also reported by Verma *et al.* (2018). Among the weed management treatments, lowest biomass of *Echinochloa colona* and *Eleusine indica* was observed in atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE than other weed management treatments. For, *Celosia argentea*, atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE as well as rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE resulted in lowest biomass in weed free plots. These treatments were equally effective in reducing biomass of Trianthema *monogyna* and *Cyperus iria*. Total weed biomass accumulation at 60 DAS was lowest with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE which was closely followed by rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE and tembotrione 120 g/ha PoE alone (**Table 2**). Low weed biomass with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE is due to the management of early appearing weeds upto 15-20 DAS by the pre-emergence application of atrazine where weeds emerged at later stages were effectively reduced by post-emergence application of tembotrione. Similar effect was found in rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE but efficiency of rice straw in *Kharif* season was hindered by displacement of mulch by heavy downpours.

On the basis of weed biomass at 60 DAS, the highest weed control efficiency (WCE) of 85.7% was recorded with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE which was followed by rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE and tembotrione 120 g/ha PoE alone with WCE of 81.3 and 80.0%, respectively. Weed index was found lowest with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE which was only 8.3% in comparison to weed free plots. Due to complex weed appearance, an overwhelming 41% weed index value was recorded in the weedy check (**Table 3**).

Effect on maize yield and economics

The highest grain yield of maize was recorded with raised bed method which was statistically at par with flatbed system. The improvement in the yield in raised bed system in comparison to zero till system was in the range of 8.0% which may be due to lower weed pressure, better management of excess water and improved availability of water and nutrients to maize that might have given the crop a competitive advantage over weeds especially at early stages (Yadav *et al.* 2021). Among the weed management treatments, highest grain yield was recorded with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE which was statistically at par with rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE and tembotrione 120 g/ha PoE alone and was comparable with weed free. Atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha resulted in 27.7% yield increase over atrazine 1000 g/ha PE alone confirming the findings of Dey and Pratap (2018).

Table 2. Effect of maize establishment methods and weed management treatments on different weeds biomass at 60 DAS in maize

Treatment	Weed biomass at 60 DAS (g/m^2)					
	Echinochloa colona	*Eleusine indica*	*Celosia argentea*	*Trianthema monogyna*	*Cyperus iria*	Total
Establishment method						
Flat bed	5.4(36.7)	2.3(5.2)	1.8(3.0)	1.6(2.0)	2.4(9.3)	8.0(56.8)
Raised bed	5.1(33.5)	2.1(4.3)	1.6(2.4)	1.5(1.6)	2.3(8.6)	7.7(54.6)
Zero till	5.5(37.9)	2.6(6.6)	1.9(3.8)	2.0(2.9)	2.7(10.5)	8.2(66.7)
LSD (p=0.05)	0.21	0.08	NS	0.06	0.08	0.04
Weed management						
Atrazine 1000 g/ha PE	7.7(59.1)	3.1(8.5)	2.1(3.8)	2.0(3.0)	2.2(3.7)	10.4(108.0)
Atrazine 1000 g/ha + rice straw mulch 5 t/ha	7.4(54.5)	2.9(7.5)	1.9(4.3)	1.8(2.3)	2.0(3.1)	9.9(97.7)
Tembotrione 120 g/ha PoE	4.5(19.9)	2.0(3.0)	1.4(0.9)	1.5(1.5)	1.7(1.9)	6.6(43.4)
Atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE	2.8(8.2)	1.5(1.6)	1.1(0.3)	1.3(0.7)	1.5(1.4)	5.4(28.3)
Rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha PoE	4.2(17.4)	2.0(3.1)	1.1(0.3)	1.4(0.9)	1.6(1.7)	6.2(38.3)
Weed free	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)
Weedy check	9.7(93.2)	3.8(13.9)	3.5(11.4)	3.0(8.2)	7.1(49.0)	16.1(256.1)
LSD (p=0.05)	0.78	0.14	0.22	0.17	0.32	0.06
Interaction	NS	NS	NS	NS	NS	NS

Note: Data are subjected to $\sqrt{x+1}$ transformation before analysis. Original values are given in parentheses. PE = Pre-emergence; PoE = Post-emergence

Table 3. Effect of establishment methods and weed management treatments on weed control efficiency, weed index, grain yield and economics of maize

Treatment	Weed control efficiency (%)	Weed index (%)	Grain yield (t/ha)	Cost of cultivation (`/ha)	Gross return (`/ha)	Net return (`/ha)	B:C ratio
Establishment method							
Flat bed	-	-	4.97	35,446	84,954	49,507	2.40
Raised bed	-	-	5.01	36,646	85,638	48,992	2.34
Zero till	-	-	4.61	32,246	76,547	44,299	2.37
LSD (p=0.05)	-	-	0.35	-		-	
Weed management							
Atrazine 1000 g/ha	56.2	28.2	4.33	30,569	71,978	41,407	2.35
Atrazine 1000 g/ha + rice straw mulch 5 t/ha	59.1	26.4	4.44	33,705	81,222	45,182	2.41
Tembotrione 120 g/ha	80.0	15.8	5.08	33,369	87,675	54,296	2.62
Atrazine 1000 g/ha *fb* tembotrione 120 g/ha	85.7	8.3	5.53	34,369	99,679	63,667	2.90
Rice straw mulch 5 t/ha *fb* tembotrione 120 g/ha	81.3	15.4	5.10	36,505	90,819	54,314	2.48
Weed free	100.0	0.0	6.03	46,005	1,09,668	65,208	2.38
Weedy check	0.0	41.0	3.56	28,833	54,142	25,308	1.87
LSD (p=0.05)	-	-	0.53	-		-	-
Interaction	-	-	S	-	-		-

Among the maize establishment methods, the cost of cultivation was lowest with zero till system which was 9.9 and 13.6% lower than flat bed system and raised bed system, respectively due to higher land preparation cost. However, initial higher cost involved in raised bed system has compensated the highest net return achieved which was 26.2% higher than zero till system. Similarly, B:C ratio was also 11.7 and 9.3% higher in raised bed system than zero till and flatbed system, respectively (**Table 3**). Among different weed management treatments, the highest net return (₹ 63,662/ha) and highest B:C ratio 2.90 was obtained with atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE which was comparable to weed free plots.

It was concluded that raised bed planting amongst maize planting methods and atrazine 1000 g/ha PE *fb* tembotrione 120 g/ha PoE amongst weed management treatments were better in terms of effectiveness to manage weed and improving the crop productivity and economic returns.

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RESEARCH NOTE

Effect of pre- and post-emergence herbicides on weeds and yield of soybean

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ABSTRACT

A field experiment was conducted at Agricultural Research Station, Ummedganj, Kota, Rajasthan during rainy *(Kharif)* season, 2019 to study the comparative efficacy of pre- and post-emergence herbicides in managing weeds and improving productivity of soybean (*Glycine max* L. Merrill). The experimental field was infested with grassy weeds (48.60%), broad-leaved weeds (39.49%) and sedges (11.91%). *Cynodon dactylon* (L.) Pers., *Eleusine indica* (L.) Gaertn., *Echinochloa crus-galli* (L.) Beauv and *Echinochloa colona* (L.) Link among grassy weeds, *Boerhavia diffusa* L. nom. cons., *Convolvulus arvensis* L., *Commelina benghalensis* L., *Digera arvensis* Forsk., *Celosia argentea* L. among broad-leaved weeds and *Cyperus rotundus* L., the sedge were major associated weeds. Maximum soybean seed yield (1800 kg/ha) and higher weed control efficiency (77.79%) were recorded with hand weeding twice at 20 and 40 days after sowing (DAS) followed by post-emergence application of sodium-acifluorfen 16.5% + clodinafop- propargyl 8% (premix) 165 + 80 g/ha (1550 kg/ha).

Keywords: Hand weeding, Herbicides, Soybean, Sodium-acifluorfen + clodinafop-propargyl, Weed management

Soybean (*Glycine max* L. Merrill) is an important oilseed and food grain legume crop in India. Soybean crop faces severe weed competition during early stages of crop growth, resulting in severe yield loss up-to 58-85%, depending on the weed intensity, nature, environmental condition and duration of weed competition (Jha *et al.* 2014). Thus, it is important to keep the crop free from weeds during the critical period to get optimal soybean yield (Kewat *et al*. 2000). Manual weeding is normally followed by farmers as it is effective, but is becoming prohibitive to use due to unavailability of adequate labourers, costly labour, greater time consumption and difficulty due to intermittent rains during the rainy season during which soybean is grown. Therefore, it is necessary, to find out the alternative methods for manage weeds during early growth period of soybean to get optimal yield economically. Herbicides were found to be economical to manage weeds. Hence, the present study was carried out to find out effective pre- and post-emergence herbicides to manage weeds in soybean.

The experiment was conducted during rainy *(Kharif)* season of 2019 at Agricultural Research Station, Ummedganj, Kota, Rajasthan. The experiment was laid out in randomized block design with eight treatments with three replications. Eight treatments include: pre-emergence application (PE) of pendimethalin 1.0 kg/ha, pendimethalin 30% EC + imazethapyr 2% SL (premix) 960 g/ha PE, post-emergence application (PoE) of sodium-acifluorfen 16.5% + clodinafop-propargyl 8% EC (premix) 165 + 80 g/ha at 20 DAS, quizalofop-ethyl 50 g/ha PoE at 20 DAS, imazethapyr 100 g/ha PoE at 20 DAS, imazethapyr 3.75% + propaquizafop 2.5% ME (premix) 50 + 75 g/ha PoE at 20 DAS, hand weeding twice at 20 and 40 days after seeding (DAS) and weedy check. The soil of the experimental field was clay loam in texture and the soil having medium fertility status. Soybean variety RKS-113 (Kota Soya-1) was used as experimental material developed at ARS, Kota (Rajasthan).

Effect on weeds

Dominating weed flora of the experimental field were: *Cynodon dactylon* (L.) Pers., *Eleusine indica* (L.) Gaertn., *Echinochloa crus-galli* (L.) Beauv and *Echinochloa colona* (L.) Link among grassy weeds, *Boerhavia diffusa* L. nom. cons., *Convolvulus arvensis* L., *Commelina benghalensis* L., *Digera arvensis* Forsk., *Celosia argentea* L. among broad-leaved weeds and *Cyperus rotundus* L., the sedge. The grassy weeds (48.60%) were more predominant than broad-leaved weeds (39.49%) and sedges (11.91%) in the experimental field. Similar observations were made earlier by Meena *et al.* (2011).

The lowest weed biomass was recorded with hand weeding twice. Among herbicide treatments,

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Table 1. Effect pre- and post-emergence (PE and PoE) herbicides on soybean yield attributing characters, yield and economics

Treatment	Pods/ plant (No.)	Seeds/ pod (No.)	Seed Yield/ plant (g)	Seed index (g)	Soybean seed yield (kg/ha)	Soybean straw yield (kg/ha)	Net returns (₹/ha)	B:C ratio
Pendimethalin 1.0 kg/ha PE	33.9	2.00	4.29	11.00	1225	1792	25350	1.07
Pendimethalin + imazethapyr (premix) 960 g/ha PE	37.2	2.13	4.85	11.20	1475	2128	34561	1.42
Sodium-acifluorfen + clodinafop-propargyl (premix) 165 + 80 g/ha PoE at 20 DAS	41.2	2.20	5.32	11.33	1550	2233	38204	1.61
Quizalofop-ethyl 50 g/ha PoE at 20 DAS	34.9	2.13	4.56	10.97	1325	1930	29370	1.24
Imazethapyr 100 g/ha PoE at 20 DAS	35.9	2.13	4.65	11.07	1425	2091	33981	1.47
Imazethapyr + propaquizafop (premix) 50+75 g/ha PoE at 20 DAS	39.5	2.13	5.21	11.10	1520	2190	36804	1.54
Hand weeding twice at 20 and 40 DAS	46.7	2.27	6.10	11.43	1800	2592	39571	1.22
Weedy check	24.1	1.93	2.82	10.93	700	1028	5859	0.26
LSD (p=0.05)	3.86	NS	0.51	NS	122.93	193.28	4921	0.20

Table 2. Effect of pre- and post-emergence (PE and PoE) herbicides on weed biomass (g/m) and weed control efficiency at 60 days after seeding (DAS)

Treatment	Biomass (g/m^2)				Weed control efficiency (%)
	Grassy weeds	Broad-leaved weeds	Sedges	Total weeds	
Pendimethalin 1.0 kg/ha PE	5.05(24.50)	4.59(20.2)	2.38(4.7)	7.09(49.3)	44.39
Pendimethalin + imazethapyr (premix) 960 g/ha PE	4.09(15.8)	3.76(13.1)	2.18(3.7)	5.80(32.6)	63.28
Sodium acifluorfen + clodinafop-propargyl (premix) 165+80 g/ha PoE at 20 DAS	4.01(15.1)	3.52(11.4)	2.04(3.2)	5.53(29.6)	66.67
Quizalofop-ethyl 50 g/ha PoE at 20 DAS	3.76(13.2)	4.81(22.1)	2.24(4.0)	6.35(39.3)	55.71
Imazethapyr 100 g/ha PoE at 20 DAS	4.48(19.1)	3.97(14.8)	2.21(3.9)	6.22(37.7)	57.52
Imazethapyr + propaquizafop (premix) 50+75 g/ha PoE at 20 DAS	4.04(15.3)	3.67(12.5)	2.18(3.8)	5.71(31.6)	64.39
Hand weeding twice at 20 and 40 DAS	3.33(10.2)	2.87(7.2)	1.81(2.3)	4.55(19.7)	77.79
Weedy check	6.87(46.3)	6.25(38.3)	2.74(6.6)	9.48(88.8)	0.00
LSD (p=0.05)	0.51	0.49	0.22	0.29	4.03

Data in parentheses are original values of weed biomass. Square root transformed value ($\sqrt{x+1}$) of weed biomass used for statistical analysis

post-emergence application of sodium-acifluorfen + clodinafop-propargyl (pre-mix) 165+80 g/ha at 20 DAS was most effective in significantly reducing the weed biomass, than the rest of herbicide treatments as also observed by Verma and Kushwaha (2019). The highest weed control efficiency at 60 DAS was recorded with hand weeding twice at 20 and 40 DAS (77.79%), followed by sodium-acifluorfen + clodinafop-propargyl (premix) 165+80 g/ha PoE at 20 DAS (66.67%).

Effect on soybean

Hand weeding twice at 20 and 40 DAS has recorded tallest plants, maximum branches/ plants, greater dry matter production, higher values of yield attributing characteristics and higher soybean straw and grain yield. Next best treatment was sodium-acifluorfen + clodinafop-propargyl (premix) 165 + 80 g/ha PoE. The current experimental findings confirmed earlier reported efficacy of hand weeding (Kamble *et al.* 2017 and Patel *et al*. 2021) and sodium-acifluorfen 16.5% + clodinafop-propargyl 8% EC (premix) 187.5 g/ha PoE (Harithavardhini *et al.* 2016 and Verma and Kushwaha 2019). The benefit: cost ratio was highest (1.61) with post-emergence application of sodium-acifluorfen + clodinafop-propargyl (pre-mix) 165 + 80 g/ha which was more remunerative than other herbicide treatments and hand weeding twice (1.22). Thus, it was concluded that hand weeding twice or sodium-acifluorfen 16.5% + clodinafop-propargyl 8% EC (pre-mix) 165 + 80 g/ha may be used for effectively managing weeds and attaining higher soybean productivity.

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RESEARCH NOTE

Effect of herbicides on associated weeds and growth of blackgram

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ABSTRACT

A field study was conducted at Research Station in Kota, Rajasthan during rainy *(Kharif)* season of 2020 to identify suitable herbicides including pre-emergence (PE) and post-emergence herbicides (PoE) for managing weeds and improve productivity of blackgram [*Vigna mungo* (L.) Hepper]. Among weed control treatments tested, the lowest weed density, weed index and highest crop growths parameters like plant population, plant height, dry matter accumulation, nodules/ plant, dry weight of nodules was recorded with hand weeding twice at 20 and 40 days after sowing (DAS), pre-emergence application (PE) of pendimethalin 1.0 kg/ha followed by (*fb*) post-emergence application (PoE) of propaquizafop 2.5% w/w 33.3 g/ha + imazethapyr 3.75% w/w (pre-mix) ME 50 g/ha at 20 DAS and pendimethalin 1.0 kg/ha PE *fb* fomesafen 11.1% w/w 220 g/ha + fluazifop-p-butyl 11.1% w/w 220 g/ha (pre-mix) PoE at 20 DAS.

Keywords: Blackgram, Fluazifop-p-butyl, Imazethapyr, Pendimethalin, Propaquizafop, Weed management

Blackgram [*Vigna mungo* (L.) Hepper] is one of the important pulse crops cultivated worldwide in tropical and subtropical regions of the world. The crop is resistant to adverse climatic conditions and improves the soil fertility by fixing atmospheric nitrogen in the soil. It has wide adaptability and can be grown round the year in different agroecological regions of the country. It contains 48.0% carbohydrates, 22.3% protein, 154 mg calcium, 9.1 mg iron, 1.4 g fat, 0.37 g riboflavin and 0.42 mg thiamine in per 100 g (Asaduzzaman *et al.* 2010). Blackgram is usually accompanied by luxuriant weed growth during the rainy (*Kharif*) season owing to abundant rainfall received during monsoons leading to serious crop losses. Unchecked weeds have been reported to cause a considerable reduction in the grain yield of blackgram ranging from 35.2 to -87% (Chand *et al.* 2004, Singh 2011, Sukumar *et al*. 2018) and critical period for crop weed competition is around 15 to 45 DAS (Khot *et al*. 2016). Blackgram is not a very good competitor against weeds (Choudhary *et al.* 2012) and is mostly susceptible to weed infestation during the first four weeks of its growth period (Randhawa *et al.* 2002). Therefore, adequate weed management is essential, particularly during critical period of crop weed competition, to ensure optimal crop growth.

The majority of farmers use hand weeding, which requires a lot of labours, time and is also less cost effective under rainfall condition. Pre-emergence herbicides only control weeds for a short period and there after late-emerging weeds begin to compete with crops. Hence, in order to keep free from weed competition, the use of pre-emergence herbicides to manage early emerging weeds and post-emergence herbicides in sequence to manage late emerging weeds may be essential. Thus, the current study was conducted to determine the weed management effectiveness of herbicides including a ready-mix herbicide combination of pre- and post-emergence herbicides for season long broad-spectrum weed management in *Kharif* (rainy season) blackgram.

A field study was conducted during rainy *(Kharif)* season of 2020 at Research Station, Ummedganj, Kota, Rajasthan. The soil of the experimental site was clay loam, having 0.53% organic carbon, 206.10, 30.50 and 480.10 kg/ha available N, P and K, respectively. The mean maximum and minimum temperature recorded were in the range of 36.7°C to 29.3°C and 18.2°C to 26.1°C, respectively (mean of one years). The mean sunshine hours among different weeks were 0.7 to 9.1 h in a day. The total evaporation observed was 0.6 to 3.1 mm/day, while total rainfall recorded 650 mm to 1000 mm during the cropping season. The relative humidity in morning (RH_1) and evening (RH_2) were recorded in the range of 67.1 to 92 and 53.6 to 85%, respectively. Experiments consisted of 10 treatments

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with three replications arranged in a randomized block design. Blackgram (cultivar: '*Mukundra Urd 2*') was sown at 30 cm row-to-row spacing using 20 kg seed/ha. Recommended dose of fertilizers (20 kg N + 30 kg P/ha) was applied to blackgram crop at the time of sowing through di-ammonium phosphate (DAP) and urea. Pre-emergence application (PE) of pendimethalin 1.0 kg/ha was done on next day of sowing and post-emergence application (PoE) of other herbicides (propaquizafop 2.5% w/w 33.3 g/ha + imazethapyr 3.75% w/w ME 50 g/ha (ready-mix), acifluorfen-sodium 16.5% EC 140 g/ha + clodinafop-propargyl 8% EC 70 g/ha (ready mix), fomesafen 11.1% w/w 220 g/ha + fluazifop-p-butyl 11.1% w/w 220 g/ha (ready-mix) and fluazifop-p-butyl 13.4% w/w 250 g/ha was done at 20 day after sowing (DAS) by using 375 l/ha of water with knapsack sprayer fitted with a flat fan nozzle. Weed density was recorded by using 0.5 m^2 quadrat at 60 DAS in all the treatments and then converted into number of weeds per m^2. Growth parameters like plant height, branches/plant, dry matter accumulation/meter row length, nodules/plant and dry weight of nodules/plant of blackgram were recorded at 30, 60 DAS and at harvest. The data on total weeds density was subjected to square root transformation $\sqrt{x+0.5}$ to normalize their distribution (Blackman and Roberts 1950). Weed index is the decrease in yield due to different treatments in comparison with recommended cultivation practices or the treatment which has the highest yield. It was calculated by using the formula by Gill and Kumar (1969).

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

Where,

X = Yield of plot with minimum weed competition

Y = Yield of treated plot

All the data were subjected to analysis of variance (ANOVA) as per the standard procedures. The comparison of treatment means was made by critical difference (RBD) at p=0.05.

Effect on weeds

The common weeds at the experimental site were monocot weeds: *Cynodon dactylon, Echinochloa crus-galli, Eleusine indica, Commelina bengalensis*; dicot weeds: *Parthenium hysterophorus, Digera arvensis, Trianthema* spp. and *Celosia argentea* and the sedge weed: *Cyperus rotundus.* All weed control treatments significantly reduced the monocot, dicot and sedge weeds density compared to weedy check. The hand weeding twice at 20 and 40 DAS recorded lowest weed density of monocots [*Cynodon dactylon* (3.18/m^2), *Echinochloa crus-galli* (4.2/m^2), *Eleusine indica* (3.32/m^2), *Commelina benghalensis* (3.12/m^2)]; dicot [*Digera arvensis* (3.32/m^2), *Celosia argentea* (3.26/m^2), *Trianthema* spp. (3.16/m^2), *Parthenium hysterophorus* (3.7/m^2)}; sedge {*Cyperus rotundus* (4.24/m^2)]; others (6.48/m^2) and total weeds (11.66/m^2) than the rest of treatments (**Table 1** and **2**). However, the density of *Commelina benghalensis* was at par with pendimethalin 1.0 kg/ha (PE) *fb* propaquizafop 33.3 g/ha + imazethapyr (pre mix) 50 g/ha PoE at 20 DAS, pendimethalin 1.0 kg/ha (PE) *fb* fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS and pendimethalin 1.0 kg/ha (PE) *fb* acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS.

The sequential application of pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE at 20 DAS has recorded the lowest total weed density (14.64/m^2). It was at par with the pendimethalin 1.0 kg/ha PE *fb* fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS and pendimethalin 1.0 kg/ha (PE) *fb* acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS. The high selectivity of herbicides to blackgram and non-selectivity to weeds was the reason for better management of weeds. Pendimethalin PE reduced emerging weed germination during initial period of growth and sequential post-emergence application of imazethapyr has suppressed the late emerging sedges and broad-leaved weeds. Imazethapyr inhibits the plastid enzyme acetolactate synthase (ALS) in plants which catalyses the first step in the biosynthesis of vital branched chain amino acids (valine, leucine, isoleucine). The ALS inhibitors thus limit cell division and reduce carbohydrate transport in the vulnerable plants (Das 2008). Imazethapyr was also recommended for usage in legumes by Papiernik *et al.* (2003). Hence, the sequential application of pendimethalin PE *fb* propaquizafop + imazethapyr or fomesafen + fluazifop-p-butyl PoE, acifluorfen-sodium + clodinafop-propargyl was more effective than sole application of pendimethalin PE, propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE and fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE in controlling weeds. These results were in conformity with the Sahu *et al.* (2019), Reddy *et al.* (2021) Jagadesh *et al.* (2021) and Singh *et al.* (2019).

Table 1. Effect of weed control treatments on dicot and sedge weeds density (no./m^2) at 60 DAS

Treatment	Dicot				Sedge
	Parthenium hysterophorus	*Digera arvensis*	*Trianthema* spp.	*Celosia argentea*	*Cyperus rotundus*
Pendimethalin 1.0 kg/ha PE	5.68(15.14)	5.56(14.46)	4.4(8.66)	6.04(17.2)	6.74(8.00)
Propaquizafop 33.3 g/ha + imazethapyr 50 g/ha (pre-mix) PoE at 20 DAS	5.14(12.2)	5.12(12.06)	3.82(6.34)	5.58(14.54)	6.2(7.44)
Acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS	5.18(12.4)	5.18(12.4)	3.9(6.6)	5.64(14.94)	6.24(7.66)
Fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	5.16(12.26)	5.16(12.26)	3.86(6.46)	5.6(14.66)	6.22(7.54)
Pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE at 20 DAS	4.7(10.06)	4.56(9.4)	3.42(4.86)	4.78(10.4)	5.8(6.14)
Pendimethalin 1.0 kg/ha PE *fb* acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS	4.8(10.54)	4.64(9.74)	3.46(5.00)	4.84(10.74)	5.86(6.4)
Pendimethalin 1.0 kg/ha PE *fb* fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	4.76(10.34)	4.6(9.6)	3.44(4.94)	4.8(10.54)	5.84(6.26)
Fluazifop-p-butyl 250 g/ha PoE at 20 DAS	5.24(12.74)	5.18(12.46)	4.1(7.4)	5.34(13.26)	5.96(16.86)
Two hand weeding at 20 and 40 DAS	3.7(5.86)	3.32(4.54)	3.16(4.00)	3.26(4.34)	4.24(4.06)
Weedy check	7.26*(25.34)	7.8(29.46)	5.66(15)	7.34(26.02)	9.08(16.14)
LSD (p=0.05)	0.16	0.16	0.22	0.18	0.28

*$\sqrt{x+0.5}$ Subjected to square root transformation values and data in parentheses are original values; PE = pre-emergence application; PoE= post-emergence application; *fb* = followed by; DAS = days after seeding

Table 2. Effect of weed control treatments on monocot, other and total weeds density (no./m^2) at 60 DAS

Treatment	Monocot				Other weeds	Total weeds
	Echinochloa crus galli	*Eleusine indica*	*Cynodon dactylon*	*Commelina benghalensis*		
Pendimethalin 1.0 kg/ha PE	5.94(16.7)	4.74(10.3)	4.24(8.0)	4.52(9.3)	9.44(43.6)	18.22(165.0)
Propaquizafop 33.3 g/ha + imazethapyr 50 g/ha (pre-mix) PoE at 20 DAS	4.76(10.3)	4.36(8.5)	4.1(7.4)	4.12(7.5)	8.42(34.4)	16.28(131.6)
Acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS	6.88(10.9)	4.42(8.7)	4.16(7.7)	4.16(7.7)	8.48(35.0)	16.48(134.8)
Fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	4.84(10.7)	4.38(8.6)	4.14(7.5)	4.14(7.6)	8.44(34.6)	16.38(133.0)
Pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE at 20 DAS	4.54(9.3)	3.84(6.4)	3.78(6.1)	3.36(4.7)	7.76(29.1)	14.64(106.1)
Pendimethalin 1.0 kg/ha PE *fb* acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS	4.62(9.7)	3.94(6.7)	3.84(6.4)	3.5(5.14)	8.14(32.1)	15.06(112.3)
Pendimethalin 1.0 kg/ha PE *fb* fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	4.58(9.5)	3.88(6.5)	3.82(6.3)	3.48(5.1)	7.82(29.6)	14.8(108.4)
Fluazifop-p-butyl 250 g/ha PoE at 20 DAS	4.68(10.0)	4.02(7.1)	3.88(6.5)	4.18(7.9)	9.34(42.6)	16.6(136.8)
Two hand weeding at 20 and 40 DAS	4.2(7.9)	3.32(4.5)	3.18(4.1)	3.12(3.9)	6.48(20.0)	11.66(67.1)
Weedy check	7.54*(27.5)	6.22(18.3)	5.86(16.1)	5.1(12.0)	12.8(81.0)	24.16(291.1)
LSD (p=0.05)	0.24	0.28	0.16	0.42	0.38	0.32

*$\sqrt{x+0.5}$ Subjected to square root transformation values and data in parentheses are original values; PE = pre-emergence application; PoE= post-emergence application; *fb* = followed by; DAS = days after seeding

Effect on blackgram

Weedy check recorded the lowest grain yield (395 kg/ha) and crop growth attributes at 30 DAS, 60 DAS and at harvest like plant height (16.72, 27.00 and 32.00 cm), branches/plant (2.17, 4.62 and 7.72), dry matter accumulation (5.37, 28.57 and 39.29 g/m row length), nodules/plant at 40 DAS (21.57) and dry weight of nodules/plant at 40 DAS (24.53 mg/plant). The higher grain yield (859 kg/ha) and growth parameters like plant height (21.76, 33.83 and 48.41 cm), branches/plant (3.53, 6.40 and 10.53), dry matter accumulation (10.17, 58.67 and 77.44 g/m row length), nodules/plant at 40 DAS (28.33) and dry weight of nodules/plant at 40 DAS (49.33 mg/plant) were observed with hand weeding twice at 20 and 40 DAS and was found at par with pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre mix) 50 g/ha PoE at 20 DAS, pendimethalin 1.0 kg/ha PE *fb* fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre mix) PoE at 20 DAS and pendimethalin 1.0 kg/ha PE *fb* acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre mix) PoE at 20

Table 3. Effect of weed control treatments on weed index, plant height, no. and dry weight of nodules/plant of blackgram

Treatment	Weed index (%)	Plant height (cm)			No. of nodules/ plants	Dry weight of nodules (mg)/plant
		30 DAS	60 DAS	At harvest	40 DAS	40 DAS
Pendimethalin 1.0 kg/ha PE	41.43	18.83	29.00	37.19	28.00	49.00
Propaquizafop 33.3 g/ha + imazethapyr 50 g/ha (pre-mix) PoE at 20 DAS	26.65	19.76	30.67	41.44	24.60	44.60
Acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre mix) PoE at 20 DAS	34.16	19.04	30.53	39.23	23.00	43.00
Fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	29.01	19.28	30.57	40.45	23.73	43.73
Pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE at 20 DAS	3.66	21.20	32.50	46.13	27.33	48.33
Pendimethalin 1.0 kg/ha PE *fb* acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS	22.98	20.56	31.67	44.71	25.23	47.13
Pendimethalin 1.0 kg/ha PE *fb* fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	9.69	21.12	32.07	45.88	26.87	47.87
Fluazifop-p-butyl 250 g/ha PoE at 20 DAS	43.71	18.84	29.93	37.49	24.67	27.30
Two hand weeding at 20 and 40 DAS	0.00	21.76	33.83	48.41	28.33	49.33
Weedy check	54.00	16.72	27.00	32.00	21.57	24.53
LSD (p=0.05)	-	1.69	1.48	2.97	3.12	2.30

*PE = pre-emergence application; PoE= post-emergence application; *fb* = followed by; DAS = days after seeding

Table 4. Effect of weed control treatments on branches/plant, dry matter accumulation and grain yield of blackgram

Treatment	Branches/ plant			Dry matter accumulation (g/m row length)			Grain yield (kg/ha)
	30 DAS	60 DAS	At harvest	30 DAS	60 DAS	At harvest	
Pendimethalin 1.0 kg/ha PE	2.37	5.77	7.70	7.60	46.43	53.00	503
Propaquizafop 33.3 g/ha + imazethapyr 50 g/ha (pre-mix) PoE at 20 DAS	2.73	5.83	8.90	8.77	51.87	64.08	630
Acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS	2.28	5.53	8.69	8.10	50.97	60.64	565
Fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	2.50	5.87	8.63	8.23	51.34	62.96	610
Pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE at 20 DAS	3.20	6.37	9.60	9.83	57.27	73.20	827
Pendimethalin 1.0 kg/ha PE *fb* acifluorfen-sodium 140 g/ha + clodinafop-propargyl 70 g/ha (pre-mix) PoE at 20 DAS	2.90	5.57	8.93	9.23	55.20	71.04	661
Pendimethalin 1.0 kg/ha PE *fb* fomesafen 220 g/ha + fluazifop-p-butyl 220 g/ha (pre-mix) PoE at 20 DAS	3.07	6.23	9.20	9.60	56.67	72.96	775
Fluazifop-p-butyl 250 g/ha PoE at 20 DAS	2.31	5.38	8.04	6.93	43.67	51.28	483
Two hand weeding at 20 and 40 DAS	3.53	6.40	10.53	10.17	58.67	77.44	859
Weedy check	2.17	4.62	7.72	5.37	28.57	39.29	395
LSD (p=0.05)	0.42	0.85	1.06	0.86	2.72	7.60	95

*PE = pre-emergence application; PoE= post-emergence application; *fb* = followed by; DAS = days after seeding

DAS (**Table 3** and **4**). This could be owing to better weed management and minimizing the competition of weeds with main crop for resources, *viz.* light, nutrients and moisture with those effective weed control treatments. Thus, reduced crop-weed competition resulted into overall improvement of crop growth as measured by plant height and dry matter accumulation, which led to better reproductive structure and translocation of photosynthates to the sink. The results corroborated with the findings of Yadav *et al.* (2014). Among different treatments, sequential application of pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE at 20 DAS recorded higher grain yield with 52.23% yield advantages over weedy check. The reduced crop weed competition, with hand weeding twice and all herbicidal weed control methods, resulted in a considerable increase in growth and yield characters ultimately led to higher grain yield of blackgram. In a weedy condition, weeds take a bigger portion of the resources available in the soil and environment for their growth during the early stages of crop growth. The results confirmed the finding of Tiwari *et al.* (2018), Harisha *et al.* (2021).

Thus, it was concluded that application of pendimethalin 1.0 kg/ha PE *fb* propaquizafop 33.3 g/ha + imazethapyr (pre-mix) 50 g/ha PoE at 20 DAS results in broad-spectrum weed management and higher crop growth parameters and grain yield in *Kharif* blackgram on sandy loam soils.

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RESEARCH NOTE

Influence of weed management practices on growth and yield attributes of mustard

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ABSTRACT

A field experiment was conducted on sandy loam soils to identify alternate weed management treatments to economically manage weeds and improve mustard growth and yield of mustard. Among tested weed management treatments, higher growth parameters, higher yield attributes (number of siliquae/plants and seeds/siliquae) and yield of mustard were observed under inter-cultivation and hand weeding twice at 15 and 30 days after seeding (DAS) which was at par with pre-emergence application (PE) of oxadiargyl 0.09 kg/ha *fb* inter-cultivation at 30 DAS.

Keywords: Hand weeding, Inter-cultivation, Oxadiargyl, Mustard, Weed management

Mustard (*Brassica juncea* (L.) Czern.) is the second most important oilseed crop in India, after groundnut, among the seven edible oilseeds. The seed is used as condiment. The leaves of young mustard plants are used as green vegetables, as it supplies sulphur and minerals in the diet. Mustard oil cake is used as feed and manure. Its green stem and leaves are a good source of green fodder for cattle. Weeds are the major biotic stress in mustard production. Weed competition in mustard is more serious during early stages (4-6 weeks), because crop growth in winter (*Rabi*) season remains slow (Mishra *et al.* 2016). However, during later stages, it grows vigorously and suppresses weeds growth. The critical period of crop -weed competition in mustard is 15-40 days and weeds cause about 24% of yield loss if they are not controlled during the critical period (Yadav *et al*. 2014). In mustard, traditionally weeds are managed by hand weeding. But, increasing wages, scarcity of labour at peak periods and high labour cost necessitates the need to identify other alternative weed management methods which are technically feasible and economically viable (Rao and Chauhan 2015). Hence, the present experiment was carried out to study the influence of weed management practices on crop growth and yield of mustard.

A field experiment was conducted during *Rabi* 2020-21 at Rajendranagar, Hyderabad on a sandy loam soil available nitrogen (223 kg/ha), available phosphorus (30.87 kg/ha) and potassium (375.72 kg/ha). Mustard variety '*NRCHB-101*' was sown with seed rate of 4 kg/ha manually at row spacing of 40 cm. Later, the crop was resorted to thinning and plant to plant spacing was maintained at 10 cm. The experiment was laid out in randomised block design with twelve treatments, *viz*. pre-emergence application (PE) of pendimethalin 1.0 kg/ha followed by (*fb*) post-emergence application (PoE) of quizalofop-ethyl 0.05 kg/ha, oxadiargyl 0.09 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE, oxyfluorfen 0.1 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE, pendimethalin 1.0 kg/ha PE *fb* straw mulch 5 t/ha, oxadiargyl 0.09 kg/ha PE *fb* straw mulch 5 t/ha, oxyfluorfen 0.1 kg/ha PE *fb* straw mulch 5 t/ha, pendimethalin 1.0 kg/ha PE *fb* inter-cultivation at 30 DAS, oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS, oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS, inter-cultivation and hand weeding at 15 and 30 DAS (weed free), inter-cultivation at 15 and 30 DAS and unweeded control with three replications. Pre-emergence herbicides were applied within 24 hours after sowing. Post-emergence herbicide was sprayed at 2-3 leaf stage of weeds. Straw mulch was applied on 15 DAS. Inter-cultivation was done with push hoe at 15 and 30 DAS. Hand weeding was done at 15 and 30 DAS. The observations were recorded, using standard procedures, on crop growth parameters *i.e.*, plant height and dry matter production, yield attributes *i.e.*, number of siliqua/plants, length of siliqua, seeds/siliquae and 1000-seed weight. For dry matter production, samples were dried in hot air oven at 65 ±

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5°C.The data on weed density and biomass for all the categories were computed using square root ($\sqrt{x+1}$) transformation.

Effect on weeds

Significantly lower weed density and biomass were observed under inter-cultivation and hand weeding twice at 15 and 30 DAS and it was at par with oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS. It was on par with oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS and pendimethalin 1.0 kg/ha PE *fb* inter-cultivation at 30 DAS. Lower total weed density was recorded with treatments might be due to their effective control of weeds at critical period of weed competition (Chandolia *et al.* 2010, Mishra 2012).

Effect on mustard growth

Maximum mustard plant height and dry matter production was noticed under inter-cultivation and hand weeding twice at 15 and 30 DAS and it was at par with oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS. It was at par with oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS and pendimethalin 1.0 kg/ha PE *fb* inter-cultivation at 30 DAS. Efficient utilization of resources by the crop due to less weed competition in those treatments resulted in higher mustard plant height that led to higher photosynthates accumulation and higher dry matter production (Bazaya *et al.* 2004, Kaur *et al.* 2013, Das 2016).

Effect on mustard yield attributes and yield

The mustard yield attributes like number of siliquae/plant and number of seeds/siliquae were significantly influenced by different weed management practices. However, length of siliquae and 1000-seed weight not influenced by weed management practices. Higher number of siliquae/plant and number of seeds/siliquae were recorded under inter-cultivation and hand weeding at 15 and 30 DAS and it was statistically on par with oxadiargyl 0.09 kg/ha *fb* inter-cultivation at 30 DAS. Oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS and pendimethalin 1.0 kg/ha PE *fb* inter-

Table 1. Weed and crop growth as influenced by weed management treatments in mustard

Treatment	Total weed density (no./m^2)	Weed biomass (g/m^2)	Mustard plant height (cm)	Mustard dry matter production (kg/ha)
Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	5.83 (32.97)	3.51(11.29)	131.88	3563.1
Oxadiargyl 0.09 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	5.68 (31.14)	3.38 (10.43)	132.93	3658.6
Oxyfluorfen 0.1 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	5.78 (32.39)	3.45 (10.88)	132.54	3591.9
Pendimethalin 1.0 kg/ha PE *fb* straw mulch 5 t/ha	5.26 (26.70)	3.08 (8.48)	140.42	4025.1
Oxadiargyl 0.09 kg/ha PE *fb* straw mulch 5 t/ha	5.12 (25.20)	2.98 (7.89)	140.85	4071.9
Oxyfluorfen 0.1 kg/ha PE *fb* straw mulch 5 t/ha	5.21 (26.15)	3.03 (8.18)	140.68	4052.2
Pendimethalin 1.0 kg/ha PE *fb* inter-cultivation at 30 DAS	4.32 (17.66)	2.58 (5.66)	148.89	4458.1
Oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS	3.85 (13.81)	2.29 (4.24)	150.92	4588.9
Oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS	4.22 (16.82)	2.53 (5.38)	149.03	4546.9
Inter-cultivation and hand weeding at 15 DAS and 30 DAS (weed free)	3.34 (10.16)	2.01 (3.05)	158.17	4861.9
Inter-cultivation at 15 and 30 DAS	5.34 (27.48)	3.17 (9.03)	139.72	3976.6
Unweeded control	11.68(135.53)	7.70 (58.30)	129.32	3173.4
LSD (p=0.05)	0.53	0.35	7.8	281.7

Note: Weed data was subjected to square root ($\sqrt{x+1}$) transformation and original values are shown in parenthesis, DAS = days after sowing; PE = pre-emergence; PoE = post-emergence

Table 2. Yield attributes and yield as influenced by weed management treatments in mustard

Treatment	No. of siliquae /plant	Length of siliquae (cm)	No. of seeds/ siliquae	Test weight (g)	Seed yield (kg/ha)
Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	84.29	5.30	11.90	3.54	895
Oxadiargyl 0.09 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	86.10	5.40	12.15	3.56	917
Oxyfluorfen 0.1 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	85.98	5.30	11.96	3.55	908
Pendimethalin 1.0 kg/ha PE *fb* straw mulch 5 t/ha	90.81	5.60	13.69	3.56	1084
Oxadiargyl 0.09 kg/ha PE *fb* straw mulch 5 t/ha	91.02	5.70	13.98	3.57	1104
Oxyfluorfen 0.1 kg/ha PE *fb* straw mulch 5 t/ha	90.90	5.60	13.95	3.56	1092
Pendimethalin 1.0 kg/ha PE *fb* inter-cultivation at 30 DAS	96.33	5.80	16.45	3.58	1267
Oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS	98.37	5.90	16.96	3.59	1349
Oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS	96.49	5.90	16.53	3.59	1320
Inter-cultivation and hand weeding at 15 DAS and 30 DAS (weed free)	100.50	6.00	17.50	3.60	1483
Inter-cultivation at 15 and 30 DAS	90.70	5.53	13.53	3.54	1070
Unweeded control	78.52	5.10	9.98	3.43	641
LSD (p=0.05)	2.30	NS	0.6	NS	140.0

*DAS: days after sowing; PE: pre-emergence application; PoE: post-emergence application

Table 3. Economics as influenced by tested weed management treatments in mustard

Treatment	Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	B:C ratio
Pendimethalin 1.0 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	21041	42201	21160	2.01
Oxadiargyl 0.09 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	21421	43246	21825	2.02
Oxyfluorfen 0.1 kg/ha PE *fb* quizalofop-ethyl 0.05 kg/ha PoE	21055	42856	21801	2.04
Pendimethalin 1.0 kg/ha PE *fb* straw mulch 5 t/ha	24531	50875	26344	2.07
Oxadiargyl 0.09 kg/ha PE *fb* straw mulch 5 t/ha	24681	51820	27139	2.10
Oxyfluorfen 0.1 kg/ha PE *fb* straw mulch 5 t/ha	24305	51234	26929	2.11
Pendimethalin 1.0 kg/ha PE *fb* inter-cultivation at 30 DAS	21181	59163	37982	2.79
Oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS	21231	62874	41643	2.96
Oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS	21125	61555	40430	2.91
Inter-cultivation and hand weeding at 15 DAS and 30 DAS (weed free)	25981	68933	42952	2.65
Inter-cultivation at 15 and 30 DAS	23531	50162	26631	2.13
Unweeded control	19531	28806	11275	1.47
LSD (p=0.05)		6353	2507	

*DAS = days after sowing; PE = pre-emergence application; PoE = post-emergence application

cultivation at 30 DAS, which were at par with oxadiargyl 0.09 kg/ha *fb* inter-cultivation at 30 DAS. The effective weed management treatments provided weed free environment during crop growth resulting in higher number of siliquae/ plant and number of seeds/siliquae (Kour *et al.* 2013). Similarly, higher mustard seed yield was recorded under inter-cultivation and hand weeding at 15 and 30 DAS and it was statistically at par with oxadiargyl 0.09 kg/ha *fb* inter-cultivation at 30 DAS. These results are in conformity with the findings of Mishra (2012), Kumar *et al.* (2013) and Yadav *et al.* (2017).

Effect on economics

The maximum gross and net returns were recorded with inter-cultivation and hand weeding twice at 15 and 30 DAS followed by oxadiargyl 0.09 kg/ha PE *fb* intercultivation at 30 DAS, oxyfluorfen 0.1 kg/ha PE *fb* inter-cultivation at 30 DAS, pendimethalin 1.0 kg/ha PE *fb* inter-cultivation at 30 DAS (**Table 3**). But higher B:C ratio was recorded with oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS because of higher cost of cultivation of hand weeding (Degra *et al.* 2006, Kalita *et al.* 2017).

Conclusion

It was inferred that, inter-cultivation and hand weeding at 15 and 30 DAS and oxadiargyl 0.09 kg/ha PE *fb* inter-cultivation at 30 DAS may be used in mustard for economically managing weeds and attain higher mustard growth and yield.

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RESEARCH NOTE

Screening of Indian borage[*Plectranthus amboinicus* (Lour) Spreng], bitter weed [*Andrographis paniculata* (Burm.f.) Nees] and Southern cone marigold (*Tagetes minuta* L.) for allelopathic potential against weeds

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ABSTRACT

Several plants express the allelopathic phenomenon through release of allelochemicals. Plants rich in allelochemicals can be used for controlling weeds in organic crop production. Current study was aimed at screening of *Andrographis paniculata (Burm.f.)* Nees (bitter weed), *Plectranthus amboinicus* (Lour) Spreng (Indian borage) and *Tagetes minuta* L.(Southern cone marigold) for allelopathic potential against upland weeds.This study was conducted from February to May 2021 in the Department of Agronomy, College of Agriculture, Vellanikkara, Kerala Agricultural University, Thrissur. The methanol extracts of *Tagetes minuta* and *Andrographis paniculate* at 25-30% concentration as pre-emergence application exhibited allelopathic effect on broad-leavedweeds.

Keywords: Allelopathy, Andrographis paniculata, *Plectranthus amboinicus, Tagetes minuta,* Weed management

Allelopathic plants could be a source of new potential herbicidal molecules for the chemical industry, which could be utilized to overcome the negative impacts of synthetic molecules. The term allelopathy generally refers to the stimulatory and inhibitory action of plants due to the direct or indirect release of some chemical compounds (Rice 1984). These plants synthesize and accumulate numerous components in the leaves, roots, fruits, flowers, and bark with various allelochemicals, including phenols, terpenoids, alkaloids, and flavonoids (Rizvi and Rizvi 1992). However, the pattern of germination inhibition and the suppression of earlier planted seedling growth have to be adequately studied.

Medicinal and aromatic plants are considered as sources of new natural allelopathic plant products (Azizi and Fuji 2006). The present experiment was conducted to assess the allelopathic potential of bitter weed (*Andrographis paniculata*), Indian borage (*Plectranthus amboinicus*), and Southern cone marigold (*Tagetes minuta*) to manage upland weeds. The experiment, on screening of selected plants for their allelopathic potential, was conducted inside the green house during February to May 2021 in the Department of Agronomy, College of Agriculture, Vellanikkara, KAU, Thrissur situated at $10^0$32'58" N latitude and $76^0$17'00" E longitude, and an altitude of 40.3 m above mean sea level.

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The experiment was laid out in a completely randomized design (CRD) in a factorial arrangement with three factors and three replications. Factor A consisted of three allelopathic donor plants *Plectranthus amboinicus, Andrographis paniculata* and *Tagetes minuta*. Factor B consisted of the method of extraction (cold water extraction, hot water extraction, and methanol extraction). Concentrations of extracts were included as third factor [5%, 10%, 15%, 0 %, 25%, 30% and Control (distilled water)].

The allelopathic effect of selected medicinal plant donors on weeds was studied using 189 plastic trays (of size 25 x 20 x 5 cm) that were filled up to three-quarters with uniform quantity of soil (1.5 kg) collected from an open area in which Chinese potato (*Solenostemon rotundifolius*) was cultivated during previous years at the Agronomy Crop Museum, College of Agriculture, Vellanikkara, Thrissur. The texture of the experimental soil was sandy clay loam and was acidic in reaction with a pH of 4.74. The trays were separated into three groups of 63 trays, each group for a donor plant *i.e.*, three group of 9 trays; within the donor plants, the trays were grouped into three groups of 27, each for each type of extract. Within each method of extraction, three groups of 21 trays were randomly assigned,each for a concentration of extract, including water in sterilised soil as control treatment and one extra control treatment for each concentration (6 trays). The quantity of water required for attaining field capacity was tested before treatment application and calculated to be 350 ml for each tray. Extracts were prepared in appropriate quantities for each concentration for three replications. The treatments were imposed to assess the allelopathic effect of selected plants on weeds germination and growth. The treatments were applied uniformly to the plastic trays immediately after filling the trays with upland soil. Trays were irrigated at two days interval starting from 3rd day after treatment application in order to maintain field capacity. Trays were examined daily for germination for one month, and observations on weed growth parameters were also recorded.

For preparing aqueous extract, 5 kg of each plant was collected and washed to remove the adhering soil. Cleaned samples were crushed, and 5 L of distilled water was added. These samples were shaken for one hour continuously in an electric shaker. The mixture was left to stand for 48 hours at room temperature, and the extracts were obtained through filtration using Whatman No. 1filter paper having a concentration of 100% w/v used as stock solution. These extracts were diluted to desired concentration of 5%, 10%, 15%, 20%, 25% and 30% using distilled water.

For preparing hot water extract, fresh and clean samples weighing 5 kg were crushed and transferred into a beaker containing 5 L distilled water and boiled for five minutes. The room cooled extract was filtered through Whatman No. 1filter paper and these extracts, having 100% concentration (w/v), were used as stock solutions. From these stock solutions, solutions of concentrations 5%, 10%, 15%, 20%, 25% and 30% were prepared using distilled water. Methanol extracts were prepared by soaking 5 kg crushed whole plant samples in analytical grade methanol of 5 L and boiled for five minutes, then shaking in an electrical shaker for one hour at room temperature. The extracts were filtered through Whatman No. 1filter paper and kept for methanol to evaporate to dryness, and the residues were collected. The residues collected were dissolved in 5L of distilled water to obtain the stock solution of 100% concentration(w/v). Desired concentrations of 5%, 10, 15, 20, 25 and 30% were prepared by adding distilled water.

The extracts were characterized biochemically. The pH and EC of extracts were measured using a pH meter and electrical conductivity meter. The total alkaloids, flavonoids, phenols, and tannins were determined using the method of Harborne (1973). Observations on germination count of weeds at weekly intervals, and weed density and dry weight (biomass) at one month after extract application were recorded. The data were analyzed statistically using analysis of variance (ANOVA) with the statistical package ‘OP Stat’ (Sheoran *et al.* 1998). The data on weed density which showed wide variation, were subjected to square root transformation to make the analysis of variance valid (Gomez and Gomez 1984).

Biochemical characterization of extracts

The pH of extracts ranged from 7.62 to 4.3, and the EC ranged from 0.21 to 0.49. All the three donor plants were rich in secondary metabolites like alkaloids, flavonoids, phenols, and tannins (**Table 1**). The content of alkaloids was comparatively higher than other secondary metabolites. Higher content of alkaloids was observed in *Tagetes minuta* (mean value of 0.485%), followed by *Andrographis paniculata* (mean value of 0.417%). Among different extraction methods, methanol was more efficient in extracting the secondary metabolites.

Weed germination

Major weeds observed during the experimentation were *Panicum* sp., *Boerhavia diffusa*, *Alternanthera bettzickiana*, *Emilia*

Table 1. Biochemical properties of leaves extracts of three donor medicinal plants selected

Medicinal plants	Method of extraction	pH	EC (dSm)	Alkaloids (%)	Flavonoids (%)	Phenols (%)	Tannins (%)
A. paniculata	Cold water	6.53	0.32	0.541	0.023	0.001	0.0007
	Hot water	7.62	0.23	0.149	0.020	0.001	0.0006
	Methanol	5.82	0.43	0.562	0.026	0.002	0.0009
	Mean	6.66	0.33	0.417	0.023	0.001	0.0007
P. amboinicus	Cold water	6.19	0.47	0.154	0.037	0.004	0.0002
	Hot water	6.70	0.49	0.156	0.027	0.003	0.0002
	Methanol	4.47	0.42	0.237	0.053	0.006	0.0003
	Mean	5.79	0.46	0.182	0.039	0.004	0.0002
T. minuta	Cold water	6.18	0.21	0.386	0.030	0.003	0.0005
	Hot water	7.03	0.49	0.218	0.024	0.003	0.0001
	Methanol	4.3	0.32	0.851	0.040	0.004	0.0007
	Mean	5.84	0.34	0.485	0.031	0.003	0.0004
LSD (p=0.05)		1.24	0.24	0.32	0.01	0.001	NS

sonchifolia, *Cleome viscosa* and *Euphobia hirta*.

Among three plants screened for their allelopathic potential, *Tagetes minuta* exhibited highest allelopathic potential in delaying germination of weeds followed by *Andrographis paniculata* and the lowest was by *Plectranthus amboinicus* (**Table 2**). Better allelopathic effect of *Tagetes minuta* and *Andrographis paniculata* can be correlated with their higher contents of total alkaloids. Inhibitory effect of *Tagetes minuta* on sun spurge (*Euphorbia helioscopia*) and Johnson grass (*Sorghum halepense*) was reported by Sadia *et al*. (2015).

Regarding the method of extraction, a significant result was noticed for methanol extract and cold water extraction. Allelopathic efficacy of plants was found to decrease when they were extracted by the hot water extraction method. Better allelopathic performance of methanol extracts can be attributed to the better extraction efficiency of secondary metabolites from plant samples. As compared to cold water (Waris *et al*. 2016) and hot water extraction methods, the contents of alkaloids and flavonoids were higher in the methanol extracts.

Table 2. Mean main effect of treatments on total germinated weeds seedling density

Treatment	Total weed density (no./m^2)	
	1st week	2nd week
Allelopathic medicinal plant		
Andrographis paniculata	8.74(86.5)	11.46(130.6)
Plectranthus amboinicus	12.44(154.9)	11.49(131.4)
Tagetes minuta	8.04(72.4)	11.58(134.2)
LSD (p=0.05)	0.21	NS
Method of extraction		
Cold water extract	9.78(103.0)	11.52(132.7)
Hot water extract	10.48(114.5)	11.52(132.8)
Methanol extract	8.95(92.1)	11.43(130.7)
LSD (p=0.05)	0.21	NS
Concentration		
5%	10.49(113.0)	11.58(134.3)
10%	10.11(105.9)	11.61(135.4)
15%	9.55(96.1)	11.68(137.2)
20%	9.20(89.8)	11.65(136.5)
25%	8.66(82.0)	11.22(126.1)
30%	7.19(67.2)	11.09(123.3)
Control	12.98(168.3)	11.47(131.7)
LSD (p=0.05)	0.32	0.398

** $\sqrt{x+0.5}$ transformed values, original values are given in parentheses

Among different concentrations tested, the best results were obtained with higher concentrations of 30 and 25%. Azambuja (2010) and Arora *et al.* (2015) also found a reduction in the allelopathic effect with a decrease in the concentration. With respect to the combined effect of all the three factors studied, the interaction was significant only in the first week after the application of treatments. In the 1st week, the lowest weed germination and weed density was observed with 30% methanol extract of *T. minuta* (6.67 no./m^2) compared to the highest (168.33 no./m^2) with control treatment (**Figure 1**). As compared to the control treatment 96.04% suppression in germination count was observed at 1st week by the application of 30% methanol extract of *T. minuta*. It was at par with methanol extract of *A. paniculata* at 30% (8.33 no./m^2) concentration. Methanol extract of *A. paniculata* at 3% concentration resulted in weed suppression of 95.05% as compared to control. *P. amboinicus* extracts at different concentrations did not exhibit any effect on the germination of weeds. As compared to *P. amboinicus*, the per cent content of total alkaloids was higher in *T. minuta* and *A. paniculata* (0.851 and 0.562%, respectively) which might have contributed to their better allelopathic performance.

Weed density and biomass at one month after application

Weed density (**Figures 2a** and **2b**) and biomass (**Figures 3a** and **3b**) recorded one month after application of treatments indicated significant difference in weed density and biomass of broad-leaved weeds and total weeds but not on grass weeds due to combined effect of allelopathic plants, methods of extraction and concentrations. Aslani *et*

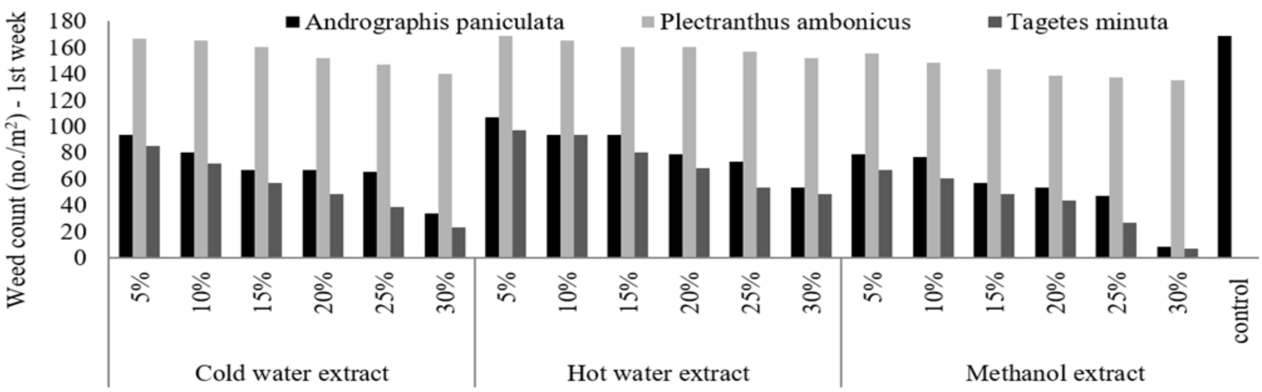

Figure 1. Interaction effect of allelopathic plants, methods of extraction and concentrations on weed count at 1st week after application

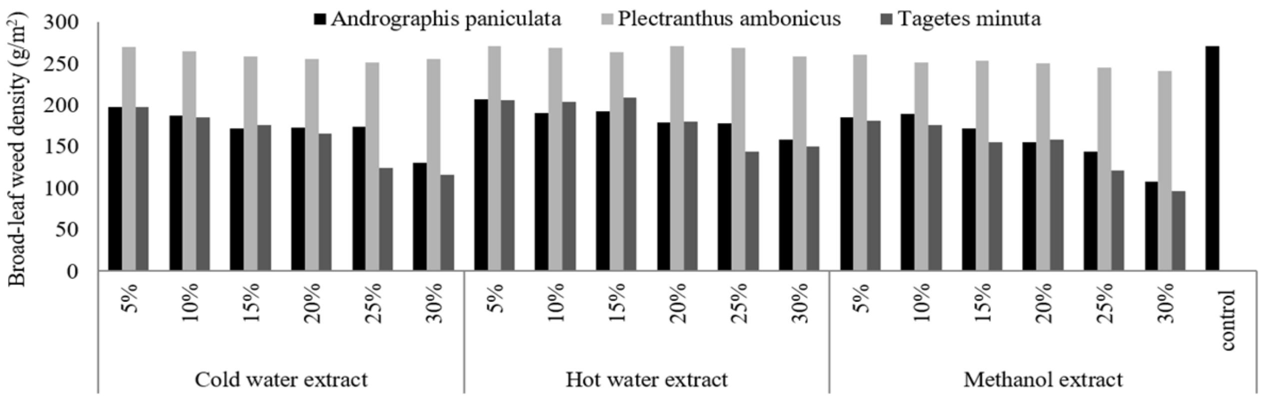

Figure 2a. Interaction effect of three allelopathic plants, methods of extraction and concentrations on density of broad-leavedweeds at one month after application

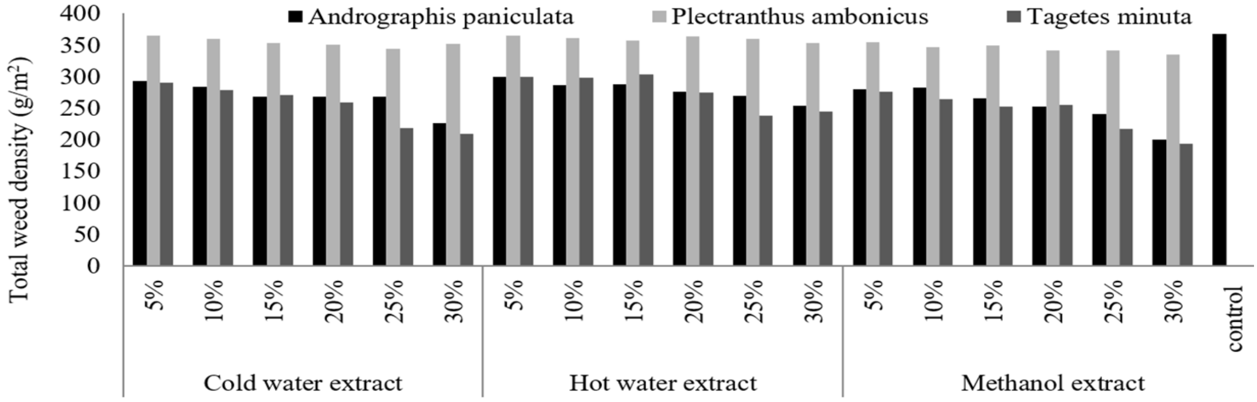

Figure 2b. Interaction effect of three allelopathic plants, methods of extraction and concentrations on total weeds density at one month after application

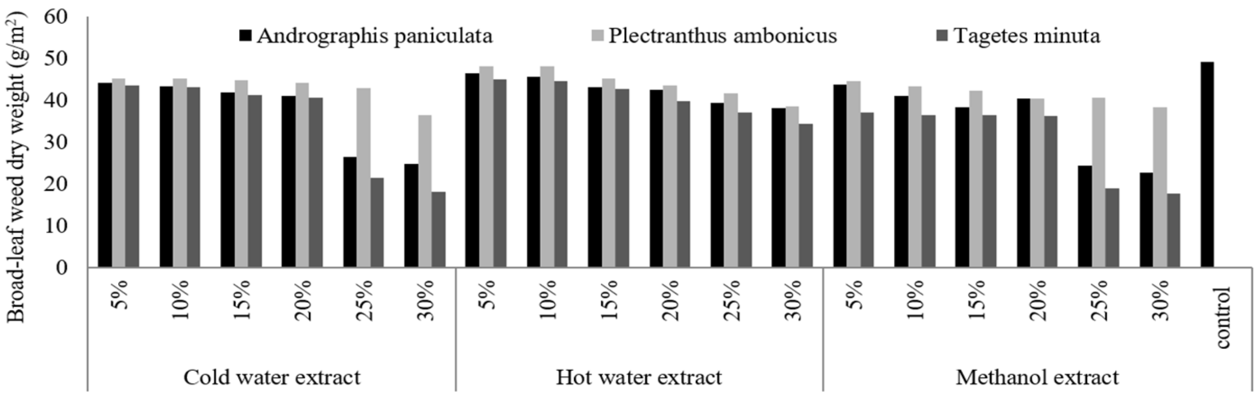

Figure 3a. Interaction effect of three allelopathic plants, methods of extraction and concentrations on broad-leaved weed biomass at one month after application

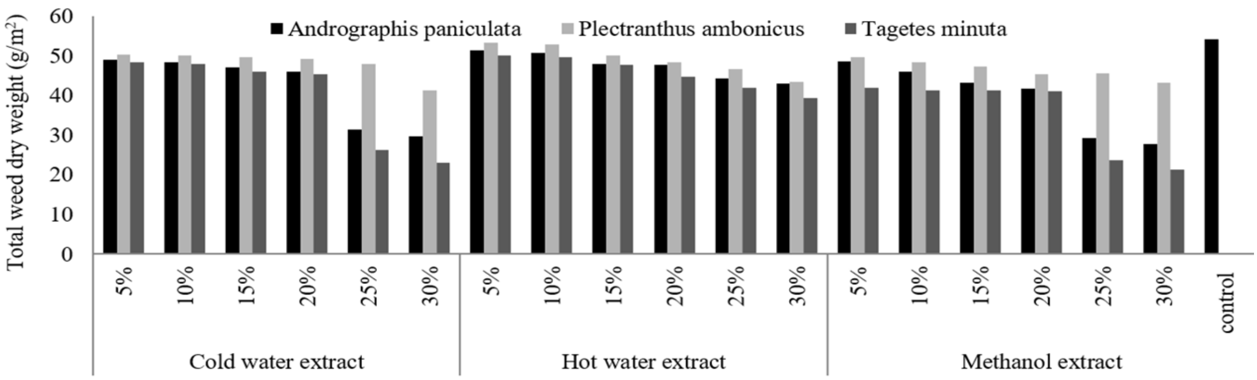

Figure 3b. Interaction effect of allelopathic plants, methods of extraction and concentrations on total weed biomass at one month after application

al. (2014) also reported that the dicot weeds were affected more severely than the monocots when treated with allelopathic plant extract.

Lower broad-leaved weed density and total density were observed with methanol and cold water extracts at 30 and 25% concentrations of *T. minuta* and *A. paniculata*. All the treatment combinations with these plants considerably reduced both weed density and biomass as compared to control. However, all treatment combinations with *P. amboinicus* could not succeed in reducing either density or dry weight of weeds. Owing to the richness of allelochemicals, *Tagetes minuta* might play a very important role in weed management through allelopathic interactions (Batish *et al*. 2007, Arora *et al*. 2015). Similarly, Li *et al*. (2010) and Kumar *et al*. (2018) reported inhibitory effect of *A. paniculata* on dicot plants. Effect of extracts on germination of weeds persisted only up to one week, indicating lack of residual action for the selected plant extracts. The germinated weed seedling density at 12 and 25 DAS did not differ significantly. In this preliminary screening study, it was observed that allelopathic plants *T. minuta* and *A. paniculata* could be effectively utilized for reducing the emergence of broad-leaved weeds. Many scientists (Bhadoria 2011, Ihsan *et al*. 2015) recommended the use of allelochemicals for the production of environment friendly herbicides since they caused few environmental problems in the soil due to the fairly high degradability.

It was concluded that maximum inhibitory effect on weeds germination and growth was observed with 30% methanol extract of *T. minuta* followed by it's 25% and the broad-leaved weeds were more sensitive to allelopathic extracts than grass weeds. The persistence of allelopathic effect of plants on weeds was significant only for a short period of time *i.e*. up to one week after the application.

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RESEARCH NOTE

Determining the nutrient removal capacity of duckweed *Wolffia globosa* under artificial conditions

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ABSTRACT

Aquatic vegetation like duckweed (*Wolffia globosa*) can eliminate contaminant from wastewater, which also can be commercial and possible options for wastewater treatment. Thus, this study aimed to estimate the nutrient removal capability of *Wolffia globosa* under artificial culture conditions. The nutrient removal capacity of *W. globosa* was evaluated in a 12-day growth trial with mineral mixture containing 173.6 mg/litre nitrogen; 40.3 mg/litre phosphorous; 100 mg/litre potassium and 0.6 g/litre as a reference fertilization rate (RF) along with five other different [RF/2; RF/4; RF/8; RF/16; RF/20 and Control (no fertilizers)] NPK fertilization rates under natural sunlight. In all the treatments, the concentrations of nitrate-nitrite, ammonia, nitrate and ortho-phosphate, decreased over the experimental period in a statistically significant (p=0.05) manner. At the end of the experiment, the total dissolved inorganic nitrogen (T-DIN) in the culture media was reduced by 99. 57% (RF/20), 100% (Control group - no fertilizers) while Ortho-phosphate (OP) by 100% in RF/16, RF/20 and control group, respectively. It was concluded that the *Wolffia globosa* is a suitable aquatic plant for nutrient removal under natural sunlight.

Keywords: Duckweed**,** Fertilization rates, Nutrient removal efficiency, *Wolffia globosa*

In India and China, around 50% of the population face the problem of water scarcity (WWAP 2017). Over 80% of wastewater is discharged into the environment without adequate remedy around the world (WWAP 2017). Domestic wastewater contains high levels of nitrogen and phosphate which accelerates the eutrophication and pollution in the aquatic environment (Verma and Suthar 2014). In view of the huge demand for water, it has become extremely important to manage the waste water by treating it properly. An ecologically affable and cost-effective solution is required for it. Aquatic plants, such as duckweed, water hyacinth, giant reed, microalgae and water lettuce are used to remove the pollutants from the wastewater (Li *et al.* 2018). Duckweeds are simple plants which have no stems or leaves (Iqbal *et al.* 2019). The abnormal leaf-like body is called a frond (Sirirustananun and Jongput 2021). Accordingly, it grows faster than most different plant life and be able to double its biomass in 2 days (Iqbal *et al.* 2019). Duckweed (*Wolffia globosa)* is capable to grow on the surface of wastewater and eliminate pollutants (particularly, nitrogen and phosphorous) from wastewater at high rates (Sirirustananun and Jongput 2021, Sirirustananun and Jongput 2021). Because of this potential, duckweed has already been used for the treatment of domestic, industrial and swine wastewaters (Gaur and Suthar 2017). Nitrate and ammonium are the principal forms of available nitrogen for the growth of duckweeds, however; the absorption of ammonium is 3 to 11 times greater than nitrates (Iqbal *et al*. 2019). Duckweed indicates best growth at phosphorus concentration of 4 and 22 mg P/l of growth medium (Al Nozaily 2000). Phosphorus removal efficiencies by duckweed ranged from of 14 to 99% and it depends on the growth rate, harvesting frequency and the available ortho-phosphate (Korner *et al.* 2003). Despite the aforementioned information from various duckweed studies, there is limited data on nutrient removal efficiency by *W. globosa*. Hence this study was conducted to quantify the removal of nitrate-nitrite, ammonia, nitrate and ortho-phosphate in the culture media by *W. globosa*.

The experiment was carried out for 12 days in September month (2017) in twenty-one thermocol fish icebox (58 x 39 cm x 30 cm) at the College of Fisheries, Central Agricultural University, Lembucherra, Tripura, India. The inner side of each thermocol box was lined with transparent plastic film and used as an experimental tank. The surface area in each box was 0.226 sq. m. The boxes were cleaned and washed copiously and were filled with groundwater to a 20 cm water depth, giving a volume of 50 litres. All boxes were set up under shade which

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made by using transparent polythene sheet and bamboo poles. A completely randomized design (CRD) with three replications was used. A modified Schenk-Hildebrandt medium (Appenroth *et al.* 2017) was used as reference fertilization (RF) to prepare different concentrations of N, P and K and of minerals (**Table 1**). A single dose of fertilization [173.6 mg/litre nitrogen; 40.3 mg/litre phosphorous; 100 mg/litre potassium and 0.6 mg/litre with vitamins and minerals mixture namely 'Agrimin Fort India' to fulfil the requirement of minerals for their growth] was done as a reference fertilization rate (RF) and five serially diluted (0-20 times) (RF/2; RF/4; RF/8; RF/16; RF/20) concentrations were prepared. Inoculums samples of Wolffia fronds were obtained from the College of Fisheries, Lembucherra (Tripura) and inoculated at a rate of 400 g /m^2 (90.4 g in each tank) in each treatment. Harvesting was done at two-day intervals.

During the cultivation period, water samples were collected on 0, 3^{rd}, 6^{th}, 9^{th} and 12^{th} day of culture for analysis of nutrients concentration. The collected water samples were passed through a glass fibre filter (pore size, 10 µm) to remove suspended materials**.** Nitrate-nitrite, ammonia, nitrate and ortho-phosphate in the culture media were measured using SKALAR Auto analyser (Model no. SA 1100, SKALAR). Water from each experimental unit was sampled for analysing pH with a glass electrode in a digital pH meter (Model FEP-20). Total alkalinity and hardness of water were also measured by the standard methodology of APHA (2005). Total chlorophyll contents in water were measured by using EXO-multi-parameter sonde. The temperature in the water was measured every day, using a digital thermometer (YSI ProODO). The sunlight intensity also measured every day in five places using a digital lux meter (model no. D. 33979).

The data obtained were analysed statistically and interpreted by using Statistical Package for Social Sciences (SPSS, version 16.0 for windows). Analysis of variance (one way - ANOVA) was performed to determine the differences between the mean values of different treatments. Differences in means were compared by Duncan's New Multiple Range test (multiple range test) at p=0.05 level.

Nutrient removal efficiency of *W. globosa*

The concentrations of nitrate-nitrite, ammonia, nitrate and ortho-phosphate in the culture media, decreased from day zero to the twelfth day (**Table 2**). Macrophytes are expected to take up nutrients to build up their biomass over time, which is why nitrates and nitrites concentration were expected to reduce over the study period (Sirirustananun and Jongput 2021). *W. globosa* prefered NH_4^+"N to NO_3^- "N as the nitrogen resource (Suppadit 2011). When *W. globosa* were grown in different treatment, the nitrate-nitrite (NO_3^- " NO_2^-) levels were also different ($P < 0.05$). After the experiments were completed, the remaining NO_3^- " NO_2^- levels ranged from 0.02 (RF) to 0.00 (control) mg N /l, down from the initial NO_3^- " NO_2^- value of 2.65 (RF) to 0.08 (control) mg N/l, depending on nutrient concentration in the culture media (**Table 2**). This might be because the *W. globosa* adsorbed NO_3^- " NO_2^- for its growth (Suppadit 2011). The nitrate (NO_3^-) concentration in the culture media were also reduced by *W. globosa*, the remaining NO_3^- levels ranged from 1.23 (RF) to 0.00 (control) mg N /l, down from the initial NO_3^- value of 43.83 (RF) to 0.27 (control) mg N/l **(Table 2**). Our results confirmed Suppadit (2011) findings on nutrient removal rate of *W. arrhiza*.

The ammonia removal showed significant differences (p=0.05) between treatments. From the initial concentration of ammonia, which was 25.55 (RF) to 0.85 (control) mg N/l, the ammonia tended to decrease as the biomass and the treatment time increased and the remaining value of ammonia was from 3.10 (RF) to 0.00 (control) mg N/l (**Table 2**). Our results are similar to those of Suppadit (2011) and Sirirustananun and Jongput (2021). The removal of total dissolved inorganic nitrogen (T-DIN) and Ortho-phosphate showed significant differences ($p<0.05$). The nutrient removal capabilities of *W. globosa* were estimated using temporal changes in nitrate-nitrite, ammonia, nitrate and ortho-phosphate concentrations in the culture media. The T-DIN removal rate (mg/l/day) of *W. globosa* was highest in RF (5.64 mg/l/day) and RF/2 (5.45 mg/l/day), as nutrient concentration in the culture media was also higher in both treatments. Similarly, ortho-phosphate removal rate (mg/l/day) of *W. globosa* was also

Table 1. Fertilization rates of different treatments

Treatment	Nitrogen (mg/l)	Phosphorous (mg/l)	Potassium (mg/l)	Mineral mixture (g/l)
Reference fertilization (RF)	173.6	40.3	100	0.6
RF/2	86.8	20.15	50.0	0.3
RF/4	43.4	10.07	25.0	0.15
RF/8	21.7	5.03	12.5	0.075
RF/16	10.85	2.51	6.25	0.037
RF/20	8.68	2.015	5.0	0.03

highest in RF (2.22 mg/l/day) and RF/2 (1.14 mg/l/day) (**Table 3**). This might be because the *W. globosa* used phosphorus in the form of orthophosphate for its growth. Whereas, at the end of the experiment, it was seen, T-DIN removal efficiency of *W. globosa* in the culture media was highest in control group (100 %) and RF/20 (99.57 %) while ortho-phosphate removal efficiency was 100 % in RF/16, RF/20 and control group, as the nutrient concentration in the culture media was also low (**Table 3**). The results of this study confirmed findings of Soda *et al.* (2013), Suppadit (2011), Fujita *et al.* (1999).

Physicochemical parameters and chlorophyll content

During the experiment, the water temperature recorded daily in the afternoon and it was within a normal range (31.21-31.59 ºC), which was suitable for the growth of *W. globosa* (**Table 4**). The duckweed species exhibit optimum growth between 17.5°C to 34°C (Hasan and Chakarbarti 2009; Soda *et al.* 2013). Sirirustananun and Jongput (2021) reported the water temperature 28.25±0.07 to 31.85±2.19 °C, optimal for the growth of *Wolffia arrhiza*. Our results are similar to those of Sirirustananun and Jongput (2021) who reported that the light intensity of 4,560±463.86 to 9,795±265.76 lux, were optimal for the growth of *W. arrhiza.* The temperature and light intensity observed in this experiment was in a productive range. During the experimental period, the pH value varied from 6.2 to 10.3 (**Table 4**). Duckweed survives at pH's among 5 and 9 but grows greatest above the pH range of 6.5-7.5 (Hasan and Chakrabarti 2009). The pH values reported in this study were in the optimal range but in later period of the culture it becomes up to 10.3. As a consequence, for the final pH, the culture media was in a slightly basic state. A similar value of pH (7.50±0.24 to 7.79±0.007) was reported by Sirirustananun and Jongput (2021) for the growth of *W. arrhiza.* Muvea *et al.* (2019) reported that the ammonia oxidation again contributed to the increase of pH from 7 to 10. During the experimental period, the total alkalinity and total hardness of the culture media varies from 38.67 to 96 mg/l and 33.33-150 mg/l, respectively (**Table 4**).

The chlorophyll content in culture medium varied from 1.55-189 µg/l indicating an increase in the later period of cultivation (**Table 4**), due to the infestation of algae in the medium. Unicellular algae are the primary competitors of duckweed for nutrients and space. Algae domination will result in a swing toward high pH and making of free ammonia, which is lethal to duckweed. The algae may also reduce the growth of *W. globosa* by inhibiting nutrient uptake and can be more dangerous to *W. globosa*, as it clogged and wrapped itself around fronds, causing shrivel and in the end die (Soda *et al.* 2013, Fujita *et al.* 1999). But, when algal infestation become excessive, it becomes important to clear the pond and restock with clean duckweed. *W. globosa* can compete with or coexist with algae and other aquatic plants if operated for long periods in open environments (Soda *et al.* 2013).

Table 2. The nutrients concentrations (means ±SE) in the culture media during different sampling periods

Sampling Occasion	Physicochemical parameters	Treatment						
		RF	RF/2	RF/4	RF/8	RF/16	RF/20	Control (no. fertilizers)
Baseline/Zero day	Nitrate-nitrite (mg N/l)	2.65 ±0.07^{e}	1.96±0.11^{d}	0.96±0.01^{c}	0.49±0.03^{b}	0.25±0.02^{a}	0.23±0.03^{a}	0.08±0.01^{a}
	Ammonia (mg N/l)	25.55±1.50^{e}	22.89±0.64^{d}	13.13±0.19^{c}	5.29±0.02^{b}	2.18±0.06^{a}	2.26±0.08^{a}	0.85±0.06^{a}
	Nitrate (NO_3^-) (mg N/l)	43.83±0.96^{g}	41.72±0.38^{f}	25.57±0.06^{e}	7.06±0.46^{d}	3.96±0.19^{c}	2.18±0.18^{b}	0.27±0.08^{a}
	T-DIN (mg/l)	72.03±0.93^{f}	66.57±1.09^{e}	39.66±0.13^{d}	12.85±0.50^{c}	6.39±0.23^{b}	4.67±0.23^{b}	1.20±0.15^{a}
	Ortho-phosphate (mg P/l)	27.12±0.22^{f}	13.68±0.70^{e}	6.51±0.34^{d}	3.45±0.21^{c}	1.38±0.08^{b}	1.17±0.04^{ab}	0.32±0.03^{a}
3rd day	Nitrate-nitrite (mg N/l)	2.68±0.02^{f}	0.54±0.04^{d}	1.16±0.01^{e}	0.31±0.03^{c}	0.15±0.01^{b}	0.10±0.01^{b}	0.01± 0.00^{a}
	Ammonia (mg N/l)	46.42±0.77^{f}	42.59±0.43^{e}	18.50±0.41^{d}	7.35±1.50^{c}	3.80±0.09^{b}	2.28±0.31^{ab}	0.45± 0.00^{a}
	Nitrate (mg N/l)	1.77±0.03^{f}	0.50±0.05^{d}	0.70±0.09^{e}	0.30±0.03^{c}	0.16±0.03^{b}	0.13±0.01^{ab}	0.00± 0.00^{a}
	T-DIN (mg/l)	50.87±0.76^{f}	43.63±0.49^{e}	20.37±0.48^{d}	7.96±1.46^{c}	4.11±0.08^{b}	2.51±0.30^{ab}	0.47± 0.00^{a}
	Ortho-phosphate (mg P/l)	16.59±0.74	7.19±0.39	3.26±0.23	1.68±0.28	0.79±0.09	0.30±0.07	0.17± 0.01
6th day	Nitrate-nitrite (mg N/l)	0.08±0.00^{d}	0.09±0.00^{d}	0.07±0.00^{c}	0.08±0.00^{d}	0.01±0.00^{ab}	0.02±0.00^{b}	0.01±0.00^{a}
	Ammonia (mg N/l)	10.06±0.54^{f}	6.05±0.09^{e}	4.54±0.18^{d}	2.28±0.10^{c}	0.90±0.03^{b}	0.94±0.00^{b}	0.00± 0.00^{a}
	Nitrate (mg N/l)	15.47±0.77^{f}	10.68±0.21^{e}	2.76±0.25^{d}	1.31±0.06^{c}	1.04±0.03^{bc}	0.10±0.03^{ab}	0.00±0.00^{a}
	T-DIN (mg/l)	25.61±0.65^{g}	16.81±0.27^{f}	7.37±0.28^{e}	3.68±0.06^{d}	1.96±0.04^{c}	1.06±0.02^{b}	0.02± 0.00^{a}
	Ortho-phosphate (mg P/l)	7.22±0.30^{e}	2.73±0.08^{d}	1.15±0.01^{c}	0.58±0.12^{b}	0.28±0.04^{ab}	0.14±0.02^{a}	0.01± 0.00^{a}
9th day	Nitrate-nitrite (mg N/l)	0.05±0.01^{bc}	0.05±0.00^{bc}	0.05±0.00^{bc}	0.07±0.01^{c}	0.03±0.01^{b}	0.04±0.01^{b}	0.00± 0.00^{a}
	Ammonia (mg N/l)	5.10±0.25^{d}	3.46±0.12^{c}	1.42±0.16^{b}	1.11±0.03^{b}	0.15±0.03^{a}	0.14±0.01^{a}	0.00± 0.00^{a}
	Nitrate (mg N/l)	5.19±0.03^{d}	3.55±0.46^{c}	1.12±0.06^{b}	0.20±0.05^{a}	0.17±0.01^{a}	0.03±0.01^{a}	0.00± 0.00^{a}
	T-DIN (mg/l)	10.34±0.25^{e}	7.05±0.38^{d}	2.59±0.16^{c}	1.37±0.06^{b}	0.35±0.02^{a}	0.20±0.02^{a}	0.01± 0.00^{a}
	Ortho-phosphate (mg P/l)	2.23±0.06^{d}	0.34±0.06^{c}	0.13±0.00^{b}	0.10±0.01^{ab}	0.06±0.02^{ab}	0.03±0.01^{ab}	0.00±0.00^{a}
12th day	Nitrate-nitrite (mg N/l)	0.02±0.01^{d}	0.01±0.00^{bcd}	0.01 ±0.00^{bcd}	0.02±0.00^{cd}	0.01±0.00^{bc}	0.00±0.00^{ab}	0.00± 0.00^{a}
	Ammonia (mg N/l)	3.10±0.04^{c}	0.74±0.33^{b}	0.32±0.05^{a}	0.15±0.03^{a}	0.05±0.02^{a}	0.01±0.00^{a}	0.00± 0.00^{a}
	Nitrate (mg N/l)	1.23±0.03^{c}	0.38±0.09^{b}	0.02±0.01^{a}	0.01±0.00^{a}	0.01±0.00^{a}	0.00±0.00^{a}	0.00± 0.00^{a}
	T-DIN (mg/l)	4.35±0.07^{c}	1.13±0.35^{b}	0.35±0.06^{a}	0.17±0.04^{a}	0.07±0.02^{a}	0.02±0.00^{a}	0.00±0.00^{a}
	Ortho-phosphate (mg P/l)	0.49±0.09^{b}	0.04±0.01^{a}	0.02±0.01^{a}	0.01±0.01^{a}	0.00±0.00^{a}	0.00±0.00^{a}	0.00± 0.00^{a}

Table 3. Total dissolved inorganic nitrogen (T-DIN) and ortho-phosphate (OP) removal by *W. globosa* in different treatments

Parameter	Treatment						
	RF	RF/2	RF/4	RF/8	RF/16	RF/20	Control
T-DIN (Zero day) (mg/l)	72.03	66.57	39.66	12.85	6.39	4.67	1.20
T-DIN (End of experiment) (mg/l)	4.35	1.13	0.35	0.17	0.07	0.02	0.00
T-DIN removal (mg/l)	67.68	65.44	39.31	12.68	6.32	4.65	1.2
T-DIN removal per day (mg/l/day)	5.64	5.45	3.28	1.06	0.53	0.39	0.10
T-DIN removal rate (%/day)	7.83	8.19	8.26	8.22	8.24	8.30	8.33
T-DIN removal efficiency (%)	93.96	98.30	99.12	98.68	98.90	99.57	100.00
OP (Zero day) (mg/l)	27.12	13.68	6.51	3.45	1.38	1.17	0.32
OP (End of experiment) (mg/l)	0.49	0.04	0.02	0.01	0.00	0.00	0.00
OP removal (mg/l)	26.63	13.64	6.49	3.44	1.38	1.17	0.32
OP removal per day (mg/l/day)	2.22	1.14	0.54	0.29	0.12	0.10	0.03
OP removal rate (% / day)	8.18	8.31	8.31	8.31	8.33	8.33	8.33
OP removal efficiency (%)	98.19	99.71	99.69	99.71	100.00	100.00	100.00

Table 4. The physicochemical parameters of water and chlorophyll content as affected by different treatments

Treatment	Ranges of physico-chemical parameters				
	Temperature (ºC)	pH	Total alkalinity (mg/l)	Total hardness (mg/l)	Chlorophyll (µg/l)
RF	31.21	6.2-8.4	96.00-92.67	150.00	1.55-5.96
RF/2	31.43	6.3-8.9	83.33-76.67	120-108.67	4.29-22.50
RF/4	31.54	6.3-10.0	73.33-60.00	86.67-72.00	35.97-157.05
RF/8	31.46	6.3-9.9	73.33-41.33	74.67-68.00	133.20-189.04
RF/16	31.48	6.3-10.3	76.00-40.00	60.67-50.67	31.35-109.93
RF/20	31.59	6.3-10.0	77.33-40.00	52.67-48.00	58.06-171.70
Control	31.50	6.3-8.0	73.33-38.67	34.67-33.33	22.81-5.45

It is concluded that *W. globosa* is capable of nutrient removal from the culture media. The high nutrient removal efficiency by vegetative fronds was 99.57-100% T-DIN and 100% Ortho-phosphate. Thus, *W. globosa* can grow very well in artificial conditions under natural sunlight and it is a useful weed, suitable for high nutrient removal due to its rapid growth rate.

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