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Volume 56 Number 2 April–June, 2024

Review article

Research articles

Research notes

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REVIEW ARTICLE

Emerging weed management techniques in agriculture: Harvest weed seed control, weed-tolerant cultivars and foam weed control

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ABSTRACT

Innovative approaches in weed management, namely harvest weed seed control (HWSC), weed-tolerant cultivars, and foam weed control, address the challenges posed by herbicide-resistant weeds and promote sustainable weed management. Firstly, HWSC offers a promising avenue for reducing weed populations and preserving the efficacy of herbicides. Methods such as chaff carts, chaff tramlining and chaff lining, narrow windrow burning, harrington seed destructor, and bale direct systems facilitate the collection and destruction of weed seeds at harvest. It disrupts the weed life cycle by destroying weed seeds before they return to the soil. Chaff tramlining and chaff lining, and narrow windrow burning are widely practiced in Australia and the USA due to their efficiency and economic feasibility. In contrast, bale direct systems and chaff carts may gain traction in developing countries where straw serves as livestock fodder. Secondly, weed-tolerant cultivars offer natural and sustainable weed control by leveraging rapid early growth, efficient canopy development, and allelo-chemicals to inhibit germination and suppress weed growth. However, these approaches pose challenges, including environmental specificity, trade-offs with crop yield, soil fertility, genetic diversity concerns, allelopathic effects, varietal selection challenges, and long-term stability. Thirdly, foam weed control enhances herbicide adhesion, reduces drift, and improves coverage. Mixing foam with hot water ensures efficient heat transfer to targeted plant tissues without dissipation into the atmosphere. However, its efficiency depends on factors such as the choice of foaming agent, foam concentration, foam persistence, water quality, application equipment, environmental conditions, weed species, growth stage, and application rate.

Keywords: Bale direct system, Chaff carts, Harrington seed destructor, Narrow windrow burning, Weed competitive cultivars, Weed suppressive cultivars

INTRODUCTION

In modern agriculture, the effective management of weeds is crucial for optimizing crop yield and sustaining agricultural productivity. Weeds significantly threaten crop yield and resource utilization by competing for essential resources such as water, nutrients, and sunlight (Saravanane *et al*. 2020, Ramesh *et al*. 2022). Among the pests, weeds cause maximum yield losses (Gharde *et al*. 2018), and the problem of weeds is exacerbated by modern farming practices, such as monoculture, fertilizer application, and the use of heavy machinery, which create ideal conditions for weed growth and spread (Gawêda *et al*. 2020). Traditional weed control methods often rely on herbicides, but their environmental impact and the evolution of herbicide-resistant weeds have made it difficult to control weed populations, further complicating this problem (Qasem 2013, Schütte *et al*. 2017, Bhullar *et al*. 2017). The phenomenon of herbicide-resistant weeds has exhibited notable and accelerating proliferation in recent decades. On a global scale, a total of 269 distinct herbicide-resistant weed species, further categorized into 154 dicots and 115 monocots, have been documented within 99 diverse crop types spanning 72 countries (Heap 2023).

Harvest weed seed control (HWSC) stands as a ground breaking concept in contemporary agriculture, offering a strategic and sustainable approach to weed management (Walsh and Powles 2014, Walsh 2018, Soni *et al*. 2020). The roots of the HWSC can be traced back to the late 20th century, emerging as a response to the alarming rise of herbicide-resistant weeds and escalating concerns regarding environmental sustainability (Bhullar *et al*. 2017). Australian agricultural researchers pioneered this concept, developing innovative strategies to target and eliminate weed seeds during the harvest process (Walsh 2018). The primary objective was to disrupt the weed life cycle by intercepting and destroying seeds before they could be returned to the soil, thereby curbing the propagation of herbicide-resistant weeds (Walsh and Powles 2014). By

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intercepting and either destroying or removing weed seeds during harvest, the HWSC disrupts the natural replenishment of the soil seedbank (Vijayakumar *et al.* 2022). This targeted approach has proven effective in mitigating herbicide resistance and reducing the overall reliance on chemical weed control methods, contributing to sustainable and environmentally conscious farming practices.

Another modern approach is the cultivation of weed-tolerant cultivars. Weed tolerance is the ability of a cultivar to maintain a high yield despite weed competition. In recent years, the focus has shifted toward exploiting the inherent abilities of certain cultivars that exhibit weed-competitive or weed-suppressive traits (Moukoumbi *et al.* 2011, Pooja *et al.* 2021a). These cultivars are specifically bred or selected for their ability to outcompete or suppress weed growth (Beckie *et al.* 2008, Chaudhari *et al.* 2014). This method harnesses natural processes to reduce weed pressure in fields and eliminates the need for synthetic herbicides, contributing to sustainable and ecologically responsible farming practices (Hoad *et al.* 2008, Moukoumbi *et al.* 2011, Pooja *et al.* 2021a). Thus, the screening process for identifying cultivars with superior weed competitiveness and suppression capabilities will play a pivotal role in enhancing agricultural resilience and fostering environmentally friendly farming systems (Langeroudi and Kamkar 2009).

Another approach to overcome the challenges of weeds in contemporary agriculture is foam weed control. Thermal weed control has emerged as an appealing alternative to chemical methods, and it is poised to play a crucial role in developing efficient and environmentally friendly weed management strategies (Mia *et al.* 2020). Flaming, hot water, and steaming are extensively investigated thermal methods, with a notable challenge being the dissipation of heat into the atmosphere rather than exclusively targeting weeds (Peerzada and Chauhan 2018). To address this, there is a growing interest in novel and more targeted thermal control methods. Foam weed control utilizes a mixture of foaming agents and hot water for targeted application. This approach minimizes heat loss to the surrounding air, ensuring effective weed control.

Several other techniques have been developed to control weeds in agriculture, including robotic weed control and unmanned aerial vehicles (UAVs). Numerous review articles are available on robotic weed control and precision weed control using UAVs. However, there are limited reviews available on HWSC, weed-tolerant cultivars, and foam weed control. The evolving nature of agriculture necessitates a continuous and comprehensive review of these promising methods and their outcomes. This will offer opportunities for the refinement and improvement of these technologies. Therefore, this review focuses specifically on these less-explored methods, HWSC, weed-tolerant cultivars, and foam weed control, emphasizing the potential benefits and associated challenges.

Harvest weed seed control

HWSC is a non-chemical method of weed control that involves the collection and/or destruction of weed seeds at harvest. This process involves a combination of cultural and mechanical management practices, all of which are designed to curtail the replenishment of weed seeds in the soil seedbank (Walsh and Powles 2014, Vijayakumar *et al.* 2022). This approach helps combat the resistance of weeds to non-selective herbicides. Herbicide-resistant weeds are the primary goal of the HWSC in Australia and North America (Walsh and Powles 2014). Tall and upright weeds that mature with crops and retain seeds until harvest are ideal targets for HWSC technologies. HWSC is applicable across a range of crops, with notable success in cereals, oilseeds, and pulses (Beam *et al.* 2019, Bitarafan and Andreasen 2020). The versatility of HWSC methods allows farmers to tailor the approach to specific crops, providing a targeted and effective means of weed control. The adaptability of the HWSC across different crops underscores its potential to become a standard practice in modern agriculture. HWSC encompasses various management practices, including the use of chaff carts, chaff tramlining and chaff lining, narrow windrow burning, the Harrington Seed Destructor (HSD), and the Bale Direct Systems (BDS). The fundamental principle behind the HWSC is that targeted weed species retain a significant proportion of their seeds at maturity. Research indicates that HWSC practices achieve substantial weed seed destruction, ranging from 75% to 99% at harvest (Walsh and Powles 2014).

Chaff tramlining and chaff lining: Directing chaff into narrow rows on specific wheel tracks during harvest is termed chaff tramlining, while directing chaff into thin rows between stubble rows is called chaff lining. These methods utilize a mulching effect to inhibit weed seed germination and emergence by concentrating the chaff material, creating an environment unsuitable for germination (Walsh *et al.* 2017). Instead of killing weed seeds, chaff lining condenses them into a much smaller area, reducing their presence in the field to less than 10% of its original extent. For these methods to be effective, the chaff lines must remain undisturbed by tillage or other field activities, as any disruption can allow weed seedlings to emerge. Walsh *et al.* (2020) reported that while chaff lines did not impact the survival of weed seeds, high quantities of chaff (>40,000 kg/ha) significantly restricted the emergence of weed plants. For every 1,000 kg/ha increase in chaff material, there was an approximately 2.0% reduction in the emergence of weeds, including rigid ryegrass, wild oat, annual sowthistle, and turnip weed, indicating a linear relationship. This relationship held true across different types of chaff from wheat, barley, canola, and lupin, suggesting that the amount of chaff, rather than its type, was the critical factor.

In contrast, Ruttledge *et al.* (2018) reported that wheat chaff had a greater suppressive effect on the emergence of annual ryegrass seedlings than barley chaff. This difference could be attributed to structural or chemical (allelopathic) variations between the chaff types. This method is most effective for crops that generate significant chaff or crop residue, such as wheat, rice, and corn, which typically produce more than 5 tons per hectare, as this method requires the concentration of large quantities of chaff material. Consequently, this technique may not be suitable for smaller-scale millers or for crops such as pulses that produce less chaff residue. Chaff lining and chaff tramlining have the potential to be widely adopted in northern Australia because they are relatively inexpensive and easy to implement. This is the second most commonly used HWSC method in Australia, following narrow windrow burning. It was recently estimated that 24% of Australian growers were using these techniques (Kondinin-Group 2020).

Narrow windrow burning: It is an efficient and cost-effective HWSC tactic. This approach employs a chute mounted on the rear of the combine, directing all the chaff into a narrow row, typically 16 to 18 inches wide. According to Lyon *et al*. (2016), the windrow width should be no more than 10% of the header width or 3 feet for a header that is 30 feet wide. These rows are subsequently burned with lower fire risks and fewer smoke issues compared to burning chaff heaps (Walsh and Powles 2022). The concentration of chaff in windrows results in higher temperatures and longer burning durations, leading to less residue loss and more effective weed seed destruction compared to burning the entire field (Walsh and Newman 2007, Lyon *et al*. 2016). The crop should be harvested close to the soil to increase the amount of crop residue that ends up in the windrow. In soybean, narrow windrow burning resulted in a 73% reduction in escaped *Amaranthus palmeri* and a 62% decrease in the soil seedbank over three years (Schwartz-Lazaro *et al*. 2017). Another study by Norsworthy *et al*. (2020) reported 100% control of Palmer amaranth, Johnson grass, barnyard grass, and pitted morning-glory seeds present in soybean crop residues. Most weed species can be killed when the windrow reaches 400°C to 500°C for 10 to 30 seconds; however, certain weeds, including crabgrass, can be killed when exposed to 85°C for 20 seconds (Hoyle and McElroy 2012, Walsh and Newman 2007).

This method has emerged as Australia's most popular HWSC system due to its high effectiveness and low cost (Walsh *et al*. 2017). The use of narrow windrow burning for weed seed control has significantly increased in Australia, with an estimated 30% of growers currently employing this technique. However, adoption rates are particularly high in Western Australia, reaching a notable 50% (Walsh and Powles 2022). This reflects a doubling of utilization since 2000 when only 21% of Western Australian growers used the method. This increasing popularity highlights the growing awareness of the effectiveness of narrow windrow burning for weed management. These systems exhibit a decline in performance when the moisture content of crop residues exceeds 12% (Schwartz-Lazaro *et al*. 2017). Similarly, cooler and damper post-harvest environmental conditions, along with stricter regulations on smoke hazards, restrict the use of narrow windrow burning systems. Before setting the fire, ensure that the windrow is dry and free of dew. Windy or dry days should be avoided because they pose a risk.

Bale direct systems: The BDS involves connecting a baler directly to the combine and transforming chaff expelled by the harvester into bales. This approach captures weed seeds without spreading them in the field, and the resulting bales can serve as fodder for livestock. Walsh and Powles (2007) demonstrated that the BDS method can effectively collect and remove up to 95% of annual ryegrass seeds from fields. However, this method has limitations, including a limited market for baled products and the potential risk of disseminating resistant weed seeds to other fields (Walsh *et al*. 2017).

Chaff cart: In this method, a chaff gathering and transfer system is connected to a combine harvester to direct weed seeds into a bulk collection container, enabling the simultaneous collection and extraction of both chaff and weed seeds from the field. The cart can be unloaded on the field edges once it has filled up. Afterward, farmers have the option of using the chaff for animal feed or burning the stacks of chaff to entirely eradicate the weed seeds. Given that crop residue is utilized as animal feed in Asia, this approach may be more suitable for Asia. However, if animals graze on chaff heaps, they may spread weed seeds (Vijayakumar *et al.* 2022). The chaff cart, which is attached behind the already sizable harvester, poses challenges in maneuvering within smaller fields. The challenge of managing large volumes of collected chaff has been the primary reason for the low adoption of this approach (Walsh *et al.* 2017). The burning of collected chaff to kill weed seeds carries a high risk of fires spreading beyond control. These slow-burning piles can be smolded for days, posing a significant fire hazard and creating severe smoke pollution (Walsh *et al.* 2022).

Harrington seed destructor: The HSD is a trailer-mounted cage mill equipped with chaff transfer systems developed by Australian agricultural experts, Ray Harrington, in 2005. It mechanically damages weed seeds at harvest. During commercial wheat, barley, and lupin crop harvest, HSD can kill up to 95% of the seeds of annual ryegrass, wild radish, and wild oats (Walsh *et al.* 2012; Walsh and Powles 2014). Studies in the US and Canada have confirmed that these machines can destroy more than 95% of seeds from major weed species, such as rice (barnyard grass and weedy rice), cereals and oilseeds (Italian ryegrass and wild oats), and soybean (Palmer amaranth and waterhemp) (Schwartz-Lazaro *et al.* 2017, Tidemann *et al.* 2017). Jacobs and Kingwell (2016) evaluated the economic value of the HSD within integrated weed management strategies. Their findings demonstrated that HSD provided greater returns than many other weed management strategies, particularly in scenarios involving non-selective herbicide resistance and large areas of high-yielding crops. The likely lower capital cost of HSD will enable its widespread adoption for weed control.

Constraints and challenges for the adoption of HWSC in Asia: The reasons for the selective adoption of the HWSC in Australia and the USA compared to Europe and Asia (Beam *et al.* 2019) are as follows.

Equipment requirements: HWSC typically requires specialized equipment, such as chaff carts, impact mills, or narrow-windrow burning systems, to effectively collect and destroy weed seeds. These machines are relatively expensive to purchase and maintain (Vijayakumar *et al.* 2022). Across Asia, farmlands are typically small and fragmented, which limits the potential for widespread mechanization. Mechanization in this region primarily targets tasks such as land preparation, planting, and harvesting (Vijayakumar *et al.* 2021a). Despite significant yield losses due to weeds, mechanized weed control has not gained much traction. The availability of cheap labour makes manual weeding the predominant practice. Although herbicide use is on the rise, herbicide resistance has not yet become a major concern. HWSC equipment has been primarily developed to address herbicide-resistant weeds. The lack of herbicide-resistant weeds, the high cost of HWSC equipment, the lack of suitable conditions on farms for easy movement, and the availability of human labour contribute to the lower adoption of HWSC in this region.

Cost-benefit ratio: Few studies have evaluated the cost-benefit ratio of HWSC in Australia, and no such studies are available for other regions, including Europe and Asia. Seed mills and narrow windrow burning are the most expensive options. Chaff carts are somewhat less expensive. Chaff lining is the least expensive option. Some studies have assessed the potential for HWSC in the USA and Europe, concluding that HWSC holds promise in specific cropping systems and regions within these countries (Akhter *et al.* 2023). The economic viability of the HWSC may vary depending on the specific farm and weed situation. The cost of implementing HWSC practices needs to be justified by the benefits gained in terms of weed seed reduction and long-term weed management. Currently, the implementation cost of HWSC is very high and cannot be justified by the benefits gained in terms of weed control in Asia (Vijayakumar *et al.* 2022). More research is needed to assess the economic feasibility of the HWSC in different cropping systems and regions.

Environmental impact: Burning crop residue has environmental impacts, resulting in concerns about air quality and the release of greenhouse gases (Vijayakumar *et al.* 2024). Additionally, frequent movement of these vehicles could create a hardpan in the soil and create problems for subsequent crops in the system. These factors contribute to its limited adoption in areas with strict environmental regulations.

Nutrient loss and fire risk: Burning crop residue leads to a loss of organic matter and nutrients. Most nitrogen is lost due to burning, while most potassium remains, albeit concentrated in a row (Vijayakumar *et al.* 2024). Windrow burning of crop residue may not be possible if the crop in the neighboring field is prone to fire or heat.

Alternate use of crop residue: In India and several other Asian countries, crop residues are commonly used as cattle fodder. Farmers without cattle often sell their crop residues to those who do, as straw commands a good price. However, the availability of dry fodder in the country is insufficient to meet the actual demand. Consequently, burning crop residue is neither viable nor economically feasible (Vijayakumar *et al*. 2021b).

Weed seed retention: High seed retention by a weed at harvest is a prerequisite for successful HWSC. Some weed species have mechanisms for seed shattering, making it difficult to collect and contain all weed seeds during harvest and reducing the overall effectiveness of HWSC (Schwartz-Lazaro *et al*. 2017). Seed production and retention by different weed species and their potential for HWSC are presented in **Table 1**.

Table 1. Seed production and retention by weeds and their potential for HWSC

Weed species	Seed retention (%)	Seeds/plant	HWSC potential	Reference
Secale cereale	49-61	-	Intermediate	Lyon *et al* (2019)
Bromus tectorum	25-87	10-6000	Low to high	
Lolium multiflorum	27-50	300	Intermediate	
Vulpia myuros	11-90	1000-1700	Low to high	
Aegilops cylindrica	>75	130-3000	High	Walsh (2018)
Avena fatua	69-84	250-500	High	Walsh and Powles (2014)
Bromus tectorum	<50	20,500-45,000	Intermediate	San Martín *et al* (2021)
Lolium perenne				
Lolium ssp. *multiflorum*				
Secale cereale	>50	485	Intermediate	
Bromus tectorum	75±2.9	10-6000	High	Soni *et al* (2020)
Secale cereale	90±1.7	485		
Aegilops cylindrica	76±4.3	130-3000		
Lolium multiflorum	63	5-10,000	Intermediate to high	(Walsh and Powles 2014)
Raphanus sativus	79			
Amaranthus palmeri	98	100,000-600,000	High	Schwartz-Lazaro *et al*. (2017)
Echinochloa crus-galli	41	31987	Intermediate	
Brassica napus	>95	543-14773	Very high	Tidemann *et al* (2017)
Echinochloa colona	42 to 56	394	Intermediate	Mahajan *et al* (2017)
Chloris virgata	67 to 75	90,030-143,180	High	
Ambrosia trifida	80	500-5,000	High	Goplen *et al* (2016)
Anagallis arvensis L.	61.6	293-428	Intermediate	Bitarafan and Andreasen (2020)
Capsella bursa-pastoris L.	52.7	1,460-7,444	Intermediate	
Chenopodium album L.	67.2	1876-4,910	Intermediate	
Geranium molle L.	58.4	117	Intermediate	
Persicaria maculosa	32.1	311-413	Low	
Polygonum aviculare L.	59.5	549-1,514	Intermediate	
Silene noctiflora L.	95.7	102-539	Very high	
Sonchus arvensis L.	23.5	460-1,954	Low	
Veronica persica	51.7	90-511	Intermediate	
Viola arvensis	33.9	22-203	Low	
Fallopia convolvulus	44	260	Intermediate	Bitarafan and Andreasen (2020a)
Sinapis arvensis	67	195	Intermediate	
Spergula arvensis	45	411	Intermediate	
Stellaria media	56	316	Intermediate	
Echinochloa crus-galli	75	31987	High	Vijayakumar *et al* (2023)
Lolium multiflorum	80	-	High	Broster *et al* (2015)
Kochia scoparia	99.8	100,000	Very high	Friesen *et al* (2009)
Galium spp.	74	300-400	High	Burton *et al* (2016);
Sinapis arvensis L.	70	2,000-3,500	High	Beckie *et al* (2017)
Polygonum convolvulus	82	12,000	High	Burton *et al* (2017)
Setaria viridis	94	34,000	Very high	Beckie *et al* (2017)
Sorghum halepense	96		Very high	Walsh (2018)
Amaranthus palmeri	91		Very high	
Amaranthus tuberculatus	88		High	
Kochia scoparia	100	14,600	Very high	Burton *et al* (2016); Tidemann *et al* (2017)
Lolium rigidum	85	-	High	(Walsh and Powles 2014)
Raphanus raphanistrum	99	160-1,875	Very high	

Integration with other practices: To achieve the best results, the HWSC should be integrated with other weed management practices, such as herbicide programs, crop rotation, and cultural practices. The adoption of HWSC practices requires education and training for farmers, as it represents a change in traditional harvest practices. Farmers need to understand the benefits and best practices associated with HWSC.

Weed tolerance cultivars

Weed tolerance in crops is achieved through two mechanisms, namely, weed suppressiveness and weed competitiveness.

Weed competitive cultivars: Weed competitive cultivars (WCCs) are specifically bred or selected for their ability to outcompete weeds for essential resources such as light, water, and nutrients (Ni *et al.* 2000, Phuhong *et al.* 2000, Norsworthy and Shipe 2006, Pooja *et al.* 2021a). These cultivars are designed to be taller and more vigorous than weeds to curtails their growth and competitive abilities. It leverages traits such as rapid early growth, efficient canopy development, and enhanced root systems to establish dominance in the early stages of crop growth, which in turn results in reduced weed establishment, competition, and improved crop yields (Ogg and Seefeldt 1999, Phuhong *et al.* 2000, Zhao *et al.* 2006, Zhao *et al.* 2007). Varieties that establish a canopy more quickly tend to occupy space first, reducing the impact of weed competition, as they suppress and weaken late-emerging weeds (Dass *et al.* 2017). Thus, the competitive advantage of WCCs stems from their ability to create a canopy that shades and suppresses weed growth, limiting their access to sunlight (Ni *et al.* 2000, Mwendwa *et al.* 2020). Additionally, the vigorous root systems of the WCC effectively compete for soil nutrients and water, further stalling weed proliferation. As a result, the need for additional weed control measures, including herbicides, is diminished, contributing to sustainable and cost-effective farming practices (Phuhong *et al.* 2000).

Weed suppressive cultivars: Weed suppressive cultivars (WSCs) are specifically bred or selected for their ability to suppress the growth of weeds through the production of allelochemicals that inhibit the growth of neighboring plants, including weeds (Khanh *et al.* 2007, Jamil *et al.* 2011). WSCs go beyond mere competition; they actively release substances known as allelochemicals into the soil, which hinder the germination and growth of neighboring weeds (Wicks *et al.* 2004, Shrestha *et al.* 2020). These allelopathic compounds can impede weed seed germination, root development, and overall growth, creating a weed-suppressive environment around the crop (Cheng and Cheng 2015). By directly inhibiting weed growth through chemical interactions, these cultivars offer an additional layer of defense against weed encroachment, complementing traditional weed control strategies (Kostina-Bednarz *et al.* 2023).

Attributes that contribute to weed tolerance in crops: For effective weed suppression, an ideal cultivar should possess several key traits, such as early and rapid establishment (seedling vigor), a large seed size that provides a food reserve, taller plant height, the ability to produce more tillers, strong root systems, a short growth duration, resilience to various biotic and abiotic stresses, and the production of allelochemicals (Zhao *et al.* 2006, Gibson *et al.* 2003). The rapid development of a large canopy with increased photosynthetic area, greater LAI, and improved root growth in terms of dry root weight, length, and volume are positively associated with the ability of crops to compete against weeds (Ni *et al.* 2000, Mason and Spaner 2006). High seedling vigor, which reflects the ability of plants to establish quickly and vigorously, plays a pivotal role in reducing the risk of weed seedling emergence and growth (Dass *et al.* 2017). Similarly, cultivars with greater root shoot characteristics have a competitive advantage in light, water, and nutrient resource acquisition, enabling them to attain greater height and grow faster.

The competition between crops and weeds becomes particularly intense when the root system, morphology, and growth pattern of weed species closely resemble those of crop plants. Moreover, crop germination and plant population significantly influence a cultivar's tolerance to weeds. Poor crop stands, often resulting from inadequate and uneven germination, lead to reduced soil coverage and increased weed pressure. The general rule is that the plant that germinates first in the field will occupy the most space by capturing the maximum amount of both below- and above-ground growth resources. Consequently, all management practices carried out in the field aim to ensure that crop plants germinate first and dominate the system. However, certain conditions, such as heavy rainfall immediately after sowing, poor or delayed seed germination due to poor seed quality or higher sowing depth, uneven land leveling, or poor irrigation management, can favor weed germination and growth over crop plant germination. Studies by Olsen (2012) and Marin and Weiner (2014) have shown that improving plant stand uniformity, in conjunction with increasing planting densities, significantly reduces weed biomass and enhances yields across several crops.

Weed-tolerant rice cultivars: Rice varieties with strong weed competitiveness have been identified in different regions. For example, in the Philippines, Apo and UPLRi-7 exhibit rapid seedling establishment and early accumulation of plant biomass, providing them with a competitive advantage against weeds (Zhao *et al.* 2006). In Latin America, *Oryzica sabana* 6 stands out due to its larger leaf area index (LAI) and higher tiller density, enabling it to intercept more light and compete more effectively with weeds (Fischer *et al.* 2001). In North America, M-202 exhibits a larger photosynthetic area and greater below-ground biomass, contributing to its ability to outcompete weeds (Gibson *et al.* 2003). In DSR, seedling vigor plays a crucial role in reducing crop-weed competition in favor of the rice crop, as it facilitates the early and robust establishment of rice plants. In dry DSR systems cultivated in rainfed and upland provinces of the tropics, greater seedling vigor in rice cultivars significantly limits weed growth and development (Hirao *et al.* 2008). Rice varieties exhibit rapid growth in the early seedling stage due to increased seedling vigor, rapid formation of a dense canopy, suppression of weeds, and increased yield by reducing the penetration of solar radiation through the leaf canopy (Fenner 1980). Thus, fast-growing rice cultivars have a distinct advantage in promoting ecological weed suppression and enhancing yields, particularly in rainfed regions (Kanbar *et al.* 2006).

Among the above-ground factors, competition for essential resources such as sunlight and CO_2 contributes to poor growth and lower yields in DSR (Fischer *et al.* 2001; Gibson *et al.* 2003, Ramesh *et al.* 2022). Weeds can reduce rice growth and yield through both shoot and root competition, with the latter resulting in 39-55% reductions in rice grain yield (Chauhan and Johnson 2010). The shading effect, primarily caused by excessive weed growth, significantly impacts the development of rice crop shoots, leading to a reduction in the production of dry matter and ultimately resulting in lower rice yields (Praba *et al.* 2004). Therefore, plant height is important for providing rice crops with advantages over weeds. However, there is a trade-off between plant height and lodging, with taller plants being more effective at suppressing weeds but also more prone to yield losses, especially in the case of transplanted rice. To suppress weeds in DSR, a relatively high seed rate is used (> 80 kg/ha to 200 kg/ha against 25 to 40 kg/ha for transplanted rice) in several countries, such as Cambodia, Vietnam, Laos, Thailand, Bangladesh, the Philippines, and India. However, there is a certain trade-off. For example, in the case of rice, farmers use seeds harvested from the previous season or year in their fields, which are of poor quality because they carry more weed seeds and a lower germination percentage. Higher seed rates also increase production costs, potentially exacerbating issues such as lodging, rodent damage, nitrogen deficiency, and insect and disease infection (Zhao *et al.* 2007).

Role of weed-tolerant cultivars in weed management: Crop rotation and intercropping systems that incorporate WCCs or WCSs enhance the resilience of agroecosystems (Gu *et al.* 2021). Farmers can strategically select and deploy cultivars that align with their specific weed management goals, creating a tailored and efficient approach. By diversifying plant species with varying weed management traits, farmers can disrupt weed life cycles and mitigate the development of herbicide-resistant weed populations. The use of WCCs and WSCs represents a compelling avenue for sustainable weed management. The global WCC and WSC reported for different crops are presented in **Table 2**.

Bottlenecks for the adoption of weed-tolerant cultivars: Although weed-competitive and weed-suppressive cultivars are environmentally friendly and economically viable alternatives to weed control, they may not be a one-size-fits-all solution (Ni *et al.* 2000, Fischer *et al.* 2001, Zhao *et al.* 2006). The feasibility of weed-tolerant cultivars may be limited when confronted with a wider range of weed species. WCC and WSC have demonstrated substantial control over specific weed species, but they may fall short in managing a broader spectrum of weeds in the field. Consequently, relying solely on weed-tolerant cultivars may not provide an optimal solution to weed management, but it can be one of several components of an integrated weed management strategy. Their success depends on various factors, including specificity, environmental conditions, crop yield trade-offs, management practices, crop type, cultivar, soil characteristics, seed rate or plant density, and timing and method of planting (Chauhan 2012).

Specificity: Agricultural fields often host a diverse range of weed species. Even if a cultivar is effective against one or a few weed species, it may not be able to manage the entire spectrum of weeds present in the field. Weeds that are not targeted by these cultivars can still thrive. Some weed species are highly competitive and may outcompete even the most competitive crop cultivars. In such cases, the crop may struggle to suppress or compete with other aggressive weed species for which the cultivar is not tolerant.

Yield trade-off: In some situations, highly competitive or suppressive cultivars may trade off some of their crop yield potential to achieve weed control (Moukoumbi *et al*. 2011, Chaudhari *et al*. 2014). Farmers may be unwilling to adopt these cultivars if they experience reduced crop yields.

Environmental factors: In addition, the effectiveness of these cultivars is influenced by environmental factors such as soil type, climate, and other local conditions. Effective weed control often requires a combination of methods, including cultural practices, herbicides, and mechanical control. Relying solely on weed-competitive or weed-suppressive cultivars may not be sufficient for comprehensive weed management.

Table 2. Weed competitive and suppressive cultivars reported globally in different crops

Crop	Cultivar	Target weed	Reference
Canola & mustard	Yellow mustard Hybrid Canola (InVigor 2663, SW5001, 45H21, InVigor5030)	Natural weed infestations	Beckie *et al* (2008)
	Baudin, Hamelin, and Flagship	Natural weed infestations	Paynter and Hills (2009)
	GT-50, Hyola 600RR, Hybrid Hyola	Natural weed infestations	Langeroudi and Kamkar (2009)
	Hybrid (Hyola-50, Hyola-571CL, 45Y77), Cultivar (AV-Garnet), *B. juncea* (Dune)	*Lolium multiflorum*	Lemerle *et al* (2011)
	Canola cultivar (Zarfam)	*Sinapis arvensis*	Mwendwa *et al* (2020)
Corn	Early-maturing, leafy reduced stature and Pioneer hybrid ('P3979')	*Chenopodium album, Amaranthus retroflexus*	Begna *et al* (2001)
	Sweet corn (hybrid Rocker, hybrid Cahill)	*Panicum miliaceum*	Williams *et al* (2008)
	Pioneer 3260' hybrid with a horizontal leaf architecture	Natural weed infestations	Sankula *et al* (2004)
Cotton	CS-B22sh	*Amaranthus palmeri*	Fuller *et al* (2021)
	Deltapine 16	*Anoda cristata*	Chandler and Meredith (1983)
Wheat	Tallness, superior early-season growth, increased leaf area and high tillering capacity	Natural weed infestations	Mason and Spaner (2006)
Rice	*Oryzica sabana* 6	*Brachiaria brizantha, B. decumbens*	Fischer *et al* (2001)
	M-202, S-201	*Echinochloa oryzoides, Echinochloa phyllopogon*	Gibson *et al* (2003)
	Apo and UPLRi-7		Zhao *et al* (2006)
	CG20	Natural weed infestations	Moukoumbi *et al* (2011)
	R-1033-968-2-1 and Kakro	Natural weed infestations	Chaudhari *et al* (2014)
	IR 84899-B-183-CRA-19-1 and CR Dhan 40	*Echinochloa colona, Trianthema portulacastrum, Physalis minia, Cyperus rotundus and Fimbristylis miliacea*	Kumar *et al* (2016)
	PI312777, PI338046, and RONDO B2 and B81 (weedy rice accessions)	*Echinochloa crus-galli, Leptochloa panicoides*	Shrestha *et al* (2020)
	IR5 or IR442-2-58; Prabhat and Krishna Hamsa	Natural weed infestations	Shekhawat *et al* (2020)
	Hybrid PHB 71, Prabhat, PR-120, IR88633, and IR83927		Mahajan *et al* (2014)
DSR,	PR 115 (125 days duration)	Natural weed infestations	Singh and Bhullar (2015)
Aerobic rice	ADT 46		Pooja *et al* (2021b)
Upland DSR	Vandana, Kalinga-III and RR-151-3	Natural weed infestations	ICAR (2007)
Soybean	Sharkey and Biloxi	*Senna obtusifolia*	Shilling *et al* (1995)
	Late maturing cultivars	Natural weed infestations	Nordby *et al* (2007)
	Short statured cultivars	*Xanthium strumarium*	Jordan (1992)
	Pioneer 96B21 and SC00–883	Natural weed infestations	Norsworthy and Shipe (2006)
Wheat	HD 3086, PBW 677, PBW 725, HD 2967, PBW 621 and PBW 550	Natural weed infestations	Bhullar *et al* (2017)
	PBW 343		Mahajan *et al* (2014)
	Tall spring cultivars, NE 78742, NE 78743	*Setaria viridis*, Summer Annual Weeds	Blackshaw *et al* (1981); Wicks *et al* (1986)
	Turkey, Arapahoe, Jules, Pronghorn and Vista	Annual Weeds	Wicks *et al* (2004)
	Taller, soft winter cultivars	*Aegilops cylindrica*	Ogg and Seefeldt (1999)

In terms of crop type, African rice (*Oryza glaberrima*) varieties have shown superior weed-smothering capabilities compared to *O. sativa*, as they possess a downward-tilted leaf configuration and a high specific leaf area (Johnson *et al.* 1998). Additionally, African rice cultivars are taller in structure than *O. sativa*. However, the low yield potential of African rice makes it impractical for large-scale cultivation.

Planting pattern: Growing weed-competitive cultivars in a paired-row planting pattern can improve the yield potential of aerobic rice cultivars and DSR (Mahajan and Chauhan 2011).

Seed rate: Increasing seeding rates beyond the optimal level can enhance a crop's ability to suppress weed growth and minimize yield losses, particularly in weedy situations (Ahmed *et al.* 2014, Phuhong *et al.* 2000). Increasing the rice density to 400 plants/m^2 significantly reduces seed production in *Rottboellia cochinchinensis* (Clayton *et al.* 2014).

Crop management: Under soil conditions characterized by resource scarcity, such as limited moisture, root competition between weeds and crops has a more pronounced negative impact than does competition among above-ground shoots. Under such circumstances, fertilizers applied during the early stages of crop growth are more likely to be intercepted by weeds than by the crop itself, resulting in the crop experiencing root competition.

Knowledge and expertise: Additionally, the use of WSCs and WCCs for weed control requires significant knowledge and expertise, as it depends on a deep understanding of the underlying processes (Pooja *et al.* 2021a, 2021b).

Foam weed control

The application of hot foam, a modification of hot water weed control patented in 1995, involves the use of biodegradable foaming agents, such as plant extracts or renewable oils, to control weeds more efficiently (Cederlund and Börjesson, 2016; Martelloni *et al.* 2019). Hot foam has been successfully used for weed control along railways in Sweden (Cederlund and Börjesson 2016). The distinctive advantage of foam lies in its ability to isolate weeds during treatment, ensuring exclusive heat transfer to targeted plant tissues without dissipation into the atmosphere. This foam-induced insulation not only shields weeds but also enhances energy transfer, resulting in reduced hot water usage and increased overall efficiency (Cederlund and Börjesson 2016). Foam innovatively delivers herbicides. Mixing foam ensures better adhesion and absorption onto weed foliage, reduces herbicide drift and unintended damage, and improves coverage, especially under challenging conditions (Cederlund and Börjesson, 2016; Antonopoulos *et al.* 2023).

Compared to using hot water alone, foam incorporation leads to reduced hot water usage, increased resilience to weather changes, and prolonged heat transfer duration (Peerzada and Chauhan, 2018). Challenging-to-control weeds such as *Cynodon dactylon*, *Digitaria sanguinalis*, *Taraxacum officinale*, and other species within the initial weed populations experienced complete mortality at lower doses of hot foam compared to hot water. The incorporation of foam into hot water treatment led to at least a 2.5-fold reduction in the hot water dose compared to the use of hot water alone (Martelloni *et al.* 2021). The insulating characteristics of the foam played a pivotal role, resulting in higher peak temperatures and a more gradual temperature decay. Consequently, weed control was more effective with reduced treatment doses than with hot water alone. The efficacy of hot foam was found to be satisfactory across a diverse range of broadleaf weeds, including those challenging to control through conventional methods (Antonopoulos *et al.* 2023).

Kup and Saglam (2014) compared the effectiveness of hot foam in weed control, specifically by targeting *Cynodon dactylon* and *Glycyrrhiza glabra* in a cotton field, to traditional methods such as spraying and hoeing. The results indicated destruction rates of 94.3%, 84.1%, and 82.5% for *Glycyrrhiza glabra* with the hoeing, spraying, and hot foam methods, respectively. For *C. dactylon*, the destruction rate was 95.1% for both the hoeing and foam methods, while spraying yielded a rate of 94.5%. The close similarity in destruction rates between hot foam and spraying methods suggests that hot foam is a viable alternative to traditional spraying methods (Kup and Saglam 2014). In another study, where hot foam was applied at a rate of 13.33 L/m^2, weed biomass significantly decreased by 81%, 88%, 90%, and 96% compared to that in the mulching, mowing, pelargonic acid, and untreated control treatments, respectively. The overall performance of hot foam was comparable to that of glyphosate (at a rate of 1,440 g/ha), positioning it as an environmentally friendly and effective alternative for weed control in olive groves (Antonopoulos *et al.* 2023). Using hot foam as a desiccant in no-till field bands before transplanting high-value vegetable crops delays weed regrowth by up to 30 days, providing vegetable crops with an extended establishment period free from weed competition (Martelloni *et al.* 2021). On average, it took 26–27 days for 90% of the ground to recover after treatment with hot foam (Martelloni *et al.* 2020). Foam primarily affects the above-ground portions of plants and is more effective at damaging the meristems of weeds. However, certain weeds, such as perennial weeds, may regrow from their below-ground components. Therefore, repeated applications of thermal control may be necessary to effectively manage such weeds (Kup and Saglam 2014, Peerzada and Chauhan 2018).

Factors influencing the efficiency of foam weed control: Various factors influence the efficiency of weed control when employing foaming techniques. These factors include the choice of foaming agent, its concentration (Martelloni *et al.* 2019), water quality, application equipment, environmental conditions (De Cauwer 2015), foam density, viscosity (Machdar *et al*. 2023), weed species, growth stage (Kup and Saglam 2014), foam persistence, and application rate (Martelloni *et al.* 2021). Careful consideration must be given to selecting foaming agents with diverse properties to achieve the desired foam stability, persistence, and adherence to weed surfaces. The concentration of the foaming agent plays a pivotal role in creating a stable foam that adequately covers weed surfaces without becoming overly diluted or concentrated (Martelloni *et al.* 2019). Water quality, including hardness, pH, and impurities, also affects foam stability. The choice of application equipment influences coverage and efficacy, with properly calibrated equipment ensuring a uniform distribution of foam. Weather conditions such as wind and temperature impact foaming performance, inducing drift and influencing stability (De Cauwer 2015). The physical properties of foam, such as density and viscosity, affect adherence to weed surfaces, necessitating optimal consistency for thorough coverage (Machdar *et al.* 2023).

Different weed species and growth stages exhibit varying responses to foaming treatments, with young, actively growing weeds being more susceptible (Kup and Saglam 2014). The surface characteristics of weeds, such as waxy or hairy coatings, influence foam adherence and penetration, with foams adept at overcoming these surface traits tending to be more efficient. The duration of foam stability on weed surfaces is crucial for prolonged contact time and enhanced heat transfer efficiency (Cederlund and Börjesson 2016). The rate of foam application influences coverage and, consequently, weed control efficiency, necessitating an appropriate application rate to ensure that sufficient foam reaches the target (Martelloni *et al*. 2021, Antonopoulos *et al.* 2023). The effectiveness of foam weed control primarily depends on the heat dose applied. An appropriate dosage can significantly improve overall efficiency (Cederlund and Börjesson 2016). The requisite level of heat varies depending on factors such as the weed species, growth stage, water status, and presence of moisture on leaf surfaces (Melander *et al.* 2017). Treating weeds every three weeks was twice as effective and energy-efficient as treating them every six weeks. Compared with the afternoon treatments, the morning treatments showed approximately half the sensitivity. Most weed species are six times more sensitive at 98°C than at 78°C and 88°C, particularly during early growth stages (De Cauwer 2015).

Interventions for scale foam weed control: To scale foam weeding, research and development efforts are crucial to optimize technology, including developing new foaming agents and refining application equipment. Comprehensive training and education for farmers on foam weeding techniques are essential for successful implementation. Facilitating the transfer of technology from research institutions to farmers is crucial, along with investing in infrastructure to seamlessly support foam weeding operations. Supportive policies and regulations promoting foam weeding adoption are necessary. Market development, including creating markets for foam weeding services and products, can stimulate demand and encourage scaling.

Conclusion

Weeds have been a challenge in agriculture since the inception of crop cultivation. Over time, the weed species causing yield losses and the methods adopted for weed control have evolved significantly. The most notable shift has been from manual weed control to herbicidal weed management, driven by labor scarcity, high wages, and the effectiveness of herbicides on young weeds. However, this shift has led to issues such as herbicide resistance and environmental pollution. Thus, modern weed management approaches now emphasize precision, ecological safety, and economic viability. This review discusses three modern technologies: HWSC, weed-tolerant cultivars, and foam weed control. HWSC is effective at managing herbicide-resistant weeds, while foam weed control improves the efficiency of thermal and herbicidal weed management. However, HWSC is prohibitively expensive for small and marginal farmers. Therefore, there is a need to develop lightweight, inexpensive, and easy-to-replicate HWSC equipment. Similarly, the efficiency of foam is affected by the weed growth stage, the type of foam used, and its concentration, water quality, *etc*.

Weed-tolerant cultivars reduce the impact of weeds on crop yields by harnessing inherent traits to enhance resource use efficiency and support sustainable farming practices. Selecting the right cultivars requires a deep understanding of local weed species, environmental conditions, and specific crop requirements. Finding cultivars with the desired weed-competitive or weed-suppressive traits can be challenging, and the available options may not provide a universal solution. Overall, incorporating weed-tolerant cultivars, HWSC, and foam weed control into integrated weed management strategies holds promise for managing herbicide-resistant weeds, reducing reliance on synthetic herbicides, and promoting sustainable agriculture. However, addressing these challenges is essential for optimizing the benefits of these strategies in diverse agricultural contexts, particularly for managing herbicide-resistant weeds and ensuring sustainable weed management.

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RESEARCH ARTICLE

Efficacy of herbicide mixtures on weed dynamics in direct-dry-seeded rice under irrigated condition

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ABSTRACT

An experiment was conducted during three consecutive *Kharif* seasons of 2021, 2022 and 2023 at Regional Research Station, Anand Agricultural University, Anand, Gujarat, India, to study the effect of weed management practices on weeds and grain yield of dry-seeded rice. The dominant grassy weeds in fields were *Echinochloa crus-galli*, *Echinochloa colona*, *Leptochloa chinensis* and broad-leaf weeds were *Digera arvensis*, *Phyllanthus niruri* and *Trianthema monogyna* on three years pooled basis. Results revealed that, early post emergence application (EPoE) of triafamone 20% + ethoxysulfuron 10% WG (pre-mix) 44.0 + 22.5 g/ha at 10-15 days after sowing (DAS) followed by (*fb*) hand weeding (HW) at 30 DAS or penoxsulam 1.02% + cyhalofop-butyl 5.1% OD (pre-mix) 120 g/ha at 10-15 DAS *fb* HW at 30 DAS or pre-emergence application (PE) of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG (pre-mix) 600 + 15 g/ha at 1-2 DAS *fb* HW at 30 DAS or hand weeding 20 and 40 DAS recorded significantly lower density and dry biomass of weeds, higher weed contol efficiency, number of tillers, grain yield of rice and B: C. Moreover, there were no any residues of applied herbicides detected in the rice grain and in soil after harvest.

Keywords: Direct-seeded rice, Herbicides, Microbial roperties, Yield, Residue, Weeds

INTRODUCTION

Rice (*Oryza sativa* L.) is an important food crop of India contributing 45% of the total food grain production. Direct-seeding eliminates the need of raising, maintaining and subsequent transplanting of seedlings besides, it is cost effective can save water through earlier rice crop establishment and allows timely sowing of wheat (Singh *et al*. 2007). There are so many factors which limit the cultivation of rice with transplanting method including water, high input costs, timely unavailability of skilled labour and suboptimal plant population. This factor leads to increase the production cost hence, economic returns are reduced. Looking to this, there has been shift in crop establishment method particularly in rice from transplanting to direct seeded rice in many Asian countries including India. Under this situation, direct seeding is a good alternative to transplanting as it is more economical and labour saving. Moreover, direct-seeded rice matures 7 to 10 days earlier than transplanted rice due to absence of transplanting shock (Rana *et al*. 2014). Under such circumstances, cultivation of rice with direct seeding may provide alternatives in sustainable production. Weeds are most severe and widespread biological constrains to crop production in India and alone cause 33% of losses out of total losses due to pests (Verma *et al.* 2015). However, direct seeding is subjected to greater weed competition than transplanted rice and high weed pressure in DSR are mainly due to absence of a weed-suppressive effect of stagnation of water at the time of crop emergence (Rao *et al*. 2007). According to Singh *et al.* (2004), weeds can reduce the grain yield of dry seeded rice (DSR) by 75.8%. Weeds by virtue of their high adaptability and faster growth dominate the crop habitat and reduce the yield potential. Therefore, the present investigation was undertaken to study the effect of herbicide mixtures for control of major weeds in irrigated dry seeded rice.

MATERIALS AND METHODS

A field experiment was conducted during three consecutive *Kharif* seasons of 2021, 2022 and 2023 at the farm of Regional Research Station, Anand Agricultural University, Anand, Gujarat on loamy sand soil. The experiment comprising of ten treatments *viz.*, pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS, pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* bispyribac-sodium 10% SC 25 g/ha PoE, pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb*

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triafamone 20% + ethoxysulfuron 10% WG 44 + 22.5 g/ha (PM) PoE, pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) PoE, pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* metsulfuron-methyl 10% + chlorimuron-ethyl 10% WP 4 g/ha (PM) PoE, bispyribac-sodium 20% + pyrazosulfuron-ethyl 15% WDG 20 + 15 g/ha (PM) EPoE *fb* HW at 30 DAS, triafamone 20% + ethoxysulfuron 10% WG 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS, penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) EPoE *fb* HW at 30 DAS, hand weeding at 20 and 40 DAS and weedy check was laid out in a randomized block design with three replications. Rice cv. *GAR 14* was sown on 5th August, 3rd August and 7th July of 2021, 2022 and 2023, respectively at a spacing of 30 cm by using seed rate of 60 kg/ha and was harvested on 1st December, 29th November and 11th November, respectively. The crop was fertilized with recommended rate of fertilizer (100-25-0 kg NPK/ ha). Nitrogen was applied in three split, 50 kg N at basal and 25 kg N/ha each at active tillering and panicle initiation stage in the form of urea and 25 kg P in the form of single super phosphate was applied at land preparation. Other agronomical and plant protection measures were followed as per the recommendation during the crop growth. Herbicides were applied as per the treatment by using battery operated knapsack sprayer fitted with flat-fan nozzle by mixing in 500 litres of water/ha. Quadrat (0.25 m^2) was randomly placed at four places in each of the plot to count density and dry weight of weeds at 30, 60 DAS and at harvest. Observations on crop growth and yield parameters, *viz.* plant stand at 15 DAS (No./ net plot), plant height at 30, 60 DAS and at harvest as well as grain and straw yield (kg/ha) were recorded. Data on various indices recorded during the experimental period was statistically analysed as per the standard procedure and weed data were transformed by square root transformation Ö(X+1) and transformed data were subjected to ANOVA analysis (Gomez and Gomez 1984).

For Soil microbial properties, representative soil samples were collected from each plot before sowing, at 1, 15 and 30 DAS as well as at harvest. All the soil samples were analyzed for total microbial populations using standard methodology inwhich, soil samples were serially diluted and inoculated on nutrient agar media and after incubation microbial count in terms of CFU was recorded (Bera and Ghosh 2014).

RESULTS AND DISCUSSION

Weed flora

In general, dominancy of grasses weed (58.7%) was observed in the experimental field during crop period wherein, major weeds in the experimental field were *Echinochloa crus-galli* (19.8%), *Echinochloa colona* (11.1%), *Leptochloa chinensis* (10.3%) and *Dactyloctenium aegyptium* (6.35%) in grassy weeds category whereas, *Digera arvensis* (16.7%), *Phyllanthus niruri* (15.9%) and *Trianthema monogyna* (5.56%) in *broad-leaf* weed category on three years pooled basis.

Density and dry biomass of weeds

All the weed management practices significantly influenced density of weed at 60 DAS (**Table 1**). Pre-mix of triafamone 20% + ethoxysulfuron 10% WG 44.0 + 22.5 g/ha applied as early post emergence (EPoE) *fb* HW at 30 DAS recorded significantly lower density and dry biomass of grasses and *broad-leaf* weed but it was at par with penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) EPoE *fb* HW at 30 DAS and twice hand weeding at 20 and 40 DAS. Pre-emergence application of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) *fb* HW at 30 DAS proved effective by reducing density and dry biomass of weeds as compared to pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) followed by sequential application of either bispyribac-sodium 10% SC 25 g/ ha PoE, triafamone 20% + ethoxysulfuron 10% WG 44 + 22.5 g/ha (PM) PoE, penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) PoE and metsulfuron-methyl 10% + chlorimuron-ethyl 10% WP 4 g/ha (PM) PoE. The effectiveness of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG (600 + 15 g/ha) in direct-seeded rice in reducing the dry biomass of weed was also reported by Shamurailatpam *et al.* (2015). Among herbicidal treatments, higher density and dry biomass of grassy weed was recorded under application of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ ha (PM) PE *fb* metsulfuron-methyl 10% + chlorimuron-ethyl 10% WP 4 g/ha (PM) PoE. This might be due to poor control of grassy weed under post-emergence application of metsulfuron-methyl 10% + chlorimuron-ethyl 10% WP 4 g/ha (PM). Integration of hand weeding with pre- and post-emergence application of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) and bispyribac-sodium 20% + pyrazosulfuron-ethyl 15% WDG 20 + 15 g/ha (PM), respectively performed better by reducing density and dry biomass of weed as compared to sequential application of pre and post emergence herbicide.

The highest weed control efficiency was attained under triafamone 20% + ethoxysulfuron 10% WG 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS (96.8%) followed by penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) EPoE *fb* HW at 30 DAS, hand weeding at 20 and 40 DAS and bispyribac-sodium 20% + pyrazosulfuron-ethyl 15% WDG 20 + 15 g/ha (PM) EPoE *fb* HW at 30 DAS. The effectiveness of this herbicide for effective control of weeds was also reported by Ramesha *et. al*. (2019). Application of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600+15 g/ha (PM) PE *fb* metsulfuron-methyl 10% + chlorimuron-ethyl 10% WP 4 g/ha (PM) PoE recorded lower weed control efficiency (47.7%) due to poor control of grassy weed especially *Echinochloa crus-galli*, *Echinochloa colona* and *Leptochloa chinensis*. Treatment with pre-emergence application of herbicide followed by hand weeding at 30 DAS recorded higher weed control efficiency as compared to sequential application of herbicide.

Effect on crop

Application of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG (pre-mix) 600 + 15 g/ha and bispyribac-sodium 20% + pyrazosulfuron-ethyl 15% WDG 35 g/ha EPoE (pre-mix) showed some phytotoxicity symptoms of leaf injury and slightly necrosis on direct-seeded rice at 7 days after herbicide application. However, plants recovered from the phytotoxicity symptoms and none of the symptoms were observed at 14 days after herbicide application.

Plant height was observed higher under herbicide treatment as compared to weedy check at 60 DAS and at harvest (**Table 2**). Application of bispyribac-sodium 20% + pyrazosulfuron-ethyl 15% WDG 20 + 15 g/ha (PM) EPoE *fb* HW at 30 DAS, triafamone 20% + ethoxysulfuron 10% WG 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS, penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) EPoE *fb* HW at 30 DAS and pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS recorded significantly higher number of effective tillers as compared to other herbicide treatment. Twice hand weeding at 20 and 40 DAS equally effective as pre-emergence application of herbicide followed by integration of hand weeding at 30 DAS for recording higher number of tillers.

Different weed management practices had significant effect on grain yield of rice during all the three years (**Table 2**). Significantly higher grain and straw yields were recorded under triafamone 20% + ethoxysulfuron 10% WG 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS followed by hand weding at 20 and 40 DAS, penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) EPoE *fb* HW at 30 DAS and pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS. The higher yield under twice hand weeding and application of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG (600 + 15 g/ha) PE (PM) *fb* HW at 30 DAS was also reported by Ramesha *et al.* (2019). Significantly lower grain yield was recorded under

Table 1. Density and dry weight of weeds in DSR under different weed management practices at 60 DAS (three year pooled)

Treatment	Weed density (no./m^2)			Weed dry biomass (g/m^2)			WCE (%)
	Grasses	Broad-leaf	Total	Grasses	Broad-leaf	Total	
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS	2.90 (8.33)	3.08 (8.78)	4.15 (17.1)	5.80 (36.3)	3.44 (11.6)	6.67 (47.9)	87.2
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* bispyribac-sodium 25 g/ha PoE	3.72 (14.9)	3.67 (12.9)	5.19 (27.8)	7.87 (71.2)	4.15 (18.1)	9.11 (89.3)	76.1
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* triafamone + ethoxysulfuron 44 + 22.5 g/ha (PM) PoE	3.11 (9.33)	3.88 (15.2)	4.91 (24.6)	7.41 (62.5)	4.98 (24.2)	8.97 (86.7)	76.8
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* penoxsulam + cyhalofop-butyl 120 g/ha (PM) PoE	3.10 (10.3)	4.45 (20.0)	5.36 (30.3)	6.44 (49.1)	3.36 (11.1)	7.23 (60.2)	83.9
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* metsulfuron-methyl + chlorimuron-ethyl 4 g/ha (PM) PoE	4.83 (24.4)	2.54 (6.56)	5.54 (31.0)	13.2 (188)	2.58 (6.53)	13.5 (195)	47.9
Bispyribac-sodium + pyrazosulfuron-ethyl 20 + 15 g/ha (PM) EPoE *fb* HW at 30 DAS,	2.95 (8.56)	3.71 (13.6)	4.66 (22.1)	4.71 (25.0)	2.52 (5.64)	5.33 (30.6)	91.8
Triafamone + ethoxysulfuron 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS	2.04 (3.78)	2.39 (5.11)	3.04 (8.90)	2.90 (7.83)	2.19 (4.21)	3.50 (12.0)	96.8
Penoxsulam + cyhalofop-butyl 120 g/ha (PM) EPoE *fb* HW at 30 DAS	2.12 (4.00)	2.90 (7.56)	3.50 (11.6)	3.49 (12.1)	2.04 (3.76)	3.98 (15.8)	95.8
Hand weeding at 20 and 40 DAS	2.31 (5.78)	2.34 (4.89)	3.20 (10.7)	4.52 (25.1)	1.71 (2.00)	4.77 (27.1)	92.8
Weedy check	5.36 (28.4)	5.14 (26.2)	7.42 (54.7)	17.9 (328)	6.79 (45.5)	19.2 (374)	-
LSD (p=0.05)	0.58	1.15	1.01	2.71	1.36	2.63	-
CV %	17.5	20.0	15.1	14.8	15.7	13.1	-

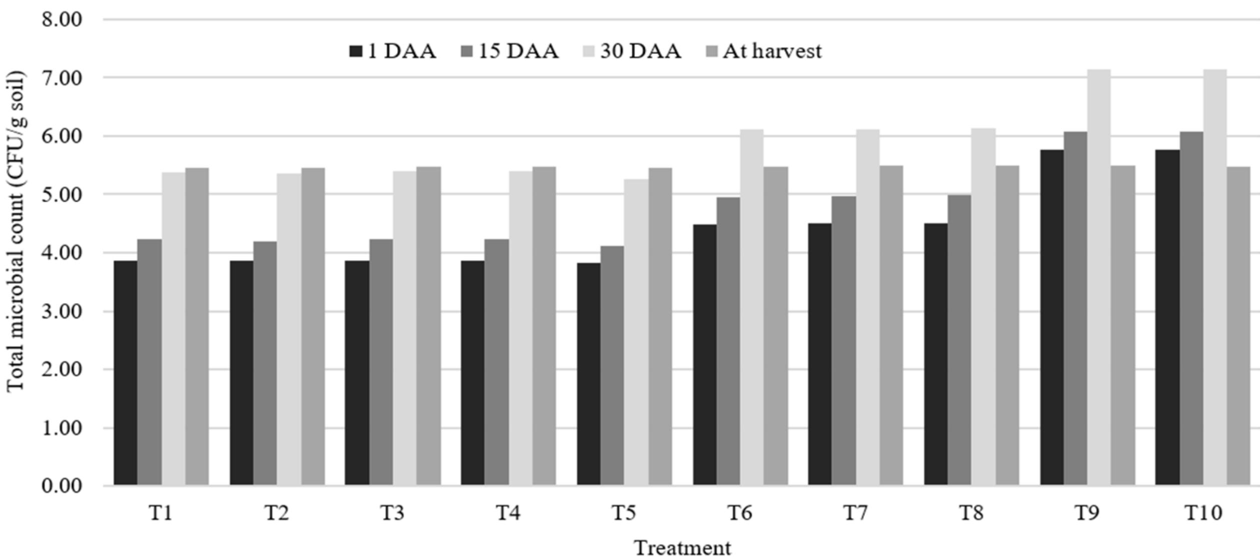
application of pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* metsulfuron-methyl 10% + chlorimuron-ethyl 10% WP 4 g/ha (PM) PoE due to poor control of grassy weed. Yield reduction due to presence of weed was observed maximum under weedy check (84.4%) followed by pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* metsulfuron-methyl 10% + chlorimuron-ethyl 10% WP 4 g/ha (PM) PoE.

Soil microbial study

Initially significant differences were observed in the soil microbial population due to different treatments. The adverse effect on soil microbial population was observed in all the pre- emergence herbicides applied in the experiment from 1 to 15 days, but the effect of herbicide on soil microbial population was gradual decrease from 30 days onwards and no adverse effect of different weed herbicides was recorded at harvest (**Figure 1**).

Table 2. Growth, yield and economics as influenced by weed management practices in DSR (three year pooled)

Treatment	Plant height (cm) At 30 DAS	At 60 DAS	At harvest	Effective tillers (no./m row length)	Grain yield (t/ha) 2021	2022	2023	Pooled	Straw yield (t/ha)	Weed index (%)	B:C
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS	37.5	84.7	98.8	109	3.05	3.20	5.54	3.93	6.97	4.29	1.38
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* bispyribac-sodium 25 g/ha PoE	36.8	85.3	98.2	104	2.79	2.93	4.36	3.36	6.21	18.2	1.30
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* triafamone + ethoxysulfuron 44 + 22.5 g/ha (PM) PoE	36.6	87.0	97.9	92.7	2.91	2.78	3.81	3.17	6.09	22.9	1.27
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* penoxsulam + cyhalofop-butyl 120 g/ha (PM) PoE	38.3	85.0	98.1	96.3	2.66	2.64	3.50	2.93	5.69	28.6	1.13
Pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* metsulfuron-methyl + chlorimuron-ethyl 4 g/ha (PM) PoE	38.2	82.2	94.5	47.0	2.06	1.61	0.47	1.38	2.95	66.4	0.56
Bispyribac-sodium + pyrazosulfuron-ethyl 20 + 15 g/ha (PM) EPoE *fb* HW at 30 DAS,	38.2	86.9	97.5	112	2.67	2.50	5.48	3.55	6.45	13.6	1.29
Triafamone + ethoxysulfuron 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS	37.7	88.2	99.0	122	3.21	3.37	5.74	4.11	7.34	-	1.48
Penoxsulam + cyhalofop-butyl 120 g/ha (PM) EPoE *fb* HW at 30 DAS	38.2	83.4	98.4	123	3.16	3.18	5.63	3.99	7.26	2.97	1.46
Hand weeding at 20 and 40 DAS	39.6	85.9	109	114	3.24	3.44	5.61	4.10	7.38	0.24	1.29
Weedy check	39.7	76.0	94.1	26.3	0.89	0.67	0.36	0.64	1.49	84.4	0.29
LSD (p=0.05)	NS	5.43	NS	27.5	0.45	0.38	0.77	0.60	1.38	-	-



T_1: pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS; T_2: pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* bispyribac-sodium 25 g/ha PoE; T_3: pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* triafamone + ethoxysulfuron 44 + 22.5 g/ha (PM) PoE; T_4: pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* penoxsulam + cyhalofop-butyl 120 g/ha (PM) PoE; T_5: pretilachlor + pyrazosulfuron-ethyl 600 + 15 g/ha (PM) PE *fb* metsulfuron-methyl + chlorimuron-ethyl 4 g/ha (PM) PoE; T_6: bispyribac-sodium + pyrazosulfuron-ethyl 20 + 15 g/ha (PM) EPoE *fb* HW at 30 DAS; T_7: triafamone + ethoxysulfuron 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS; T_8: penoxsulam + cyhalofop-butyl 120 g/ha (PM) EPoE *fb* HW at 30 DAS; T_9: hand weeding at 20 and 40 DAS; T_{10}: weedy check

Figure 1. Soil microbial count as influenced by different weed management practices

Economics

Application of triafamone 20% + ethoxysulfuron 10% WG 44.0 + 22.5 g/ha (PM) EPoE *fb* HW at 30 DAS showed effective reduction in density and dry biomass of weed, higher WCE, grain yield and recorded maximum benefit cost ratio of 1.48 which was followed by application of penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha (PM) EPoE *fb* HW at 30 DAS and pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS.

Conclusion

It was concluded that application of triafamone 20% + ethoxysulfuron 10% WG 44.0 + 22.5 g/ha EPoE (pre-mix) *fb* HW at 30 DAS or penoxsulam 1.02% + cyhalofop-butyl 5.1% OD 120 g/ha EPoE (PM) *fb* HW at 30 DAS, pretilachlor 30% + pyrazosulfuron-ethyl 0.75% WG 600 + 15 g/ha (PM) PE *fb* HW at 30 DAS or two manual weeding carried out at 20 and 40 DAS were found effective for the management of complex weed flora in direct-seeded rice under middle Gujarat conditions with higher gross return, net return and benefit cost ratio.

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RESEARCH ARTICLE

Herbicide-based weed management on weed prevalence, crop productivity and profitability in transplanted rice

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ABSTRACT

The efficacy of pre- and post-emergence herbicide-based weed control methods was evaluated and compared with hand weeding twice and weedy check in transplanted rice. Hand weeding twice (20 and 40 days after transplanting) was found to be significantly (p=0.05) effective in controlling various groups of weeds, resulting in 86.4% weed control efficiency (WCE) and a rice grain yield of 6.99 t/ha. Additionally, sequential application of pyrazosulfuron 20 g/ha followed by (*fb*) bispyribac-sodium 25 g/ha and pendimethalin 1000 g/ha *fb* bispyribac-sodium was found to be highly effective in providing prolonged weed control. Bispyribac-sodium applied alone showed 78% WCE, which was significantly better than fenoxaprop and pyrazosulfuron. Pre-emergence *fb* post-emergence herbicides were found to be more profitable (B: C of 2.13-2.23) and productive (6.58-7.17 t/ha). The findings suggested that the sequential application of pyrazosulfuron 20 g/ha or pendimethalin 1000 g/ha *fb* bispyribac-sodium 25 g/ha could provide broad-spectrum weed control, higher crop productivity, and profitability in transplanted rice.

Keywords: Economic return, Productivity, Transplanted rice, Weed prevalence

INTRODUCTION

In India, ~44 million hectares (M ha) area is under rice cultivation, with ~124 million tonne (Mt) production, which shares 21.5% of world rice production (DES 2024). India is largely self-sufficient in rice production, but to sustain self-sufficiency by 2050 and feed a projected population of 1.64 billion people, 197.4 Mt of rice will be needed. An additional challenge is that the extra rice will be produced with a lower environmental footprint with limited resources (*i.e.*, land, labour, water, agrochemicals, *etc*.) (Ahmad *et al.* 2021). Biotic and abiotic stresses are a major concern in the modern-day input-intensive agricultural production system as they cause serious economic losses. Among biotic stresses, weeds are major biological constraints and cause a 37% yield loss (Mishra *et al.* 2021). In majority, rice being a rainy season (June–October) crop, climatic and edaphic conditions are highly favourable for weed growth (Kabdal *et al.* 2018). Improper weed management may lead to a 95% yield reduction, and sometimes complete crop failure takes place in direct-seeded rice (DSR) (Maity and Mukharjee 2008, Naresh *et al.* 2011).

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Puddle-transplanted rice has several advantages, including the retention of a thin layer of water, formation of hardpan that prevents percolation losses, the suppression of weeds, and supply of nutrients (Choudhary *et al.* 2021). Rice crop is heavily infested with annual grasses, broad-leaf weeds, and sedges, posing a challenge to weed management (Choudhary and Dixit 2018). The depth of standing water affects the type and density of weed flora and the efficacy of applied herbicides. However, despite these benefits, multiple weed flushes lead to heavy weed pressure during the cropping period, resulting in a serious yield penalty that cannot be controlled by adopting one or two methods. Manual weeding is suggested as the best weed management method, but frequent rains, labour shortages, and high labour wages make it challenging, time-consuming, and uneconomical, especially during the critical period of weed competition (Choudhary and Dixit 2018).

Pre-emergence (PE) herbicides can effectively control weeds during the initial stages of crop growth, while post-emergence (PoE) herbicides are best used for killing the initial flush of weeds. Maintaining desired water levels after herbicide application can enhance their efficacy (Kaur *et al.* 2016). Sequential application of PE followed by (*fb*) PoE herbicides either premixes or tank mixes of herbicides with different modes of action can provide broad-spectrum weed control and found better results than using PE or PoE herbicides alone. Additionally, use of tank mix or premix can also reduce herbicide load, leads to cost savings. Despite its importance, comprehensive information on these aspects is scarce, and there is a need to develop productive and cost-effective weed management options as a substitute for costly and labour-intensive weeding of transplanted rice.

MATERIALS AND METHODS

A field study was carried out between June and November in 2015 and 2016 at the research farm of ICAR-National Institute of Biotic Stress Management, Raipur (21° 22' 50.4" N 81° 49' 31.9" E, 289 m above mean sea level), India. The study site experienced an average annual rainfall of 1250 mm, with 80% received during the south-west monsoon from July to September. The region has a subtropical climate with hot summers and a mean minimum temperature of 12°C in December, while May is the hottest month with a mean maximum temperature of 45°C. The soil was of Arang Series with a loamy texture containing 26% clay, 42% silt and 32% sand. The soil had a neutral pH of 6.9 and low soil organic carbon content of 0.37%. The soil was low in $KMnO_4$ oxidizable nitrogen (220.8 kg/ha), medium in 0.5 N $NaHCO_3$ extractable phosphorus (17.8 kg/ha) and high in 1 N NH_4OAc exchangeable potassium (345.0 kg/ha) in 0–20 cm soil depth.

The study was conducted with rice variety '*Swarna'*, 21 days old seedlings were transplanted in a puddled field at a spacing of 20 × 10 cm, which was prepared by using two passes of a cultivator in dry condition and one pass of a rotavator after flooding. The treatments were pyrazosulfuron 20 g/ha (2 days after transplanting, DAT) followed by (*fb)* bispyribac-sodium 25 g/ha (25 DAT); fenoxaprop + 2,4-D (tank mix) 60 + 500 g/ha (25 DAT); pretilachlor + pyrazosulfuron (premix) 615 g/ha (6 DAT); pretilachlor + pyrazosulfuron (tank mix) 600+15 g/ha (6 DAT); bispyribac-sodium + 2,4-D (tank mix) 25 + 500 g/ha (25 DAT); fenoxaprop + chlorimuron + metsulfuron (tank mix) 60 + 4 g/ha (25 DAT); pendimethalin 1000 (2 DAT) *fb* bispyribac-sodium 25 g/ha (25 DAT); bispyribac-sodium 25 g/ha (25 DAT); pyrazosulfuron 20 g/ha (2 DAT); fenoxaprop 60 g/ha (25 DAT); hand weeding at 20 and 40 DAT and weedy check were imposed using a randomized complete block design (RCBD) with three replications with a gross plot size of 8 m × 20 m. Herbicide application was done using a backpack knapsack sprayer equipped with a flat fan nozzle. Spray volume of 500 L/ha was used for herbicides applied at 2 DAT, while 375 L/ha spray volume for herbicides applied at 25 DAT. The crop was fertilized with 100: 60: 40 kg N, P and K/ha through urea (N), di-ammonium phosphate (part of N and complete P) and muriate of potash (K), where the full dose of P and 75% of K fertilizers were applied at the time of transplanting. Nitrogen was applied in three splits at 22, 22, 32 kg N/ha at 10, 30 and 60 DAT. At 60 DAT, the remaining 10 kg/ha of potash was applied along with nitrogen. To prevent insect infestation, one spray of flubendiamide at 24 g/ha (against stem borer and leaf folders), dinetofuron at 35 g/ha (against brown plant hoppers and other sucking insects) was applied. Additionally, mancozeb + carbendazim at 563 g/ha was applied to control diseases.

Weed parameters (density and biomass) were recorded, at two random locations using quadrates measuring 0.25 m^2 (0.5 m × 0.5 m dimension) at 45 and 75 DAT. Weeds of different groups were identified, counted and cut at collar portion of the plants and placed them separately in brown paper bags for sun drying for 3–5 days. After drying off the excess moisture, these paper bags were placed in an oven at 70±2°C for 72 hours (h) until the weed samples attained a constant weight, which was considered the biomass of the respective weed species. The mean of both quadrates was converted into numbers/m^2 and g/m^2, respectively, for analysis and interpretation. The weed control efficiency was calculated from total weed biomass.

To homogenize the variance, a square root ($\sqrt{x+0.5}$) transformation was performed to the weed data (density and biomass). Statistical analysis of all field data was conducted using SAS statistical software (version 9.3). The Tukey's Honest Significant Difference test was selected, and analysis of variance (ANOVA) was performed to determine the level of significance (p=0.05) between treatment means. As the effect of year was significant in most of the cases, results were presented separately for each year.

RESULTS AND DISCUSSION

The study area was found to have a significant presence of various grassy and broad-leaf weeds, as well as sedges. Among grassy weeds, jungle rice [*Echinochloa colona* (L.)], saramolla grass [*Ischaemum rugosum* (Salisb.)], viper grass [*Dinebra retroflexa* (Jacq.)], knot grass [*Paspalum distichium* (L.)] and large crabgrass [*Digitaria sanguinalis* (L.)] were identified. In addition, broad-leaf weeds like primerose willow [*Ludwigia parviflora* (Jacq.)], water clover [*Marselia quadrifolia* (L.)], smooth joyweed [*Alternanthera sessilis* (L.)], false daisy [*Eclipta alba* (L.)], and common dayflower [*Commelina communis* (L.)], as well as sedges like fimbry [*Fimbristylis miliacea* (L.)], rice flatsedge [*Cyperus iria* (L.)], gooseweed [*Sphenoclea zeylanica* (Gaertn.)] and smallflower umbrella sedge [*Cyperus difformis* (L.)] were also present. During cropping season in both the years, the dominant grassy weeds were *Echinochloa colona* and *Ischaemum rugosum,* while *Ludwigia parviflora* and *Alternanthera sessilis* were broad-leaf weeds. Among sedges, *Cyperus iria* and *Fimbristylis miliacea* were most prevalent.

Weed parameters

In both 2015 and 2016, weed density at 45 DAT followed almost a similar trend. The highest total weed density was observed in the weedy check (114–125/m^2) with a composition of 31–33% grasses, 42% broad-leaf weeds, and 25–27% sedges (**Table 1**). However, hand weeding at 20 and 40 DAT completely controlled both grassy and broad-leaf weeds, but only counted 2 sedges/m^2 during both years. Herbicide-based weed management showed a wide range of efficacy, with the suppression of grassy weeds ranging between 11–94%, broad-leaf weeds by 4–94%, and sedges by 6–89% over weedy check. The majority of grassy weeds were suppressed with pendimethalin 1.0 kg/ha *fb* bispyribac sodium 25 g/ha, while broad-leaf weeds and sedges were controlled with sequential application of pyrazosulfuron 20 g/ha *fb* bispyribac-sodium 25 g/ha and a tank mix of bispyribac-sodium + 2, 4 D (25 + 500 g/ha). These herbicides noticeably suppressed all the weeds and were found to be more effective than other weed management practices. Twice hand weeding resulted in the minimum weed biomass accumulation (1 g/m^2), while the weedy check had the highest (15.6–19.6 g/m^2) in both years. Pyrazosulfuron *fb* bispyribac-sodium resulted in WCE of 83% followed by pendimethalin *fb* bispyribac-sodium (82%) than the weedy check. At 75 DAT, weed parameters were also influenced by weed management practices (**Table 2**). The weedy check had the highest number of grasses (76/m^2), broad-leaf weeds (109–113/m^2), sedges (52–56/m^2), and total weed density (238–245/m^2), while twice hand weeding had the lowest density for all group of weeds. Among the herbicide-based treatments, pyrazosulfuron *fb* bispyribac-sodium suppressed weeds by 92% grasses, 94% broad-leaf weeds, 83% sedges and 88% total weeds, followed by pendimethalin *fb* bispyribac-sodium (91, 90, 83 and 89%, respectively) over the weedy check. Suppression of weeds reduced the total weed biomass, resulting in a higher WCE in the sequential application of PE *fb* PoE herbicides. The results demonstrate that the use of a sole application of pyrazosulfuron was weak against grasses, controlling only 11–27%, while sole application of fenoxaprop was weak against broad-leaf (4–7%) and sedges (6–

Table 1. Weed density and biomass at 45 DAT as influenced by different treatments in transplanted rice

Treatment	Grasses (no./m^2)		BLW (no./m^2)		Sedges (no./m^2)		Total weed density (no./m^2)		Weed biomass (g/m^2)		WCE (%)	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Pyrazosulfuron 20 g/ha 2 DAT *fb* bispyribac-sodium 25 g/ha (25 DAT)	2.4(5)	2.6(6)	2.2(4)	1.9(3)	2.0(3)	2.4(5)	3.7(13)	3.9(15)	1.9(3)	1.9(3)	81.2	83.8
Fenoxaprop + 2,4-D (TM) 60 + 500 g/ha (25 DAT)	2.5(6)	2.3(5)	3.2(10)	2.5(6)	2.7(7)	2.7(7)	4.8(23)	4.2(17)	2.4(5)	2.6(6)	66.9	67.5
Pretilachlor + pyrazosulfuron (PM) 615 g/ha (6 DAT)	2.0(4)	2.0(3)	2.8(7)	2.3(5)	2.5(6)	2.4(5)	4.1(17)	3.8(14)	2.1(4)	2.3(5)	75.6	76.4
Pretilachlor + pyrazosulfuron (TM) 600+15 g/ha (6 DAT)	2.4(5)	2.5(6)	4.0(16)	3.2(10)	3.6(12)	3.3(10)	5.8(33)	5.1(26)	2.3(5)	2.5(6)	68.6	71.6
Bispyribac-sodium + 2,4-D (TM) 25 + 500 g/ha (25 DAT)	2.5(6)	2.5(6)	2.4(5)	1.9(3)	2.0(4)	2.0(4)	3.9(15)	3.6(13)	2.6(7)	2.9(8)	58.3	59.4
Fenoxaprop + chlorimuron + metsulfuron (TM) 60 + 4 g/ha (25 DAT)	2.3(5)	2.0(4)	2.7(7)	2.2(4)	2.9(8)	2.3(5)	4.4(19)	3.7(13)	2.5(6)	2.4(5)	61.8	72.3
Pendimethalin 1000 (2 DAT) *fb* bispyribac-sodium 25 g/ha (25 DAT)	1.7(2)	1.7(2)	2.5(6)	2.3(5)	2.4(5)	2.5(6)	3.7(13)	3.7(13)	1.9(3)	1.8(3)	78.8	85.2
Bispyribac-sodium 25 g/ha (25 DAT)	2.4(5)	2.8(7)	2.9(8)	3.0(9)	2.5(6)	3.2(10)	4.4(19)	5.2(26)	2.2(4)	2.5(6)	73.3	69.7
Pyrazosulfuron 20 g/ha (2 DAT)	5.8(34)	5.4(29)	3.5(12)	3.3(10)	2.9(8)	2.8(7)	7.3(53)	6.8(46)	2.6(6)	2.7(7)	61.3	65.5
Fenoxaprop 60 g/ha (25 DAT)	2.5(6)	2.3(5)	6.8(46)	7.0(48)	5.3(27.3)	5.6(31)	8.9(79)	9.2(84)	3.0(9)	3.2(9)	44.9	51.5
Hand weeding at 20 and 40 DAT	0.7(0)	0.7(0)	0.7(0)	0.7(0)	1.6(2)	1.7(2)	1.6(2)	1.7(2)	1.2(1)	1.3(1)	93.8	94.0
Weedy check	6.2(38)	6.3(39)	6.9(48)	7.2(52)	5.4(29)	5.8(34)	10.7(114)	11.2(125)	4.0(16)	4.5(20)		
LSD (p=0.05)	0.37	0.35	0.45	0.40	0.54	0.56	0.31	0.20	0.60	0.56		

DAT: days after transplanting; BLW, broad-leaf weeds; WCE, weed control efficiency; HW, hand weeding; PM, premix; TM, tank mix; values in parenthesis are original and outside are transformed $\sqrt{x+0.5}$

9%). Thus, using only PE or PoE herbicides is not efficient enough to provide broad-spectrum weed control. Sequential use of PE herbicides such as pyrazosulfuron or pendimethalin followed by PoE herbicide (bispyribac-sodium) broadly controls mixtures of weed flora in transplanted rice. This is because broad-leaf weeds, sedges and some grasses were effectively controlled by pyrazosulfuron, whereas pendimethalin takes care of grasses and some broadleaved weeds. Subsequent applications of bispyribac-sodium control the large group of weeds left after PE herbicide or late emerged weeds. Mahajan and Chauhan (2013) also reported that bispyribac-sodium controlled around 52% of weed density and 50% of weed biomass, while pendimethalin *fb* bispyribac-sodium controlled 92% of weed density and 93% of weed biomass. Mixing auxin-based herbicides with other modes of action of herbicides requires compatibility study prior to mixing or application. As tank mix application of bispyribac-sodium + 2, 4-D recorded considerably poor weed control than bispyribac-sodium alone, possibly due to escape of grassy weeds and some shocks to the rice crop due to 2, 4-D. However, Tripathy *et al.* (2018) reported that bispyribac-sodium + 2, 4-D was more effective in controlling weeds. Applications of PE herbicides significantly suppress initial weed establishment, and subsequently, bispyribac-sodium (25 g/ha) takes care of the weeds at a later crop stage. Similarly, application of PE and PoE herbicides in sequence or compatible tank mix or premix herbicides with different mode of action is superior to weedy check in controlling weeds (**Tables 1** and **2**).

Crop growth and yield attributes

During 2015 and 2016, effective tillers per unit area were highest with pyrazosulfuron *fb* bispyribac (450–463/m^2), followed by twice hand weeding and pendimethalin *fb* bispyribac-sodium, while the weedy check had the least effective tillers (**Table 3**). Twice hand weeding and pyrazosulfuron *fb* bispyribac-sodium improved tiller production by 16.7–57.4%, leading to better establishment of seedlings with no negative effect on the rice crop. In addition, the LAI was higher with pendimethalin *fb* bispyribac-sodium (2.81–3.12), followed by pyrazosulfuron *fb* bispyribac-sodium, whereas the weedy check had the lowest LAI (1.69–1.89). Higher LAI was mainly due to more tillers, longer and wider leaves. However, the application of fenoxaprop was phytotoxic to the plants, which might have retarded the initial growth and development of leaves, resulting in a lesser LAI (Choudhary and Dixit 2018). Pendimethalin *fb*

Table 2. Weed density and biomass at 75 DAT as influenced by different treatments in transplanted rice

Treatment	Grasses (no./m^2)		BLW (no./m^2)		Sedges (no./m^2)		Total weed density (no./m^2)		Weed biomass (g/m^2)		WCE (%)	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Pyrazosulfuron 20 g/ha 2 DAT *fb* bispyribac-sodium 25 g/ha (25 DAT)	3.4 (11)	3.7 (13)	2.5 (6)	2.9 (8)	2.3 (5)	3.7 (13)	4.7 (22)	5.9 (34)	2.1 (4)	2.9 (8)	80.9	81.8
Fenoxaprop + 2,4-D (tank mix) 60 + 500 g/ha (25 DAT)	2.9 (8)	3.1 (9)	4.0 (16)	3.8 (14)	3.3 (11)	3.6 (12)	5.9 (34)	6.0 (36)	2.6 (6)	3.59 (12)	70.3	71.8
Pretilachlor + pyrazosulfuron (premix) 615 g/ha (6 DAT)	3.3 (11)	3.7 (13)	3.8 (14)	3.4 (11)	3.7 (13)	3.5 (12)	6.2 (38)	6.1 (36)	2.2 (4)	3.1 (9)	79.1	79.2
Pretilachlor + pyrazosulfuron (tank mix) 600+15 g/ha (6 DAT)	4.1 (17)	4.5 (19)	5.7 (32)	4.8 (23)	5.0 (24)	4.7 (22)	8.6 (73)	8.1 (64)	2.5 (6)	3.5 (12)	72.3	72.8
Bispyribac-sodium + 2,4-D (tank mix) 25 + 500 g/ha (25 DAT)	3.9 (15)	4.1 (16)	3.1 (9)	3.2 (10)	2.3 (5)	3.0 (8)	5.4 (29)	5.9 (35)	2.7 (7)	3.9 (15)	65.9	66.6
Fenoxaprop + chlorimuron + metsulfuron (tank mix) 60 + 4 g/ha (25 DAT)	2.5 (6)	2.5 (6)	4.1 (16)	3.5 (12)	3.4 (11)	3.7 (13)	5.8 (33)	5.6 (31)	2.7 (7)	3.8 (14)	67.6	68.8
Pendimethalin 1000 (2 DAT) *fb* bispyribac-sodium 25 g/ha (25 DAT)	2.5 (6)	2.9 (8)	3.3 (11)	3.4 (11)	2.7 (7)	3.4 (11)	4.9 (24)	5.6 (31)	2.1 (4)	2.9 (8)	81.1	81.5
Bispyribac-sodium 25 g/ha (25 DAT)	3.8 (14)	4.0 (16)	3.7 (13)	3.9 (15)	3.4 (11)	4.2 (17)	6.2 (38)	6.9 (48)	2.3 (5)	3.2 (9)	77.7	78.6
Pyrazosulfuron 20 g/ha (2 DAT)	8.1 (65)	8.5 (72)	4.4 (19)	4.3 (18)	4.1 (16)	3.9 (15)	10.0 (100)	10.3 (105)	2.8 (7)	4.0 (15)	64.0	65.3
Fenoxaprop 60 g/ha (25 DAT)	3.0 (9)	2.8 (8)	9.5 (90)	9.3 (86)	6.7 (45)	7.1 (50)	12.0 (143)	12.0 (143)	2.8 (7)	4.1 (16)	63.8	62.9
Hand weeding at 20 and 40 DAT	2.2 (4)	2.6 (6)	2.6 (6)	3.2 (10)	2.4 (5)	2.7 (7)	4.1 (16)	4.8 (23)	1.9 (3)	2.4 (5)	84.8	88.0
Weedy check	8.8 (77)	8.7 (76)	10.5 (109)	10.7 (113)	7.2 (52)	7.5 (56)	15.4 (238)	15.7 (245)	4.6 (21)	6.6 (44)		
LSD (p=0.05)	0.49	0.47	0.45	0.54	0.64	0.49	0.45	0.50	0.32	0.41		

BLW, broad-leaf weeds; WCE, weed control efficiency; values in parenthesis are original and outside are transformed $\sqrt{x+0.5}$

bispyribac-sodium resulted in longer (24.4 cm in 2015 and 24.1 cm in 2016) and heavier panicles (3.1 and 3.8 g/panicle, respectively) followed by premix and tank mix of pretilachlor+pyrazosulfuron, whereas the weedy check produced shorter and lighter panicles (21.7 and 21.5 cm, 2.9 and 2.8 g/ panicle, respectively). Moreover, the filled grains/ panicle were higher with twice hand weeding (167 and 156, respectively), followed by pyrazosulfuron *fb* bispyribac-sodium (161 and 148, respectively), whereas the weedy check had fewer grains/panicle (84 and 77, respectively). Overall, other weed management practices were better in terms of yield attributes than the weedy check. The weedy check had higher chaffy grains (20–22 grains/panicle) than the other treatments.

Crop yield

The highest grain yield was obtained under twice hand weeding in 2015 (7.45 t/ha), whereas pyrazosulfuron *fb* bispyribac-sodium showed the highest yield in 2016 (6.58 t/ha). The premix of pretilachlor + pyrazosulfuron followed by pendimethalin *fb* bispyribac-sodium was the next best treatment, which gave a significantly higher rice grain yield than other treatments. These provided an extended weed–free environment, which allows rice plants to utilize available resources such as water, nutrients, sunlight and space. It promoted the production of higher LAI, leading to increased photosynthesis, translocation to different plant parts, and ultimately, higher total dry matter production, longer and heavier panicles, more filled grains, and fewer chaffy grains (**Table 4**), leading to higher grain and straw yield in rice. These findings are consistent with earlier studies by Teja *et al.* (2016), Kumar *et al.* (2018), and Singh *et al.* (2018). Similarly, Walia *et al.* (2008) reported that the application of pendimethalin 0.75 kg/ha *fb* bispyribac-sodium 25 g/ha resulted in 372% more rice grain yield due to better weed control over the weedy check. Weedy check had the lowest grain yields (3.62 and 3.61 t/ha, respectively) due to severe weed competition, leading to reduced yield characters, growth, nutrient uptake, and yield

Table 3. Growth parameters and yield attributes as influenced by different treatments in transplanted rice

Treatment	Tillers (no./m^2)		Leaf area index		Panicle length (cm)		Panicle weight (g/panicle)		Filled grain (no./panicle)		Chaffy grain (no./panicle)	
	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016	2015	2016
Pyrazosulfuron 20 g/ha 2 DAT *fb* bispyribac-sodium 25 g/ha (25 DAT)	450.0	463.3	3.03	2.81	23.5	23.2	3.34	3.22	161.0	148.0	10.5	12.0
Fenoxaprop + 2,4-D (TM) 60 + 500 g/ha (25 DAT)	350.0	355.0	1.93	1.77	22.7	22.6	3.03	2.99	117.8	106.8	14.7	16.7
Pretilachlor + pyrazosulfuron (PM) 615 g/ha (6 DAT)	383.3	390.0	2.64	2.52	22.4	22.6	3.44	3.40	152.8	140.8	11.0	12.0
Pretilachlor + pyrazosulfuron (TM) 600+15 g/ha (6 DAT)	366.7	353.3	2.41	2.20	23.7	23.5	3.61	3.57	117.1	107.1	13.6	15.6
Bispyribac-sodium + 2,4-D (TM) 25 + 500 g/ha (25 DAT)	396.7	380.0	2.93	2.67	23.7	23.5	3.48	3.39	125.1	114.1	12.6	13.6
Fenoxaprop + chlorimuron + metsulfuron (TM) 60 + 4 g/ha (25 DAT)	366.7	345.0	2.50	2.27	23.2	23.3	3.70	3.66	101.3	89.3	15.2	17.2
Pendimethalin 1000 (2 DAT) *fb* bispyribac-sodium 25 g/ha (25 DAT)	435.0	413.3	3.12	2.81	24.4	24.1	3.81	3.79	150.6	140.6	11.5	13.5
Bispyribac-sodium 25 g/ha (25 DAT)	420.0	400.0	2.85	2.59	22.7	22.8	3.13	3.08	133.0	121.0	12.3	14.8
Pyrazosulfuron 20 g/ha (2 DAT)	395.0	393.9	2.68	2.53	23.3	23.1	3.38	3.32	133.0	122.0	16.3	17.3
Fenoxaprop 60 g/ha (25 DAT)	358.3	356.7	2.12	1.95	23.4	23.2	3.23	3.18	98.9	88.9	19.7	20.7
Hand weeding at 20 and 40 DAT	472.2	447.8	2.93	2.81	23.3	23.2	3.57	3.52	166.6	155.6	8.4	8.9
Weedy check	300.0	293.3	1.89	1.69	21.7	21.5	2.90	2.82	83.7	76.7	20.9	21.9
LSD (p=0.05)	72.73	75.63	0.75	0.72	1.55	1.51	0.47	0.48	20.00	20.00	6.93	6.94

Table 4. Grain, straw and biological yield as influenced by different treatments in transplanted rice

Treatment	Grain yield (t/ha)		Straw yield (t/ha)		Biological yield (t/ha)		Yield loss (%)	
	2015	2016	2015	2016	2015	2016	2015	2016
Pyrazosulfuron 20 g/ha 2 DAT *fb* bispyribac-sodium 25 g/ha (25 DAT)	7.17	6.58	8.05	7.84	15.22	14.43	3.8	-3.9
Fenoxaprop + 2,4-D (tank mix) 60 + 500 g/ha (25 DAT)	5.34	5.25	5.57	7.21	10.92	12.46	27.4	16.9
Pretilachlor + pyrazosulfuron (premix) 615 g/ha (6 DAT)	7.03	6.22	7.43	6.39	14.47	12.61	5.1	1.6
Pretilachlor + pyrazosulfuron (tank mix) 600+15 g/ha (6 DAT)	5.59	6.01	5.90	7.60	11.49	13.61	25.0	5.2
Bispyribac-sodium + 2,4-D (tank mix) 25 + 500 g/ha (25 DAT)	5.72	6.20	6.81	7.75	12.52	13.95	22.3	2.1
Fenoxaprop + chlorimuron + metsulfuron (tank mix) 60 + 4 g/ha (25 DAT)	4.80	5.65	5.20	7.70	10.00	13.36	35.6	10.5
Pendimethalin 1000 (2 DAT) *fb* bispyribac-sodium 25 g/ha (25 DAT)	6.92	6.00	7.06	7.37	13.97	13.37	6.7	5.1
Bispyribac-sodium 25 g/ha (25 DAT)	6.02	6.06	6.84	6.84	12.86	12.90	19.2	4.2
Pyrazosulfuron 20 g/ha (2 DAT)	4.56	5.77	4.90	6.59	9.46	12.37	38.6	9.0
Fenoxaprop 60 g/ha (25 DAT)	4.43	4.95	4.77	6.48	9.20	11.43	40.3	21.7
Hand weeding at 20 and 40 DAT	7.45	6.35	9.24	6.56	16.69	12.91	0.0	0.0
Weedy check	3.62	3.61	4.55	4.75	8.17	8.36	51.1	42.8
LSD (p=0.05)	1.16	0.62	0.91	0.75	1.26	1.37		

parameters of the crop (Nagarjun *et al.* 2019). The trend for straw yield followed a similar pattern, with the highest yield observed in 2015 with twice hand weeding (9.24 t/ha) and in 2016 with pyrazosulfuron *fb* bispyribac-sodium (7.84 t/ha). The lowest straw yield was obtained in weedy check (4.55 and 4.75 t/ha, respectively). Biological yield also followed the same trend. Yield loss in rice was the highest in weedy check, ranging between 43–51%, although the loss was higher in 2015 than in 2016. The relationship between grain yield and weed density (at 45 DAT) followed a quadratic relationship with a coefficient of determination (R^2) of 0.75 in 2015 and 0.54 in 2016 (**Figure 1a**). Similarly, rice grain yield had a quadratic relationship with weed biomass following R^2 of 0.86 in both years (**Figure 1b**). At 75 DAT, rice grain yield followed the quadratic relationship with weed density (R^2, 0.75 and 0.83, respectively) (**Figure 2a**) and weed biomass (R^2, 0.93 and 0.83, respectively) **(Figure 2b**).

Economics

The economic parameters were significantly affected by the weed management practices adopted in the study (**Table 5**). The highest cost of production was observed with twice hand weeding (₹ 41560/ha) due to requirement of a greater number of manual labourers for weed removal, followed by pendimethalin *fb* bispyribac-sodium (₹ 31660/ha), while the lowest cost was incurred in the weedy check (₹ 29160/ha). With regard to gross returns, twice hand weeding showed the highest value in 2015, whereas pyrazosulfuron *fb* bispyribac-sodium showed the highest value in 2016. However, in terms of net returns (₹ 66157-69153/ha) and B: C (2.13–2.23), the highest values were observed with pyrazosulfuron *fb* bispyribac-sodium in both years, followed by premix of pretilachlor + pyrazosulfuron, which could be due to the lesser cost of cultivation and higher grain yield (Nagarjun *et al.* 2019). Herbicide-based weed management in rice has been reported as an alternative option for selective and economic weed management, supporting better growth, competitive superiority, higher yields, and economic viability (Singh *et al.* 2016, Yogananda *et al.* 2017). The lowest net returns and B: C values were obtained in the weedy check.

Conclusions

Based on the experimental results, it was found that the use of pre-emergence herbicide such as pyrazosulfuron or pendimethalin in combination with

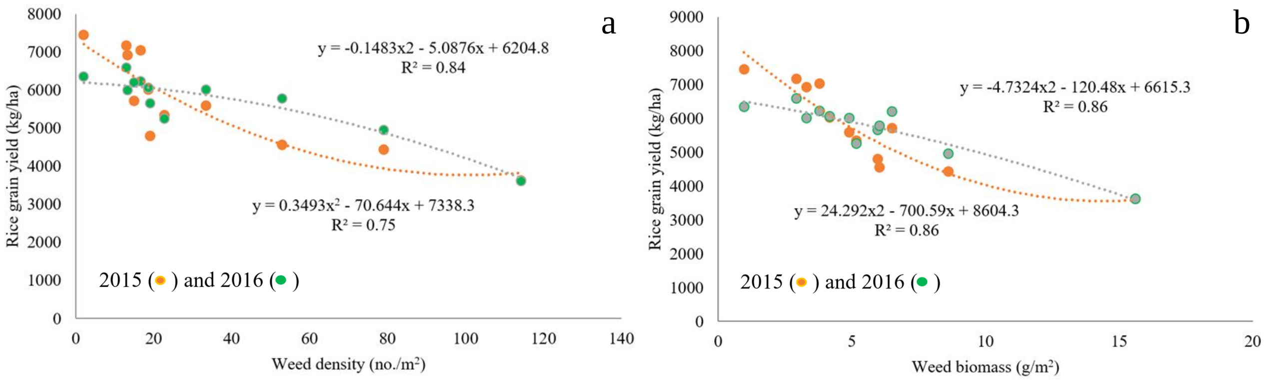

Figure 1. Effect of herbicide-based weed management practices at 45 DAT on a) weed density (m^2) and b) weed biomass (g/m^2) during 2015 and 2016

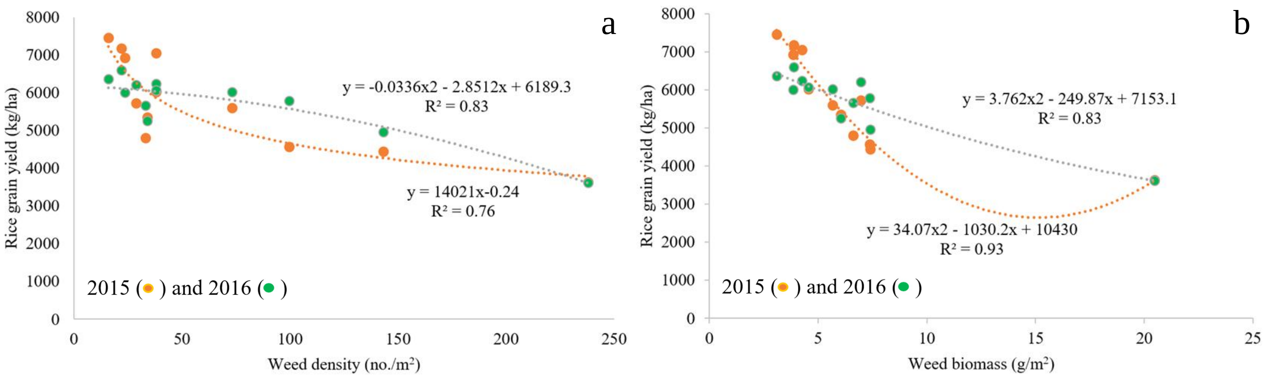

Figure 2. Effect of herbicide-based weed management practices at 75 DAT on a) weed density (per m^2) and b) weed biomass (g/m^2) during 2015 and 2016

Table 5. Economics of rice cultivation as influenced by different treatments in transplanted rice

Treatment	Cost of cultivation (x10^3 `/ha)	Gross returns (x10^3 `/ha)		Net returns (x10^3 `/ha)		B:C	
		2015	2015	2015	2016	2015	2016
Pyrazosulfuron 20 g/ha 2 DAT *fb* bispyribac-sodium 25 g/ha (25 DAT)	31.03	97.19	97.19	66.16	69.15	2.13	2.23
Fenoxaprop + 2,4-D (tank mix) 60 + 500 g/ha (25 DAT)	30.99	72.23	72.23	41.24	49.46	1.33	1.60
Pretilachlor + pyrazosulfuron (premix) 615 g/ha (6 DAT)	31.16	95.15	95.15	63.99	62.89	2.05	2.02
Pretilachlor + pyrazosulfuron (tank mix) 600+15 g/ha (6 DAT)	30.38	75.64	75.64	45.26	61.30	1.49	2.02
Bispyribac-sodium + 2,4-D (tank mix) 25 + 500 g/ha (25 DAT)	30.85	77.72	77.72	46.87	63.76	1.52	2.07
Fenoxaprop + chlorimuron + metsulfuron (tank mix) 60 + 4 g/ha (25 DAT)	31.05	65.00	65.00	33.95	55.57	1.09	1.79
Pendimethalin 1000 (2 DAT) *fb* bispyribac-sodium 25 g/ha (25 DAT)	31.66	93.45	93.45	61.79	59.76	1.95	1.89
Bispyribac-sodium 25 g/ha (25 DAT)	30.56	81.64	81.64	51.08	61.38	1.67	2.01
Pyrazosulfuron 20 g/ha (2 DAT)	29.63	61.71	61.71	32.07	58.06	1.08	1.96
Fenoxaprop 60 g/ha (25 DAT)	30.70	60.02	60.02	29.32	44.97	0.95	1.46
Hand weeding at 20 and 40 DAT	41.56	101.47	101.47	59.91	54.41	1.44	1.31
Weedy check	29.16	49.29	49.29	20.13	26.11	0.69	0.90
LSD (p=0.05)				14.96	9.45	0.48	0.30

(1US$=72 Indian Rupees at the time of study)

bispyribac-sodium in transplanted rice leads to better weed control for a longer duration, resulting in higher productivity and profitability. Moreover, the sequential application of herbicides helps in achieving higher net returns and B: C.

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RESEARCH ARTICLE

Effect of 2,4-D dose and formulation for brown manuring on weed dynamics, yield and economics in wet seeded rice

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ABSTRACT

Field experiments were conducted during 2021 and 2022 with twelve treatments on sandy clay loam soil in randomized block design (RBD), replicated thrice. The treatment consisted of rice co-culture with *Sesbania bispinosa* (*Sesbania*) and applied with different formulations of 2,4-D sodium salt, ethyl-ester and amine at varied levels (0.50, 0.75 and 1.0 kg/ha), hand weeding twice, weed free and unweeded control. Application of 2,4-D ethyl-ester 1.0 kg/ha proved effective in weed management by exhibiting significantly lower densities of grass (70.7/m^2), sedges (14.7/m^2), and broad-leaved weeds (0.0/m^2) with higher weed control efficiency of 74.3% at 60 DAS. Brown manuring through application of 2,4-D ethyl-ester 1.0 kg/ha led to higher grain yield (3.62 t/ha) and B:C ratio (2.03) and it was followed by 2,4-D sodium salt 1.0 kg/ha. Therefore, 2,4-D ethyl-ester 1.0 kg/ha can be recommended for effective brown manuring and eco-friendly weed management in rice, which would provide higher rice grain yield and B: C ratio. The next best treatment was rice co-culture with dhaincha and applied with 2,4-D sodium salt 1.0 kg/ha in wet seeded rice of deltaic coastal ecosystem.

Key words: Wet seeded rice, Brown manuring, *Sesbania*, 2,4-D formulations

INTRODUCTION

Rice (*Oryza sativa* L.) is the principal source of food for more than half of the world's population who depends for daily sustenance. India is the second largest producer and consumer of rice in the world, which occupies an area of 45.07 million hectares with the total production and productivity of 122.27 million tonnes and 2,713 kg/ha, respectively.

Rice is mostly grown as transplanted crop which demands high quantity of water along with various intercultural operations like land preparation, puddling, nursery raising, transplanting *etc*. and thus, increases cost of cultivation (Maity and Mukherjee 2009). Therefore, direct seeding of pre-germinated rice seeds can be a suitable alternative for transplanting and weeds control. Weed infestation in wet seeded rice can cause around 45-90% yield reduction (Saravanane and Chellamuthu 2016). Success of wet seeded rice depends on effective weed management strategy as well as better soil health. These twin objectives may be very well achieved through brown manuring. Rice and *Sesbania bispinosa* (*Sesbania*) also known as *Sesbania aculeata*, are co-cultured, and killed by spraying a selective post emergence (PoE) herbicide after 25-30 days of sowing (Tanwar *et al*. 2010). These *Sesbania* plants turn into brown colour due to knock down effect of the selective post-emergence herbicide and die, hence they are called brown manure plants. The dead plants are kept standing in the field without incorporating into the soil, allowing the residues of brown manure plants to fall and cover the soil surface as well as to decompose and add nutrients and organic carbon into the soil. This practice is mostly noticed in direct-seeded rice under the cases of both line sowing and broadcasting rather than in transplanted rice. Brown manuring is the zero tilled version of green manuring, one of the weed suppression and carbon farming approaches to manage weeds and sequester carbon. Brown manure can suppress or smother weeds by occupying land space and early accumulating dry matter or shading through greater canopy coverage. In general, herbicides hold the major role in the success of brown manuring and the use of post-emergence selective herbicides, *viz*. 2,4-D and bispyribac-sodium, in particular. Keerthi *et al*. (2022) revealed that knocking down of *Sesbania* using 2,4-D was found to be the best compared to use of bispyribac-sodium. However, very less research works has been carried out on the 2,4-D formulation and different doses used for brown manuring, Thus, keeping the above information, two season experiment were conducted to study the "Effect of 2,4-D dose and

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formulation for brown manuring on weed dynamics, yield and economics in wet seeded rice" at Karaikal, Puducherry, U.T.

MATERIALS AND METHODS

Field experiments were conducted under puddled condition at Pandit Jawaharlal Nehru College of Agriculture and Research Institute, Karaikal during June to October, 2021 and January to May, 2022. The experimental site was located at 10° 55′ North latitude and 79° 49′ East longitude and at an altitude of 4 m above the mean sea level. The soil has a sandy clay loam texture with a pH of 6.7 and EC 0.17 dS/m, respectively. The soil fertility status was low in available nitrogen (206.9 kg/ha), high in available phosphorus (29.7 kg/ha) and medium in available potassium (171.6 kg/ha), respectively. The experiment was carried out with twelve treatments, *viz.* 2,4-D sodium salt 0.50 kg/ha, 2,4-D sodium salt 0.75 kg/ha, 2,4-D sodium salt 1.0 kg/ha, 2,4-D ethyl-ester 0.50 kg/ha, 2,4-D ethyl-ester 0.75 kg/ha, 2,4-D ethyl-ester 1.0 kg/ha, 2,4-D amine 0.50 kg/ha, 2,4-D amine 0.75 kg/ha, 2,4-D amine 1.0 kg/ha, hand weeding twice at 15 and 30 DAS (farmer's practice), weed free and unweeded control in a randomized block design with three replications. Treatments from T_1 to T_9 were maintained uniformly with rice co-culture with *Sesbania* upto 28 DAS.

Pre-germinated rice seeds of *ASD 16* variety were sown in line by adopting a spacing of 15 x 10 cm. *Sesbania* seeds (25 kg/ha) were evenly broadcasted on the same day of rice sowing. 2,4-D formulations were sprayed on 28 days after sowing as per the treatment schedule. The field was irrigated one week after sowing and subsequent irrigations were given as and when needed depending on the soil moisture condition. A recommended dose of fertilizers (150:50:50 kg N:P:K/ha) was applied as urea, single superphosphate and muriate of potash, respectively. The entire quantity of phosphorus and half dose of K was applied as basal dose in all the plots. Nitrogen was applied in three splits (50%, 25% and 25%) at 15 DAS, maximum tillering stage and flowering stage, respectively. The remaining 50% of K was applied in two splits along with N at maximum tillering stage and flowering stage, respectively. Thrips were managed by spraying thiomethoxam 25% WG (0.4 g/L). Data on weed density were recorded at 60 DAS using quadrate of size 0.5 m x 0.5 m placed at two random places in each plot and the relative density (RD) was computed using standard formula. Weeds were cut at ground level during weed observation at 60 DAS, washed with running water, sun-dried, oven-dried at 70°C for 48 h, and then weighed to record weed biomass. Rice grain yield was measured from the net plot leaving the border rows and expressed in t/ha at 14% moisture content.The data on weed density and dry weight was transformed to square root transformation ($\sqrt{x+0.5}$) to normalize their distribution before analysis. Grain yield and weed biomass relationships at harvest were assessed using linear regression analysis. The experimental data were subjected to standard statistical analysis.

RESULTS AND DISCUSSION

Effect on weeds

The weed flora of the experimental field consisted of grasses (3 species), sedges (3 species) and broad-leaved weeds (6 species). Grasses made up the majority, representing 47.7% season and 44.2% during 2021 and 2022, respectively. Among grasses, *Leptochloa chinensis* (22.1%) was the most prevalent during and followed by *Echinochola crusgalli* (19.9%). *Cyperus difformis* (13.7 and 14.9%) and *Eclipta alba* (5.9 and 6.3%) were dominant among sedges and BLW's in both years, respectively (**Table 1**).

Formulations and doses of 2,4-D influenced the weed density (**Table 2**). 2,4-D ethyl-ester 1.0 kg/ha had the lowest grass weed density at 70.7/m^2 closely followed by 2,4-D sodium salt and 2,4-D amine, with grass weed densities of 85.3/m^2 and 86.7/m^2, respectively. The 2,4-D ethyl-ester treatment recorded lower densities of sedges (14.7/m^2) and broad-leaved weeds respectively. Effectiveness of 2,4-D ethyl-ester was attributed to the lipid-soluble nature of esters, facilitating quicker absorption through the plant's surface and inducing uncontrolled growth, leading to the demise of susceptible weed plants (Tanwar *et al.* 2010). Similar trend was observed with weed dry weight in both seasons. 2,4-D ethyl-ester 1.0 kg/ha significantly exhibited the lowest dry weight of grassy, sedges, broad-leaved and total weeds, respectively. This efficacy may be attributed to the suppression of *Sesbania* by ethyl-ester, which forms a residue mulch on the soil surface, hindering weed emergence by limiting sunlight and providing a physical barrier. Moreover, 2,4-D ester, being a selective herbicide, acidifies weed cell walls, inducing uncontrolled cell elongation, RNA, DNA, and protein synthesis, leading to excessive cell division and vascular tissue destruction, resulting in the death of susceptible broad-leaved weeds and sedges (Sraw *et al.* 2017) (**Table 2**). Among the brown manuring treatments, rice co-culture with *Sesbania* and applied with 2,4-D ethyl-ester 1.0 kg/ha recorded higher WCE of 74.3 per cent at different crop growth stages. Similar results of higher weed control efficiency were recorded by Datta *et al*. (2017). All the brown manuring practices lowered the total weed density at all the stages of crop growth which might be due to vigorously growing *Sesbania* that smothered and reduced the photosynthetic activity of weeds by intercepting light leading to greater reduction in weed interference (Anitha *et al*. 2012).

Effect on crop

Among the brown manuring treatments, 2,4-D ethyl-ester 1.0 kg/ha recorded better plant height (87.7 cm) and LAI (3.92) and rice yield (3.62 t/ha), and found to be on par with 2,4-D sodium salt 1.0 kg/ha, 2,4-D amine 1.0 kg/ha and 2,4-D ethyl-ester 0.75 kg/ha (**Table 3**). 2,4-D ethyl-ester 1.0 kg/ha gave 56% higher grain yield compared to unweeded control). This might be due to higher weed control efficiency, increased plant height, increased number of leaves/plant attributed to increase in the size of the photosynthetic area. Nawaz *et al*. (2017) reported that brown manuring supplied substantial amount of nitrogen which favoured in increasing leaf area and dry matter production. Maintaining weed free condition throughout crop growth recorded superior growth and higher rice yield (3.95 t/ha) whereas the unweeded control recorded a lower grain yield of 1.95 t/ha (**Table 3**). Effective controlling of weeds might have enhanced the availability of nutrients, soil moisture and other resources which in turn improving the growth and yield attributes of rice, which ultimately enhanced the grain and straw yield (Kumari and Kaur 2016). Significant negative correlation of weed dry weight was observed with grain yield (**Figure 1**). This might be due to decrease in the grain due to decrease control of weeds. Weed index (WI), is a measure of crop yield reduction due to weed competition in comparison to weed free. All the brown manuring treatments, substantially

Table 1. Weed floristic composition in the experimental field

Botanical name	Common name	Vernacular name	Family	Relative density (%) 2021	Relative density (%) 2022
Grasses					
Echinochloa colona Link.	Jungle grass	*Kudirai vali*	Poaceae	7.2	7.9
Echinochola crus-galli L.	Barnyard grass	*Koravampul*	Poaceae	18.4	19.9
Leptochloa chinensis (L.) Nees.	Chinese sprangletop	*Vakka pul*	Poaceae	22.1	16.4
Total grasses				47.7	44.2
Sedges					
Cyperus difformis L.	Variable flatsedge	*Vattakorai*	Cyperaceae	13.7	14.9
Cyperus iria L.	Ricefield flatsedge	*Pookorai*	Cyperaceae	5.8	6.2
Fimbristylis miliacea L.	Hoorah grass	-	Cyperaceae	10.4	10.6
Total sedges				29.9	31.7
Broad-leaved weeds					
Bergia capensis L.	Cape ash	*Nandukal keerai*	Elatinaceae	2.4	2.8
Eclipta alba (L.) Hassk	False daisy	*Karisilanganni*	Asteraceae	5.9	6.3
Hydrolea zeylanica (L.) Vahl	Ceylon hydrolea	*Vellel*	Hydrophyllaceae	4.6	5.3
Ludwigia perennis L.	Water primerose	*Neerkerambu*	Onagraceae	2.2	2.4
Marsilea quadrifolia L.	European waterclover	*Allakodi*	Marsileceae	2.8	3.6
Sphenoclea zeylanica Gaertn.	Goose weed	*Neer thipili*	Sphenocleaceae	4.5	3.7
Total broad-leaved weeds				22.4	24.1
Total no. of weeds				100%	100%

Table 2. Weed density and dry weight as influenced by brown manuring practices at 60 DAS in wet seeded rice (pooled data of 2 seasons)

Treatment	Grass weeds Density (no./m^2)	Grass weeds Dry weight (g/m^2)	Sedge weeds Density (no./m^2)	Sedge weeds Dry weight (g/m^2)	Broad-leaved weeds Density (no./m^2)	Broad-leaved weeds Dry weight (g/m^2)	Total weeds Density (no./m^2)	Total weeds Dry weight (g/m^2)
2,4-D sodium salt 0.50 kg/ha	10.67(113.2)	8.13(65.6)	8.00(64.0)	4.36(18.6)	4.10(16.3)	2.79(7.3)	13.9(193.5)	9.59(91.5)
2,4-D sodium salt 0.75 kg/ha	9.97(98.8)	7.82(60.6)	5.10(25.7)	2.72(6.9)	3.20(9.8)	2.34(5.0)	11.6(134.3)	8.54(72.6)
2,4-D sodium salt 1.0 kg/ha	9.23(85.3)	7.06(49.3)	3.97(15.3)	1.93(3.3)	0.70(0.0)	0.71(0.0)	10.1(100.7)	7.28(52.6)
2,4-D ethyl-ester 0.50 kg/ha	10.70(113.7)	7.55(56.7)	7.97(63.0)	4.34(18.4)	3.60(12.7)	2.58(6.2)	13.8(189.3)	9.04(81.3)
2,4-D ethyl-ester 0.75 kg/ha	9.83(96.0)	7.29(52.7)	4.60(20.8)	2.42(5.4)	2.47(5.8)	2.02(3.6)	11.1(122.7)	7.88(61.7)
2,4-D ethyl-ester 1.0 kg/ha	8.43(70.7)	6.14(37.3)	3.87(14.7)	2.01(3.6)	0.70(0.0)	0.71(0.0)	9.26(85.3)	6.43(40.9)
2,4-D amine 0.50 kg/ha	11.37(128.5)	8.13(65.6)	6.57(42.5)	3.59(12.4)	4.50(19.8)	2.97(8.3)	13.8(190.8)	9.32(86.3)
2,4-D amine 0.75 kg/ha	10.70(113.8)	7.79(60.2)	4.10(16.3)	2.10(4.0)	3.50(12.0)	2.51(5.8)	11.9(142.2)	8.39(70.0)
2,4-D amine 1.0 kg/ha	9.33(86.7)	7.31(53.0)	4.00(15.5)	1.94(3.3)	0.70(0.0)	0.71(0.0)	10.1(102.2)	7.53(56.3)
Hand weeding twice	6.77(45.2)	6.90(47.1)	9.67(92.8)	5.25(27.1)	7.23(51.8)	4.38(18.7)	13.8(189.8)	9.67(93.0)
Weed free	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)	0.71(0.0)
Unweeded control	13.83(192.2)	9.51(90.0)	11.33(128.0)	6.17(37.6)	9.83(96.3)	5.66(31.6)	20.4(416.2)	12.63(159.2)
LSD(p=0.05)	0.47	0.38	0.46	0.25	0.41	0.20	0.55	0.36

Figures in parentheses are original values, Data were subjected to square root transformation ($\sqrt{x+0.5}$)

Table 3. Growth, yield and B:C ratio influenced by brown manuring practices in wet seeded rice

Treatment	Plant height (cm)	LAI	Grain yield (t/ha)			Weed index	Net returns (`/ha)	B:C ratio
			2021	2022	Pooled			
2,4-D sodium salt 0.50 kg/ha	81.8	2.54	2.73	3.40	3.07	22.6	25507	1.78
2,4-D sodium salt 0.75 kg/ha	83.7	2.73	2.80	3.37	3.08	22.1	25634	1.78
2,4-D sodium salt 1.0 kg/ha	85.0	3.43	3.10	3.63	3.37	14.9	30992	1.94
2,4-D ethyl-ester 0.50 kg/ha	80.2	2.33	2.50	2.77	2.63	33.4	16978	1.51
2,4-D ethyl-ester 0.75 kg/ha	84.1	3.33	2.60	2.90	2.75	30.5	19041	1.57
2,4-D ethyl-ester 1.0 kg/ha	87.7	3.92	3.50	3.73	3.62	8.5	34759	2.03
2,4-D amine 0.50 kg/ha	77.5	2.45	2.30	2.97	2.63	33.6	17228	1.52
2,4-D amine 0.75 kg/ha	81.3	3.15	2.50	3.20	2.85	28.1	21100	1.64
2,4-D amine 1.0 kg/ha	84.7	3.43	3.03	3.47	3.25	17.8	28558	1.86
Hand weeding twice	84.4	3.02	2.97	3.43	3.20	19.1	21192	1.53
Weed free	89.4	4.18	3.80	4.10	3.95	0.0	11050	1.18
Unweeded control	75.9	1.92	1.80	2.10	1.95	50.7	6625	1.22
LSD (p=0.05)	4.28	0.64	0.42	0.81	0.44	-	-	-

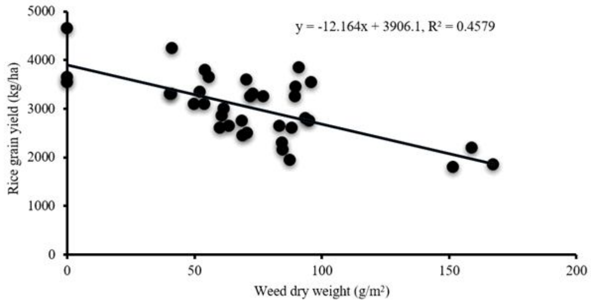

Figure 1. Relationship between grain yield and weed dry weight in wet seeded rice (pooled mean)

reduced the competition by weeds and thus registered lower weed index. Among the brown manuring treatments, 2,4-D ethyl-ester 1.0 kg/ha recorded lower weed index (8.5) followed by 2,4-D sodium salt 1.0 kg/ha, 2,4-D amine 1.0 kg/ha. However, higher weed index was recorded under unweeded control (50.7%).

Economics

Managing the weeds enhanced the net return and B:C ratio as compared to unweeded control. Among the brown manuring treatments, the maximum net return (₹ 34759/ha) and the B:C ratio (2.03) were obtained in 2,4-D ethyl-ester 1.0 kg/ha followed by 2,4-D Na salt 1.0 kg/ha (₹ 30992/ha) and B:C ratio (1.94). This may be due to higher grain yield obtained due to effective suppression of weed growth and less cost of cultivation. These findings are in line with Tanwar *et al*. (2010). Significantly lower net return was obtained under unweeded control ₹ 6625/ ha). Lower B:C ratio (1.18) was recorded weed free condition due to utilization of more labours for weeding, which lead to higher cost of cultivation (Anitha *et al.* 2012).

Conclusion

Thus, it was concluded that rice co-culture with *Sesbania* and applied with 2,4-D ethyl-ester 1.0 kg/ha was effective in minimizing weed population, weed dry weight, crop weed competition and enhancing crop growth, grain yield and economics. In case of non-availability of 2,4-D ethyl-ester, other promising formulation of 2,4-D sodium salt 1.0 kg/ha can be used in wet seeded rice.

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RESEARCH ARTICLE

Weed suppression and productivity influenced under conservation agriculture and organic weed management practices in rice-maize rotation

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ABSTRACT

Weeds pose a significant threat to crop productivity, and ineffective management can exacerbate the issue. Therefore, it is crucial to reduce weed severity to maintain and enhance crop productivity. With this aim, a field study was conducted at Dr. Rajendra Prasad Central Agricultural University to evaluate the impact of organic weed management (OWM) on the weed dynamics and yield of rice–maize rotation under conservation agriculture. Four tillage practices as main plots and five OWM treatments as subplots arranged in split-plot design with three replications. The tillage management treatments included ZTR *fb* ZTM: zero-tillage (ZT) direct-seeded rice (DSR) followed by (*fb*) ZT-maize, PBDSR+R *fb* PBDSM+R: DSR *fb* maize both in permanent bed (PB) with residue retention, PBDSR-R *fb* PBDSM-R: DSR *fb* maize both in PB without residue retention and CTR *fb* CTM: conventionally tilled rice *fb* maize. In OWM, five treatments were as follows: UWC: unweeded check, VM: vermicompost mulching, PVM: phosphorous (P) enriched VM, LM: live-mulch of *Sesbania* spp. in rice and *Pisum sativum* in maize, WFC: weed-free check. PBDSR+R *fb* PBDSM+R recorded significantly lowest weed biomass and highest weed control efficiency over other treatments in both the years. Except weed free treatment, LM reported significantly higher yield attributes and grain yield of rice and maize over other OWM practices across the two years of study. The PBDSR+R *fb* PBDSM+R recorded significantly highest grain yield of rice (6.3, 6.6 t/ha) and maize (9.3, 9.4 t/ha) throughout the study. The study revealed that residue incorporation under rice–maize rotation with permanent bed system along with LM improved the weed control efficiency, yield attributes and yield.

Keywords: Conservation tillage, Maize, Organic weed management, Permanent bed, Residue, Rice, Weed control efficiency

INTRODUCTION

Rice-based cropping systems are prevalent in the Eastern regions of India. However, in continuous intensive tillage and chemical weed management systems, yield and productivity of rice-maize rotation is declining consistently (Roy *et al*. 2023). This decline is associated with the deterioration of soil physicochemical properties and a increase in weed density. Furthermore, weeds pose a significant challenge to rice (*Oryza sativa* L.) and maize (*Zea mays* L.) production, leading to a considerable decrease in crop yield ranging from 24 to 65% . In Eastern India specifically, the yield loss is even more pronounced, falling within the range of 32 to 46% (Duary *et al*. 2021). Recently, most crop producers have transitioned to herbicide-based weed management strategies due to their effectiveness, ease of use, and reduced manpower requirements compared to traditional cultural and mechanical methods. However, relying solely on herbicides for weed control can create herbicide selection pressure, leading to the emergence of herbicide-resistant weed species (Kumar *et al*. 2023). Low-input or organic production systems offer an alternative to conventional methods for addressing current challenges in crop production in Eastern India. These systems reduce reliance on synthetic external inputs, instead depending on ecological and natural processes to maintain crop productivity and ensure crop protection.

To address the issue of climate change, soil health degradation, and challenges related to water, energy, and labor shortages in rice-based cropping system, the adoption of conservation agriculture (CA) practices, notably zero tillage (ZT), no-tillage (NT), and minimum tillage (MT) can be a viable solution (Alhammad *et al*. 2023). The global acceptance and popularity of CA have grown

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significantly in recent years. Several studies suggest that ZT not only contributes to reduced fuel consumption but also results in lower production costs and higher net income as compared to conventional tillage (CT) (Stanzen *et al*. 2017). Studies have shown that the adoption of ZT coupled with crop residue retention decreased weed biomass and enhance yields compared to CT across various crops (Ghosh *et al*. 2022). Traditional tillage practices expose old and dormant weed seeds to suitable light and ambient climatic conditions, promoting their germination and contributing to a higher weed population (Dayal *et al*. 2023). Conversely, CA practices often create conditions unfavorable for weed germination, effectively reducing weed populations (Travlos *et al.* 2020).

To address the limitations of an intensive herbicide system, conventional farmers are now turning to organic production methods, necessitating a grasp of fundamental organic farming principles. Organic weed management (OWM) has emerged as a practice that integrates traditional approaches with modern innovation and science. Its significance has grown in response to the escalating demand for alternative, healthy food sources, while also prioritizing soil health and ecosystem conservation (Herzog *et al*. 2019). OWM emphasizes key components of effective weed management, incorporating cultural and mechanical methods such as mulching, crop residue utilization, and the application of compost extracts (Mhlanga *et al*. 2015). Mulching, in particular, has proven to be a dependable method for managing the agroecosystem, simultaneously addressing environmental concerns associated with weed management (Rhioui *et al*. 2023). Retaining crop residues of live plant as mulch can inhibit weed germination and establishment and contributes to enhanced crop productivity (Choudhary 2023). While vermicompost is recognized for enhancing soil organic matter decomposition, improving soil structure, and enhancing aeration and moisture retention (Rehman *et al*. 2023), it has been observed that using vermicompost as mulch effectively controls weeds. Additionally, this practice enriches the soil with nutrients, ensuring sustained crop yield without compromising soil health (Ganguly *et al.* 2022).

Weed dynamics can vary significantly under different tillage and crop establishment systems due to the complex interactions between weeds and tillage practices. To address these challenges, CA-based sustainable intensification of the rice-maize system utilizing ZT, surface residue retention, and use of organic sources along with inorganic source of nutrients has been identified as an effective approach. However, very few research data are available on the dynamics of major weeds under CA systems with OWM practices. The hypothesis proposed that CA based practices, mulching through organic amendment and live plant could be employed to suppress weeds and enhance productivity. Consequently, this study aimed to investigate the effects of tillage combined with crop residue mulching on soil surface coverage, weed suppression, crop productivity, and the weed seed bank within a maize-rapeseed cropping system. Keeping all the above facts in view, an attempt was made to compare the effect of CT and CA based crop establishment with OWM practices on weed dynamics, and yield of rice-maize in Eastern India.

MATERIALS AND METHODS

The field experiment was conducted for two years during the summer and winter seasons of 2019-20 and 2020-21 at the Crop Research Centre of Dr. Rajendra Prasad Central Agricultural University (20º 58' 49.0'' N latitude, 85º 40' 33.41'' E longitudes, at an altitude of 173 m above the mean sea level), Pusa, Bihar, India. The climate of the experimental site is characterized by a hot sub-humid eco-region that experiences cold and dry winters and hot and humid summers. This investigation is consisted of four main treatments and five sub-treatments in a split-plot design with three replications. The main plot treatments consisted of zero-tillage direct seeded rice and zero-tillage maize (ZTR *fb* ZTM); ZTDSR and maize both on permanent raised beds with residue retention (PBDSR+R *fb* PBDSM+R); PBDSR and PBM without residue retention (PBDSR-R *fb* PBDSM-R) and conventional tillage puddled transplanted rice and conventional tillage maize (CTR *fb* CTM). 50 % rice residue retention for maize, 25% maize residue retained on the soil surface for rice in PB and ZT treatments. All the remaining 50% rice and 75% maize residues were utilized as fodder for cattle. The subplots comprised unweeded control (UC); vermicompost mulch (VM) at the rate of 5 t/ha before sowing/transplanting; P- enriched vermicompost mulch (PVM) at the rate of 5 t/ha before sowing/ transplanting; live mulch (LM) with *Sesbania* spp. in rice and *Pisum sativum* in maize and weed-free (WF). In LM treatment, seeds of *Sesbania* spp. and *Pisum sativum* were broadcast at a seeding rate of 40 kg/ha. After 30 days of live mulching, the mulched plants were turned down on the soil and left as mulch cover. The nutrient content of the *Sesbania* spp. used in the experiment was 3.5% N, 0.6% P, and 1.2% K, while *Pisum sativum* contained 0.9% N, 0.3% P, and 0.4% K. Furthermore, the physicochemical composition of the vermicompost was 2.21, 1.11, and 1.25% N, P, and K, respectively whereas in P-enriched vermicompost it was 2.30, 1.23, and 1.37% N, P and K, respectively.

The study was conducted on a gross plot size of 7.0 × 3.6 m with a net plot size of 6.0 × 2.6 m during each year in the same plot. Rice cv. Rajendra Mahsuri was sown with seed rates of 25 kg/ha, 20 kg/ha and 12 kg/ha under ZTR, PBDSR, and conventional treatments, respectively. Winter maize cv. DKC 9081 was sown with a uniform seed rate of 25 kg/ha in all the treatments. ZT and PB rice was sown on June 8, 2019, and June 3, 2020, and harvested on November 23, 2019, and November 15, 2020, respectively. In contrast, CT rice was sown on June 30, 2019, and June 27, 2020, and harvested on November 25, 2019, and November 18, 2020. Whereas, maize crops were sown on December 5, 2019, and November 27, 2020, and harvested on May 22, 2020, and May 7, 2021. During the growing season, monsoon rice received a dose of N: P: K: Zn - 150: 26: 17.5: 10 kg/ha and winter maize received a dose of N: P: K: Zn-200:35:26:10 kg/ha. During both years, 50% N and whole P, K, and Zn were applied as basal fertilizer using di-ammonium phosphate, muriate of potash, and zinc sulphate heptahydrate applied with seed cum-fertilizer drills. During tillering and panicle initiation in rice and V5 and VT phases in maize, the remaining N was applied as urea in two equal splits. Weed biomass of total weeds was taken by placing a quadrat of 50 × 50 cm (0.25 m^2) randomly in the sampling area. At 30 days after sowing (DAS), the weeds were uprooted, cleaned by washing, placed in sunlight for few hours and were kept in a hot air oven for drying at 70 °C for 72 hours or more till constant weights were recorded. Weed control efficiency (WCE) (%) was then computed based on weed density as formulated by Mani *et al.* (1973):

Weed control efficiency (%) =(WDc - WDt)/WDc×100

Where, WDc is weed density of unweeded control

WDt is weed density in the treated plot under consideration

The weed index (WI) (%), otherwise known as the weed competition index, is the yield reduction caused by the presence of weeds relative to the weed-free plot. The formula was used to compute the weed index as given by Gill and Vijaykumar (1969):

Weed Index (WI) (%) = (Ww - Wt)/Ww×100

Where, Ww is the grain yield of a weed-free plot

Wt is grain yield from the treated plot

Ten random plants were selected plants for measurements of all yield attributes of rice-maize rotation. Grain yields (t/ha) were assessed from a 10 m^2 sampling area at the center of each subplot. Grain yield was recorded at 14% moisture content.

The weed biomass data underwent a square root transformation, and the transformed data were employed for analysis. The statistical analysis was conducted using R-3.6.3, employing a split plot design at a significance level of 5%. as given by Gomez and Gomez (1984).

RESULT AND DISCUSSION

Weed flora and biomass

During two years of study, the experimental field was infested with *Dinebra retroflexa* (Vahl.), *Cyperus rotundus* (L.) *Digitaria sanguinalis* (L.) Scop., *Echinochloa colona* (L.) Link., *Eclipta alba* (L.), *Gnaphalium indicum* (L.), *Polygonum plebeium* R.Br., *Solanum nigrum* (L.) and *Sphaeranthus indicus* (L.) as major weeds. However, *Convolvulus arvensis* (L.), *Alternanthera sessilis* (L.) and *Eleusine indica* (L.) also recorded as minor weeds under rice-maize rotation.

Among the tillage and residue management methods, significantly lower weed biomass (2.8, 2.5 g/m^2 average of two years) was recorded in with PBDSR-R *fb* PBDSM-R in both rice and wheat, respectively (**Figure 1**). This might be because of residue retention in PB that significantly suppressed the weed seed germination and emergence in PBDSR-R *fb* PBDSM-R, which ultimately resulted in lower weed biomass. Choudhary and Sharma (2023), Ghosh *et al.* (2022) also observed reduction in total weed density and biomass under CA-based practices. Weed free treatment recorded minimum weed biomass but LM practices recorded significantly lower weed biomass of 2.7 and 2.3 g/m^2 over the others OWM practices during both the years of experimentation. This might be due to better weed control by live mulching that favoured crop growth, which resulted in quick coverage of ground and more shading affect by crop thereby reducing growth of weeds. Moreover, mulching smothers weeds by blocking light and creating a physical barrier that prevents their germination and emergence (Bahadur *et al.* 2015, Jaiswal *et al.* 2023).

Weed control indices

The WCE differed according to treatments during the study period (**Table 1**). Among the various residue and tillage management practices in rice, the

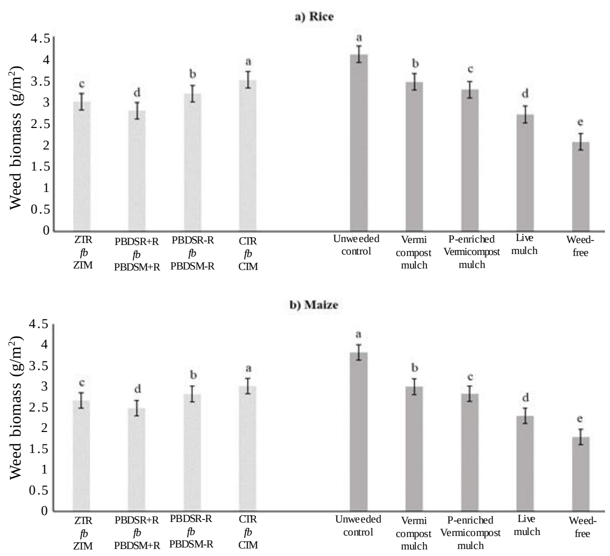

Figure 1. Weed biomass (g/m²) at 30 DAS (combined data of 2 years) of rice (a) and maize (b) as affected by tillage, residue, and organic weed management practices. Treatment means followed by the unlike lower-case letters are significantly diverse at $\sqrt{x+0.5}$ levels of significance as per Duncan's multiple range test.

PBDSR+R *fb* PBDSM+R showed 2.5 and 4.8% higher WCE relative to CTR *fb* CTM across the years respectively but the lowest WCE was recorded with PBDSR-R *fb* PBDSM-R. Whereas, in the case of maize during 2019-20 highest WCE was obtained with ZTR *fb* ZTM but during 2020-21 maximum WCE was recorded with PBDSR+R *fb* PBDSM+R. Likewise in maize, CTR *fb* CTM recorded 7.4 and 10.7% lower WCE relative to PBDSR+R *fb* PBDSM+R during 2019-20 and 2020-21 respectively. Apart from weed-free treatment, the highest WCE was found with live mulch in rice, which was 52.5 and 54.6% more relative to P-enriched vermicompost mulch across the years respectively. A similar was witnessed in maize.

WI was found maximum with CTR *fb* CTM in rice-maize rotation. However, during the first year (2019) of rice, ZTR *fb* ZTM recorded minimum WI but in the second year (2020) minimum WI was observed in PBDSR+R *fb* PBDSM+R treatment. Across the years of field experiments in maize, the minimum weed index was recorded with PBDSR+R *fb* PBDSM+R (2.17 and 2.04, respectively) (**Table 1**). Under various organic weed management regimes in rice-maize rotations, WI was found highest in unweeded control for both years of the experiment. Live mulch recorded 75.2 and 58.5% lower WI than vermicompost mulch in rice for 2019 and 2020 respectively. Additionally in maize, the live mulch recorded 96.9, 83.5 and 66.3% lower WI relative to unweeded control, vermicompost mulch, and P-enriched vermicompost mulch treatment respectively during the 2019-20. A similar trend was witnessed in the second year (2020-21) in maize.

This results proved that tillage exposes weed seed on the upper layer of the soil and enable seedlings to emerge from deeper in the soil, which may account for a higher weed population than un-tilled soil (Alhammad *et al.* 2023). Choudhary and Sharma (2023) also noted the highest WCE in ZT+R than CT. In our experiments, different organic weed management strategies were tested, among them *Sesbania* and *Pisum* as live mulch were able to provide, within a short period, a long-lasting soil cover (Mishra *et al*. 2022). Similar findings were consistent with Chetan *et al.* (2023).

Table 1. Weed control indices in rice-maize rotation in response to tillage and residue management practices and organic weed management in rice-maize rotation

Treatment	WCE (%)		WI (%)		WCE (%)		WI (%)	
	2020	2021	2020	2021	2019-20	2020-21	2019-20	2020-21
Tillage and residue management								
ZTR *fb* ZTM	46.27	47.87	14.81	16.77	37.69	38.00	4.06	3.39
PBDSR+R *fb* PBDSM+R	46.87	49.90	15.97	15.77	36.79	38.74	2.17	2.04
PBDSR-R *fb* PBDSM-R	43.05	45.75	15.58	17.85	34.90	35.20	4.45	4.04
CTR *fb* CTM	42.97	46.03	19.05	21.84	31.96	32.08	4.69	4.93
LSD (p=0.05)	-	-	-	-	-	-	-	-
Organic weed management								
Unweeded control	0.00	0.00	53.94	53.13	0.00	0.00	49.26	48.08
Vermicompost mulch	27.81	29.92	17.24	16.62	28.85	29.15	9.29	8.60
P- enriched Vermicompost mulch	35.53	38.54	6.30	13.65	37.56	37.67	4.55	4.08
Live mulch	47.79	51.23	4.27	6.89	50.15	51.37	1.53	1.73
Weed-free	68.03	69.87	0.00	0.00	60.12	61.83	0.00	0.00
LSD (p=0.05)	-	-	-	-	-	-	-	-

ZTR-Zero tillage rice followed by zero tillage maize; PBDSR+R *fb* PBDSM+R- DSR *fb* maize both in permanent bed (PB) with residue retention; PBDSR-R *fb* PBDSM-R-DSR *fb* maize both in PB without residue retention; CTR *fb* CTM- Conventionally tilled rice *fb* maize

Crop yield attributes and yield

Rice: Tillage, residue, and weed management had a substantial influence on yield characteristics and yield of rice over the two-year experimental period (**Table 2**). The PBDSR+R *fb* PBDSM+R treatment consistently had the highest number of panicles/m², with values of 404.8 and 430.7 throughout the two years. Among the various organic weed management strategies, weed-free treatment had the utmost number of panicles/m² in 2019 and 2020, which was statistically at par with the application of live mulch. Similarly, panicle length, panicle weight, number of filled grains/panicle, and test weight were uppermost in PBDSR+R *fb* PBDSM+R and minimum in CTR *fb* CTM. Additionally, in weed management treatments, the number of filled grains/panicle was recorded maximum *i.e.* 114.3 and 118.8 with weed-free treatment and was statistically the same with live mulch during both years respectively. A similar trend was observed in panicle weight, panicle length, and test weight for both years. In a long term application of CA practices with integrated weed management practices resulted in higher yield attributes in rice under the PB with legume residue than no-residue, and this might be due to better soil health and microenvironment created by the continuous adoption of these resources conserving practice (Kumar *et al.* 2024, Ganapathi *et al.* 2023).

Moreover, the maximum grain yield of 6.36, 6.60 t/ha during the both the years respectively was achieved in PBDSR+R *fb* PBDSM+R (**Table 2**). The findings of Kumar *et al.* (2023) and Roy *et al.* (2023) are also in agreement with it. Amongst the weed management options, unweeded treatment recorded the minimum grain yield during both years. The weed-free treatment showed highest grain yield among weed management strategies and was statistically similar with live mulch. Furthermore, the live mulch had 16.0 and 12.3% greater grain yield than vermicompost mulch respectively. This might be due to lower crop weed competition for growth resources throughout the crop growing period enabling the crop for maximum utilization of nutrients, moisture, light and space, which enhanced the vegetative and reproductive potential of the crop (Stanzen *et al.* 2017).

Maize: Yield attributes and yield of maize were affected by tillage and organic weed management strategies across the years. The result revealed that cob circumference, cob length, and cob weight were found to be maximum with bed planting of rice with retention of crop residues (PBDSR+R *fb* PBDSM+R) and was statistically the same with ZTR *fb* ZTM and PBDSR-R *fb* PBDSM-R during both years of study. During the first year of the experiment, the number of grains/cob, the weight of grains/cob and test weight was recorded maximum in PBDSR+R *fb* PBDSM+R *i.e.* 462.8, 65.9g, and 28.57g which was 9.3, 7.0 and 5.8% higher than PBDSR-R *fb* PBDSM-R respectively (**Table 3**). The CTR *fb* CTM recorded 11.0, 16.5, and 9.8% lower weight of grains/cob, number of grains/cob, and test weight in comparison to PBDSR+R *fb* PBDSM+R respectively during the year 2020-21. ZT and PB which improves the physical and chemical qualities of the soil, that may greatly impact on root development, is likely to give similar or even higher yield attributes than CT. These findings were in agreement with Dayal *et al.* (2023) and Parihar *et al.* (2016).

Table 2. Yield attributes and grain yield of rice as affected by tillage, residue, and organic weed management in rice

Treatment	No. of panicles/m²		Panicle length (cm)		No. of filled grains/panicle		Test weight (g)		Grain yield (t/ha)	
	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
Tillage and residue management (T)										
ZTR *fb* ZTM	392.7^{a}	416.9^{a}	23.6^{a}	24.2^{ab}	101.7^{a}	104.4^{a}	21.13^{b}	21.50^{b}	5.70^{b}	6.18^{b}
PBDSR+R *fb* PBDSM+R	404.8^{a}	430.7^{a}	24.2^{a}	25.3^{a}	107.4^{a}	110.3^{a}	22.99^{a}	23.30^{a}	6.36^{a}	6.60^{a}
PBDSR-R *fb* PBDSM-R	372.1^{a}	403.7^{a}	22.6^{a}	23.2^{b}	88.2^{b}	90.4^{b}	20.73^{bc}	21.17^{bc}	5.52^{b}	5.74^{c}
CTR *fb* CTM	332.5^{b}	346.0^{b}	19.6^{b}	20.2^{c}	78.5^{c}	80.5^{c}	19.74^{c}	20.04^{c}	4.90^{c}	4.76^{d}
LSD (p=0.05)	34.5	32.9	2.1	1.4	9.3	9.1	1.12	1.37	0.43	0.38
Organic weed management (W)										
Unweeded control	240.6^{d}	256.3^{c}	17.3^{d}	17.8^{c}	63.5^{d}	63.8^{d}	19.71^{b}	20.06^{d}	3.08^{d}	3.31^{d}
Vermicompost mulch	381.5^{c}	400.6^{b}	21.1^{c}	22.2^{b}	90.6^{c}	94.6^{c}	21.10^{a}	21.15^{bcd}	5.56^{c}	5.92^{c}
P- enriched Vermicompost mulch	398.1^{bc}	416.1^{b}	23.0^{b}	23.9^{b}	96.6^{c}	97.2^{c}	21.23^{a}	21.57^{ac}	6.31^{b}	6.14^{c}
Live mulch	424.2^{ab}	458.8^{a}	25.0^{a}	25.5^{a}	104.7^{b}	107.5^{b}	21.68^{a}	22.26^{ab}	6.45^{ab}	6.65^{b}
Weed-free	433.2^{a}	464.8^{a}	26.2^{a}	26.9^{a}	114.3^{a}	118.8^{a}	22.02^{a}	22.48^{a}	6.71^{a}	7.09^{a}
LSD (p=0.05)	28.7	27.4	1.7	1.6	8.0	7.6	0.93	1.14	0.36	0.31
T×W										
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	S	S

Treatment means followed by the unlike lower-case letters are significantly diverse at $\sqrt{x+0.5}$ levels of significance as per Duncan's multiple range test, NS: non-significant, S: significant

In weed management practices, the weed-free treatment showed the highest cob length (19.61 cm), cob circumference (18.15 cm), and cob weight (159.8 cm) which was on par with live mulch in the year 2019-20. Similarly, in the second year 40.1, 16.8 and 10.2 % higher cob length, cob circumference, and cob weight were found in weed-free treatment than in unweeded control, vermicompost mulch, and P-enriched vermicompost mulch respectively. Additionally, the weight of grains/cob, the number of grains/cob, and test weight were found highest in weed-free treatment. Among the other treatments except for weed-free, was found highest with the application of live mulch which recorded 105.4, 39.0, and 31.1 % higher weight of grains/cob, number of grains/cob, and test weight in the first year and 38.1, 106 and 31% in the second year relative to unweeded control respectively (**Table 3**).

Among tillage and residue management practices, CTR *fb* CTM recorded lowest grain yield of 7.95, 8.04 t/ha during the two years of study respectively; whereas, PBDSR+R *fb* PBDSM+R which showed maximum grain yield of 9.30, 9.43 t/ha respectively. The ZTR *fb* ZTM showed 11.3, 12.2% higher grain yield than CTR *fb* CTM and was on par with PBDSR+R *fb* PBDSM+R (**Table 3**). The lowest grain yield was found with unweeded control and maximum in weed-free treatment. The weed-free treatment recorded grain yield of 9.80 and 9.90 t/ha respectivly but was found statistically similar to P-enriched vermicompost mulch and live mulch. The findings of this study showed the paybacks of shifting from flats to permanent bed systems coupled with residue retention. This might be due to low weed density during the initial crop growth stage (30 DAS) in these treatments. Conventional and zero tillage treatments with residue retention resulted in higher values of yield attributes. This could be due to sustaining optimum soil moisture, improved nutrient availability, and moderate soil temperature. The raised bed may have led to effective control of irrigation and drainage, reducing the short-term temporary aeration stress under high rainfall conditions. The higher yield attributes in weed-free could be accredited to increased soil temperature, effective weed control, and better soil moisture conservation (Dayal *et al.* 2023) The lower grains per cob in the unweeded control may be ascribed to increased interspecific competition and weed infestation. Similarly, a field experiment conducted at Ludhiana (India), found about 25% higher grain yield with a PB planting of maize than flat sowing (Kaur and Mahey 2012). Straw mulch increases soil moisture storage and productivity (Verma and Acharya 2004, Jaiswal *et al.* 2023). Higher soil water content improves yield with mulching (Paswan *et al.* 2023).

In the second year of maize, grain yield had a negative correlation (R^2=-0.87) with weed biomass (**Figure 2**). The yield attributes of maize were significantly positively corelated with grain yield. Whereas, higher weed biomass resulted in lower yield as yield attributes were negetavively corelated with weed biomass. Chauhan and Opena (2013) also noted a direct association between weed biomass and rice grain yield at harvest under direct-seeded conditions. This showed that effective and timely weed management through the OWM practices reduced the weed dry matter accumulation of various weed

Table 3. Yield attributes and grain yield of maize as influenced by tillage, residue, and organic weed management in maize

Treatment	Cob length (cm)		Cob weight (g)		Cob circumference (cm)		No. of grains/ cob		Weight of grains/cob (g)		Test weight (g)		Grain yield (t/ha)	
	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21	2019-20	2020-21
Tillage and residue management (T)														
ZTR *fb* ZTM	18.32^{ab}	18.45^{ab}	146.8^{ab}	148.6^{a}	15.75^{ab}	16.04^{ab}	444.9^{ab}	453.2^{ab}	64.0a^{b}	64.5a^{b}	27.35a^{b}	28.51a^{b}	8.85^{a}	9.02^{a}
PBDSR+R *fb* PBDSM+R	18.89^{a}	19.15^{a}	151.1^{a}	152.2^{a}	16.24^{a}	16.54^{a}	462.8^{a}	470.5^{a}	65.9^{a}	66.7^{a}	28.57^{a}	29.78^{a}	9.30^{a}	9.43^{a}
PBDSR-R *fb* PBDSM-R	17.59^{ab}	17.86^{abc}	137.5^{bc}	138.8^{b}	14.91^{bc}	15.25^{b}	423.4^{b}	431.5^{b}	61.6a^{bc}	61.9^{bc}	26.99^{abc}	28.14^{abc}	8.08^{b}	8.19^{b}
CTR *fb* CTM	16.64^{c}	16.81^{c}	135.5^{c}	137.0^{b}	13.94^{c}	14.16^{c}	385.5^{c}	392.7^{c}	58.2^{c}	59.3^{c}	25.77^{c}	26.86b^{c}	7.95^{b}	8.04^{b}
LSD (p=0.05)	1.3	1.4	10.6	9.1	0.97	0.91	28.7	27.6	4.6	4.2	1.73	1.80	0.64	0.57
Organic weed management (W)														
Unweeded control	14.03^{d}	14.22^{d}	114.0^{c}	112.8^{d}	11.61^{d}	11.83^{d}	339.5^{d}	346.3^{d}	36.6^{d}	36.9^{d}	22.30^{d}	23.25^{d}	5.00^{d}	5.17^{d}
Vermicompost mulch	17.72^{c}	17.93^{c}	136.8^{b}	138.3^{c}	13.04^{c}	13.29^{c}	413.6^{c}	421.5^{c}	57.9^{c}	58.6^{c}	26.17^{c}	27.28^{c}	8.90^{c}	9.06^{c}
P-enriched vermicompost mulch	18.47^{bc}	18.68^{abc}	145.0^{b}	148.0^{b}	15.86^{b}	16.16^{b}	437.6^{b}	445.9^{b}	63.8^{b}	64.8^{b}	27.85^{b}	29.03^{b}	9.36^{abc}	9.49^{abc}
Live mulch	19.49^{ab}	19.71^{ab}	158.0^{a}	159.4^{a}	17.39^{a}	17.73^{a}	471.8^{a}	478.4^{a}	75.2^{a}	76.0^{a}	29.24^{ab}	30.48^{ab}	9.66^{ab}	9.73^{ab}
Weed-free	19.61^{a}	19.80^{a}	159.8^{a}	162.3^{a}	18.15^{a}	18.48^{a}	483.4^{a}	492.8^{a}	78.7^{a}	79.3^{a}	30.30^{a}	31.59^{a}	9.80^{a}	9.90^{a}
LSD (p=0.05)	1.1	1.2	8.8	7.6	0.81	0.76	23.9	22.9	3.8	3.5	1.44	1.50	0.53	0.48
T×W														
LSD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Treatment means followed by the unlike lower-case letters are significantly diverse at $\sqrt{x+0.5}$ levels of significance as per Duncan's multiple range test, NS: non-significant, S: significant

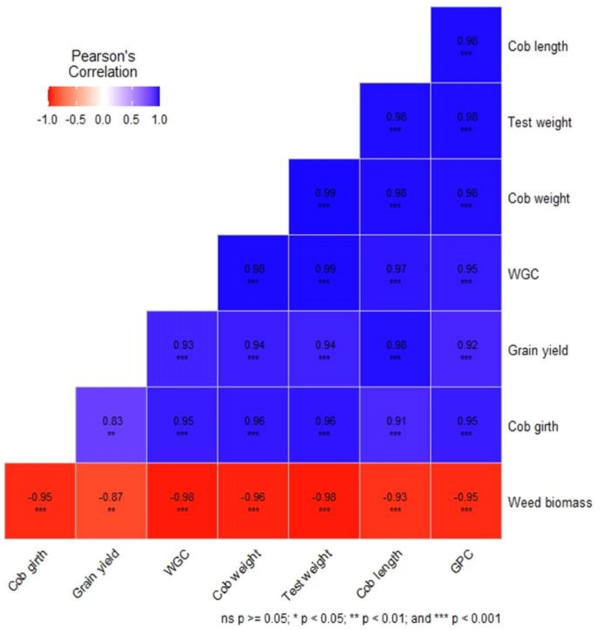

Figure 2. Pearson's correlation of yield attributes, grain yield, and weed biomass, across the years (mean of 2 years), as augmented by different residue, tillage, and weed management methods in maize. GPC (grains per cob); WGC (weight of grains per cob)

species throughout the crop's life cycle, as well as the competition for nutrients, moisture, light and space, resulting in higher grain yield. Similar observations on integrated weed management were also reported by Kaur and Singh (2019), Jain *et al.* (2022).

Conclusion

It is evident from the results that CA practices reduced weed biomass during the two years of experimentation. Live mulch and P-enriched vermicompost suppressed the emergence of weeds. Moreover, PBDSR+R *fb* PBDSM+R with live mulch practices had significant importance in achieving higher WCE and WI in both of the crops. PB and OWM practices in rice-maize rotation under conservation agriculture, realised higher grain yield besides managing agro-ecosystem for improved and sustained productivity than other tillage and weed management practices. Thus, PBDSR+R *fb* PBDSM+R with live mulching may be an effective weed management option for rice-maize rotation in Eastern India.

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RESEARCH ARTICLE

Differential response of grass weeds to ALS inhibiting broad-spectrum herbicide bispyribac-sodium

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ABSTRACT

An experiment on assessing the differential response of *Leptochloa chinensis* and *Echinochloa colona* to the varying concentrations of broad-spectrum herbicide bispyribac-sodium (BS) was carried out in the midland laterites of Kerala. Seedlings of both weeds at 4-5 leaf stage were treated with 50, 100 and 200% field recommended dose (FRD) of bispyribac-sodium, 10 SC, PI Industries) 0.0125, 0.025 and 0.05 kg/ha, respectively. Differential response by weeds was evaluated using amino acid content estimation and protein profiling by Sodium Dodecyl Sulphate - Poly Acrylamide Gel Electrophoresis. The amino acid content of *L. chinensis* was not influenced by the increasing concentration of BS, whereas it was found to decrease with an increasing concentration of BS in *E. colona*. The parameters examined to evaluate the varying response, *viz.* protein content, number of proteins expressed and molecular weight of proteins shown higher values in *L. chinensis* compared to *E. colona*, irrespective of the concentration. However, increase in concentration of BS reduced the amino acid levels in *E. colona*. The reduced effectiveness of BS in inhibiting the biochemical processes associated with amino acid and protein synthesis in *L. chinensis* might explain its poor performance. The study verified the contrasting expression of amino acids and proteins in *L. chinensis* and *E. colona*, despite being from the same family. The study validated the need to identify suitable herbicides for broad spectrum weed management in direct seeded rice, especially when *L. chinensis* dominated the grass weed flora.

Keywords: Direct-seeded rice, *Echinochloa colona*, Grass weeds, *Leptochloa chinensis*, Protein profiling

INTRODUCTION

Bispyribac-sodium, chemically, sodium 2, 6-bis [(4, 6-dimethoxy-2-pyrimidinyl) oxy] benzoate, is a popular rice herbicide recommended against a wide range of weeds, including grasses, broadleaf weeds and sedges. It is absorbed through the roots and leaves and inhibits the enzyme acetolactate synthase (ALS) in susceptible weed plants. ALS, also referred to as acetohydroxyacid synthase, is the enzyme in the biosynthetic pathway leading to the production of branched-chain amino acids, *viz.* leucine, isoleucine, and valine. The absence of essential amino acids hinders protein synthesis and growth resulting in plant mortality (WSSA 2007). Bispyribac-sodium (BS), is prone to developing resistance to specific weed accessions rapidly (Tranel and Wright 2002). The fact has more relevance in the context that nearly 126 weed species have already developed resistance to ALS inhibitors (Tranel *et al.* 2012).

As rice fields contain complex weed flora, the knowledge on the response of weeds to applied herbicides has several practical implications, *viz.* developing appropriate weed management strategies, including the development of models capable of predicting the overall weed control level achievable with a specific herbicide (Khedr *et al.* 2018). *Leptochloa chinensis* (L.) Nees and *Echinochloa colona* (L.) Link are two major grass weeds infesting the rice fields of Kerala. *Leptochloa chinensis*, generally known as 'Chinese sprangletop' or 'Red sprangletop' or 'Asian sprangletop' has been reported as one of the most problematic grass weeds in direct-seeded rice fields (Chin 2001). *Echinochloa colona* (jungle rice or barnyard grass), a vigorous C4 annual species, is one of the world's most serious grass weeds in rice (Holm *et al.* 1991). It has been identified as a troublesome weed in 35 crops in more than 60 countries (Holm *et al.* 1991). Population density of two to six *L. chinensis*/m^2 can cause grain yield loss of 14 to 44% in rice (Bergeron 2017), and that for *E. colona* is 27 to 62% (Rao and Matsumoto 2017). Studies conducted by Sekhar (2021) revealed

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that season long weed competition in wet seeded rice (WSR) with *L. chinensis* as a major weed caused a yield reduction of 59.95%.

Preliminary field studies revealed that BS 0.025 kg/ha (100% field recommended dose) was effective against *Echinochloa colona* but not against *Leptochloa chinensis,* which is a major grass weed in wet seeded rice, thus preventing broad-spectrum weed control (Sekhar *et al.* 2020a). As BS is effective for other grass weeds, including *E. colona*, and not for *L. chinensis*, despite the fact that they both belong to the Poaceae family, the possibility of differential response is valid. In this context, the present study was aimed to assess the differential response of *Leptochloa. chinensis* and *Echinochloa colona* to the broad-spectrum herbicide BS at varying concentrations.

MATERIALS AND METHODS

The study on assessing the differential response of *Leptochloa chinensis* and *Echinochloa colona* to BS at varying concentrations was carried out at College of Agriculture, Thiruvananthapuram, Kerala (midland laterites) during 2020. The mean temperature ranged between 28.6^{o}C to 31^{o}C and mean relative humidity ranged between 57.44% to 76.37%, with a direct normal irradiation of 72.93 - 318.75 W/m^2. No rainfall was received during the experimental period. Mature seeds of *L. chinensis* and *E. colona* were collected from lowland rice fields of the Integrated Farming System Research Station, Karamana, Thiruvananthapuram (8^0 N latitude and 76^0 E longitude). Panicles were collected from more than 50 arbitrarily selected plants. Shattered seeds were bulked up, cleaned, and stored at room temperature in airtight plastic containers for experimental purposes.

The experiment was conducted by sowing 20 seeds of each weed separately in pots (27 cm in diameter and 22 cm in height) filled with soil collected from rice fields (the soil was solarized to destroy the soil seed bank). The soil used for the experiment was sandy clay loam with medium texture and acidic in reaction with a pH of 5.3. The available N, P and K content was 175.6, 29 and 377.6 kg/ha, respectively. Seeds of both weeds were placed on the soil surface for germination and allowed to grow under open conditions. After one month, 10 seedlings of both weeds were retained in each pot. The seedlings at 4-5 leaf stage were treated with 50, 100 and 200% field recommended dose (FRD) of BS (Nominee Gold®, 10 SC, PI Industries), *i.e*., 0.0125, 0.025 and 0.05 kg/ha, respectively. The experimental design was a completely randomized block design (CRD) and three replicate pots were used per herbicide treatment and control. The specimens were collected three days herbicide application to study the early response, allowing a 48-hour period for the absorption and translocation of the herbicide, then stored on ice packs for analysis. ALS inhibitors mainly affects meristematic tissues, a key site for amino acid synthesis, and symptoms appear about 7–8 days after herbicide spray (Prakash *et al*. 2017). The differential response of *L. chinensis* and *E. colona* to varying concentrations of BS was evaluated using amino acid content estimation and protein profiling by Sodium Dodecyl Sulphate - Poly Acrylamide Gel Electrophoresis (SDS PAGE).

Amino acid content

The amino acid content was estimated using standard procedures (Sadasivam and Manikam, 2007). Total free amino acids were estimated using ninhydrin reagent. Ninhydrin (triketohydrindene hydrate) reacts with an amino acid to form a purple colour complex (Riemann's purple) with maximum absorption at 570 nm. Ninhydrin oxidises the amino acid to aldehyde, releasing ammonia and carbon dioxide in the process, and then reduces to hydridatin. In the presence of ammonia, the hydridatin form condenses with Ninhydrin to form a purple complex. The tissue sample (1.0 mg) was homogenized in 1 mL of phosphate buffer (pH 7.0). It was then centrifuged at 10,000 rpm for 20 minutes. The pellet was resuspended in 1 mL of phosphate buffer (pH 7.0) after the supernatant had been removed. It was made up to a volume of 4 mL with distilled water and 1 mL of Ninhydrin reagent was added. The contents of the tubes were mixed by vortexing and were placed in a boiling water bath for 15 minutes. The test tubes were cooled in cold water and 1 mL of ethanol was added. After cooling, the absorbance was measured at 570 nm using a UV Visible Spectrophotometer. The concentration of amino acid was calculated using the standard curve for proline.

Protein profiling

Protein samples were collected from leaves of all the treatments of both the weeds, three days after treatment application and analyzed by SDS PAGE as suggested by Sadasivam and Manikam (2007). A 10% resolving gel and a 5% stacking gel were prepared using 30% acrylamide stock solution, 10% SDS, 10% ammonium per sulphate solution, TEMED (N,N,N´N´-tetramethylethylene-1-diamine), and tris HCl (1.5M - pH 8.8 for resolving gel and 0.5M - pH

6.8 for stacking gel), along with distilled water. The sample buffer was composed of tris HCl (pH 6.8), bromophenol blue, β-mercaptoethanol, SDS, and glycerol. The electrophoresis buffer contained tris base, glycine, and SDS. The staining solution was prepared by mixing coomassie brilliant blue R 250, glacial acetic acid, methanol, and distilled water. Data generated were analyzed for completely randomised design using the online statistical analysis platform-KAU-GRAPES (General R-shiny based Analysis Platform Empowered by Statistics) (Gopinath *et al*., 2021).

RESULTS AND DISCUSSION

Weeds in crop fields belonged to a wide range of types and categories, with some belonging to the same family while others were distinct. This made it impossible to predict the level of control that a specific herbicide would provide against a range of weeds. Information on the response of weeds to various herbicides is essential for developing effective management techniques as components of integrated weed management systems. The application of the herbicide BS resulted in a reduction of amino acid content in plants, as BS targets ALS, a key enzyme in the biosynthesis of branched-chain amino acids. Significant reduction in branched chain amino acids (BCAAs), *viz*. valine, leucine, and isoleucine levels in plants treated with ALS inhibitor herbicides, leading to a selective depletion of BCAAs as a proportion of the total free amino acid pool, coupled with a noticeable decline in protein synthesis was reported earlier by many researchers (Ray 1984, Anderson and Hibbard 1985).

There was no significant difference (p=0.05) between the relative amino acid contents at various concentrations of BS in *L. chinensis* (**Table 1**). The highest content of amino acid (0.3440 mg/g) in *L. chinensis*, was observed at 50% FRD of BS (0.0125 kg/ha). Considering the relative amino acid contents, it was inferred that the amino acid content at 50% FRD was statistically similar to that of 100 and 200% FRD, with an amino acid content of 0.3440, 0.2904 and 0.3234 mg/g, respectively (**Table 1**). This indicated that, regardless of the herbicide concentration, there was no observable non-inhibitory impact of BS on *L. chinensis*. Several authors have observed the inefficiency of BS in managing *L. chinensis* (Jacob 2014, Awan *et al*. 2015, Sekhar *et al*. 2020b). Compared to control (without herbicide spray), the amino acid content was higher in the *L. chinensis* plants treated with bispyribac-sodium. However, an increase in the concentration of BS had an effect on the amino acid content of *E. colona*. The amino acid content of *E. colona* decreased as the concentration of BS increased.

Critical appraisal of the data identified higher content of amino acid in *L. chinensis* compared to *E. colona*, irrespective of the concentration BS. The amino acid content in *E. colona* was 0.2437 mg/g with the 50% FRD (0.0125 kg/ha) of BS, whereas it was 0.3440 mg/g in *L. chinensis*. At 100% FRD, the amino acid content was 0.1520 and 0.2904 mg/g and at 200% FRD, it was 0.0627 and 0.3234 mg/g respectively, in *E. colona* and *L. chinensis*. The amino acid content in *E. colona* decreased by 32.38, 57.82 and 82.60%, respectively, at 50, 100 and 200% FRD of BS compared to control. However, in *L. chinensis*, amino acid content increased by 39.38, 28.20 and 35.52% at 50, 100 and 200% FRD (**Table 1**). The study implied that BS was ineffective in inhibiting amino acid synthesis in *L. chinensis*, as evident from the higher amino acid content compared to *E. colona*. Imidazolinone application ceases growth because of inhibited cell division and DNA synthesis and some of these changes relate in some way to the disruption of the synthesis of the branched-chain amino acids (Shaner 1991). A significant increase in protein content was specifically observed in *E. colona* control plants which could be attributed to inherent biological processes within the plant, such as natural growth and development cycles or regulatory mechanisms that modulate protein synthesis.

Differential expressions of proteins were observed in *L. chinensis* and *E. colona* with varying

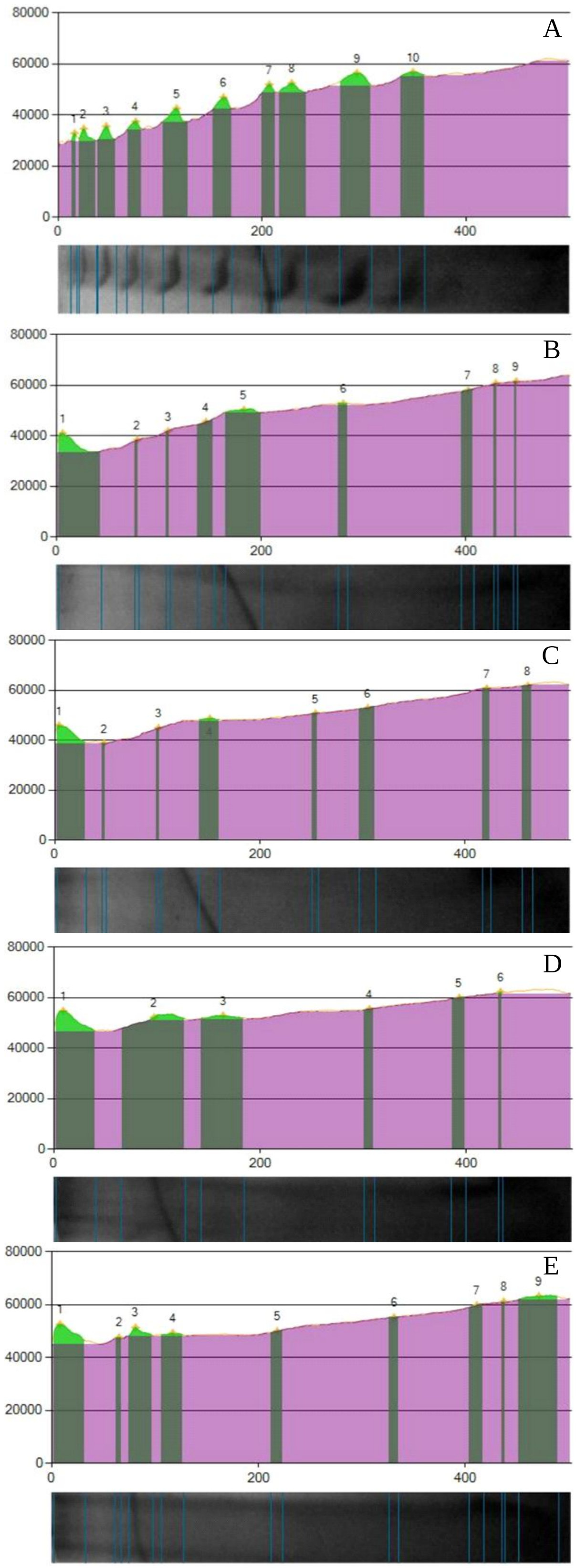
Table 1. Differential response of *Leptochloa chinensis* and *Echinochloa colona* to bispyribac-sodium

Concentration	Amino acid content (mg/g)		Protein content (mg/g)		No. of proteins expressed		Molecular weight of total proteins (kDa)	
	L. chinensis	*E. colona*	*L. chinensis*	*E. colona*	*L. chinensis*	*E. colona*	*L. chinensis*	*E. colona*
Bispyribac-sodium 0.0125 kg/ha (50% *FRD)	0.3440	0.2437	0.5401	0.2061	7	7	639.86	377.3
Bispyribac-sodium 0.025 kg/ha (100% FRD)	0.2904	0.1520	0.4762	0.1420	6	4	460.76	248.82
Bispyribac-sodium 0.05 kg/ha (200% FRD)	0.3234	0.0627	0.4827	0.1009	8	3	629.06	107.84
Control (no herbicide)	0.2085	0.3604	0.5021	0.4599	8	6	610.86	622.27
LSD (p=0.05)	0.037	0.018	-	0.059	-	-	-	-

concentrations of BS from lower to higher concentrations (**Table 1**). However, a statistically significant reduction was not observed in the protein content, the number of proteins expressed and the molecular weight of proteins in *L. chinensis* with the application of BS from a lower to a higher concentration.

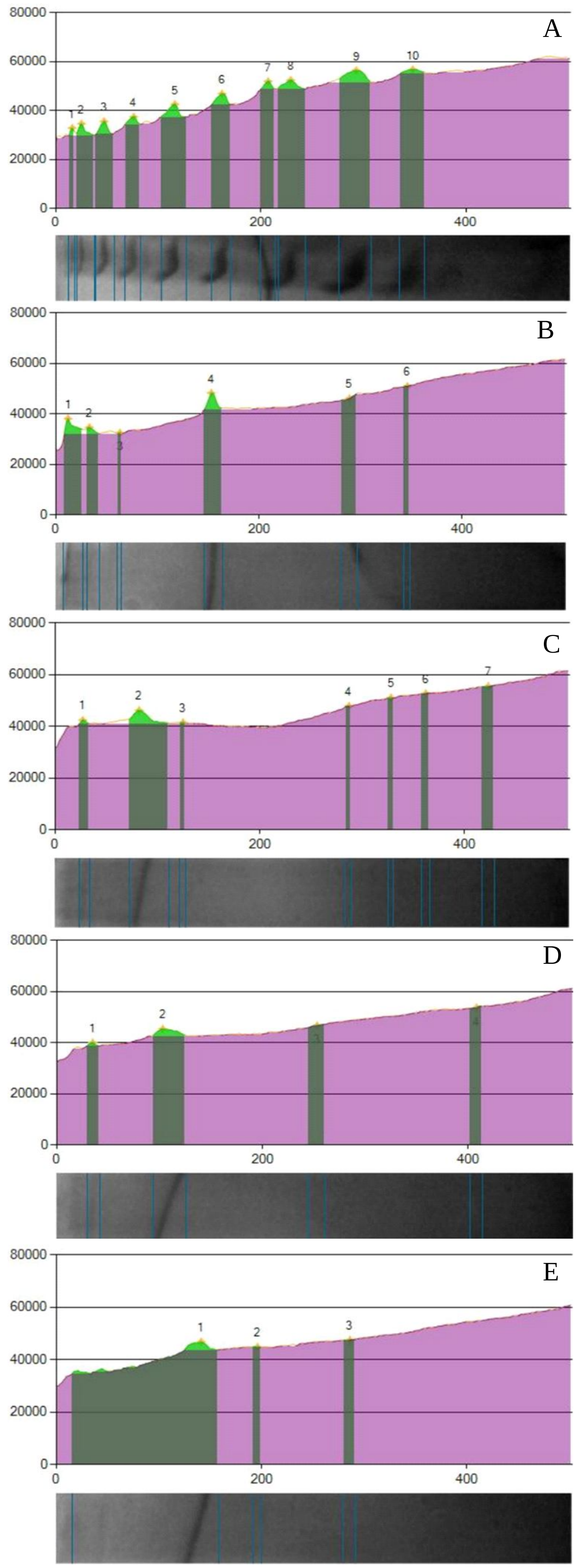
In *E. colona*, the protein content and molecular weight of total proteins were found to decrease with BS application compared to control. The number of proteins expressed, the molecular weight of proteins and protein content diminished with increasing concentration of BS. The negative correlation of total protein content, number of proteins expressed and the molecular weight of proteins with the concentration of BS could be due to the fact that this herbicide is known to induce oxidative stress. The application of herbicides, even if selective, can cause biochemical and physiological changes, resulting in oxidative stress (Langaro *et al*. 2016). Drop in protein levels as a biochemical and physiological consequence with the primary action of ALS inhibitors has been observed by Sidari *et al.* (1998). Rhodes *et al*. (1987) proposed that an increase in protein turnover caused the drop in protein content which could be due to accelerated degradation of existing proteins. The lowest protein content of 0.1009 mg/g was registered at 200% FRD in *E. colona*. This was statistically comparable with 100% FRD with a protein content of 0.1420 mg/g. The highest protein content (0.4599 mg/g) and molecular weight of total proteins (622.27 kDa) were registered in control without any herbicide application. Among various concentrations, the application of BS at 50% FRD recorded the highest protein content (0.2061 mg/g) and molecular weight of total proteins (377.3 k Da) in *E. colona*. In general, a higher molecular weight of total proteins was observed in *L. chinensis* compared to *E. colona* in herbicide-treated plants (**Figure 1** and **2**).

A total of seven proteins were expressed in both *L. chinensis* and *E. colona* at 50% FRD of BS. As the concentration increased from 50 to 200% FRD, the total number of proteins expressed in *E. colona* was found to decrease from seven to three, whereas it decreased to six at 100% FRD and then increased to eight at 200% FRD in the case of *L. chinensis.* Among the varying concentrations of BS, 100% FRD resulted in lower protein content, molecular weight of total proteins and the number of proteins expressed in *L. chinensis* compared to its higher and lower concentrations. There was also a reduction in protein content, low molecular weight of total proteins and



A – Marker; B – Control; C – bispyribac-sodium 0.0125 kg/ha (50% FRD); D – bispyribac-sodium 0.025 kg/ha (100% FRD); and E – bispyribac-sodium 0.05 kg/ha (200% FRD)

Figure 1. Protein profiling by SDS PAGE (*Leptochloa chinensis*)



A – Marker; B – Control; C – bispyribac-sodium 0.0125 kg/ha (50% FRD); D – bispyribac-sodium 0.025 kg/ha (100% FRD); and E – bispyribac-sodium 0.05 kg/ha (200% FRD) (*FRD – Field recommended dose)

Figure 2. Protein profiling by SDS PAGE (*Echinochloa colona*)

less number of proteins expressed in *L. chinensis* at 100% FRD of BS compared to control, which was not observed at 50 and 200% FRD. This confirmed that increasing the concentration of BS did not have much effect on *L. chinensis*.

The parameters analyzed to assess the differential response of grass weeds to BS registered a higher value in *L. chinensis* than in *E. colona* regardless of the concentration. The differential response of the grass weeds, *viz. Echinochloa crus-galli* and *E. colona* to BS was earlier reported (Riar *et al*. 2012, Kaloumenos *et al*. 2013, Khedr *et al*. 2018). The poor performance of BS in *L. chinensis* could be attributed to its lower efficiency in inhibiting the biochemical processes related to amino acid and protein synthesis. The study confirmed the differential expression of amino acids and proteins in *L. chinensis* and *E. colona*, even though they belong to the same family. In a flora dominated by *L. chinensis*, the use of BS may not be suitable for broad spectrum weed management, emphasizing the importance of assessing the weed species present and identifying appropriate herbicides when implementing chemical control methods.

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RESEARCH ARTICLE

Assessment of herbicide resistance in *Phalaris minor* and managing clodinafop-resistance with alternative herbicides

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ABSTRACT

Studies were conducted to assess and quantify the level of herbicide resistance in *P. minor* towards major used herbicides through a field survey in 2015-16 followed by dose-response assays in 2016-17. A total of 16 *P. minor* populations were collected from farmer's fields and screened against four majorly used herbicides in Haryana, *viz.* clodinafop, sulfosulfuron, mesosulfuron + iodosulfuron {Ready mix (RM)} and pinoxaden with its four graded doses (0X, ½X, X and 2X times of recommended dose). It was found that even at double of recommended dose, <80% mortality was observed in seven different populations under clodinafop; three under sulfosulfuron; one each under mesosulfuron + iodosulfuron (RM) and pinoxaden. These tested populations are generally categorized as resistant to highly resistant levels. Out of 16 populations, one showed multiple resistance towards ALS and ACCase inhibitor herbicides. Hence, for effective management of resistant *P. minor* and minimizing the probability of resistance development, field experiment with 16 different herbicide combinations was conducted during 2016-17 followed by 2019-20 to identify effective herbicide combinations for better management of clodinafop resistant *P. minor.* Field experiment advocated that sequential application of tank-mixed pre-emergence herbicides (pendimethalin with pyroxasulfone or metribuzin) followed by post-emergence (mesosulfuron + iodosulfuron (RM) or pinoxaden) along with their rotational application was effective against clodinafop-resistant *P. minor* and possibly a potent tool to minimize chances of resistance development.

Keywords: *Phalaris minor*, herbicide resistance, dose-response assay, sequential application of herbicide, wheat

INTRODUCTION

North-western Indo-Gangetic plains (IGPs) of India comprising states of Haryana, Punjab, and western Uttar Pradesh contributing more than 50% of national wheat production. Haryana producing 11.87 mt from an area of 2.53 mha with a productivity of 4.7 t/ha (Anonymous 2021), is one of the major wheat-growing states of India. However, weeds are the major biotic constraint in wheat production. They emerge concurrently along with crop seedling and if not managed till critical crop - weed competition period may cause significant reduction in crop yield (≥15-40% or more) and quality (Punia and Yadav 2009), having substantial economic impact on overall wheat production (Mamta and Sharma 2019).

Wheat is generally infested by diverse weed flora encompassing both grassy and broad-leaved weeds (BLWs). Among them, *Phalaris minor* Retz. (little seed canary grass) is major problematic and mimic weed of wheat. It predominates in the irrigated rice-wheat cropping system and severely infests wheat fields in the north-western IGPs of India including Haryana (Singh *et al.* 1999). Cultivation of semi-dwarf wheat varieties provides favourable and conducive micro-climate for the growth and development of *P. minor* (Singh *et al.* 1995). Additionally, rice straw burning before sowing of wheat tends to boost *P. minor* germination (Chhokar *et al.* 2009). Due to its morphological similarity to wheat, it frequently eludes manual and mechanical control methods. Thus to control this weed, application of selective herbicides is the most appropriate tool along with cost- and time effectiveness. However, use of same herbicide repeatedly develops selection pressure resulting resistant weed population. Simultaneously, the sole dependence on herbicides with a single mode of action has the greatest risk for herbicide-resistance evolution (Beckie 2006). During 1991-92, the first case of herbicide resistance was testified in *P. minor* against isoproturon in India (Malik and Singh 1995). The sole dependence on herbicides led to the evolution of multiple resistance in *P. minor* in due course of time. Also, some of the biotypes developed

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resistance to some new herbicides, *viz*. pinoxaden and mesosulfuron + iodosulfuron (RM). As of now, multiple herbicide-resistant *P. minor* is endemic causing significant yield reductions in rice-wheat cropping system of IGPs; and it is estimated that *P. minor* invades about 50% (15 mha) of the wheat growing areas in India. Of this area, the multiple herbicide-resistant *P. minor* affects about 3.0 mha (20% of *P. minor* infected area) of wheat (Chhokar *et al*. 2019, Soni *et al.* 2023). However, the exact information on herbicide resistance level in *P. minor* under different herbicides is still not known. Therefore, information on the level of herbicide resistance in *P. minor* is of prime importance. This can be managed within a field by using different herbicides with different mode of actions (MOAs). Herbicide-resistant *P. minor* in wheat was found susceptible to pre-emergence (PE) herbicides such as pendimethalin, metribuzin and pyroxasulfone (Dhawan *et al*. 2012). The PE herbicides offer an alternate mode of action to many post-emergence (PoE) herbicides, reduce selection pressure on subsequent PoE herbicide applications along with a reduction in early season weed competition for crop. Moreover, only PE herbicide application is not enough to control *P. minor* and its cohorts. The PE herbicides require a mixing partner for improved and broad-spectrum control. Mixing partners, such as herbicide combinations or compatible mixtures, provide various advantages including broad-spectrum action, increased efficacy through synergistic or additive effects, reduced application quantities, cost-effective weed management, prevention of weed shifts and resistance mitigation (Powles and Shaner 2001). Cavan *et al*. (2000), through a simulation model, showed that alternate herbicides with a different mechanism of action used in rotation resulted in delaying of development of resistance up to 45 years. In light of this background, an experiment was undertaken to determine the level of herbicide resistance by screening graded doses of herbicides and at the same time searching the effective combination of herbicides and their sequential application to manage this problem.

MATERIALS AND METHODS

Survey and collection of *P. minor* seeds

Based on the problem lodged by farmers towards poor efficacy of herbicides against *P. minor* at recommended dose (RD), a survey was conducted during *Rabi* (winter) 2015-16 from different locations in Haryana state, India. To represent one population, 30 matured ear heads of survived *P. minor* were randomly collected from a particular locality (Burgo 2015). Similarly, a total of 16 locations were surveyed and sampled that represented 16 populations (**Table 1**). The collected ear heads were shade dried, seeds were removed from each ear head and stored in craft paper bags at room temperature.

Dose-response bioassay for confirmation of resistance level

A dose-response bioassay for determination of herbicide resistance level in 16 *P. minor* populations was conducted in the earthen pots (20 cm diameter and 20 cm height) at the screen house of CCS HAU, Hisar (29°8'41.50"N, 75°42'15.72"E). The soil was taken from HAU Research Farm that was not subjected to any herbicide application for the last two years and was free from *P. minor* infestation. The soil was air-dried, crushed, well-grounded and passed through a 2 mm sieve. Earthen pots were filled with sieved soil: vermicompost mixture of 4:1 ratio. Seeds of each *P. minor* population were sown during *Rabi* (winter) 2016-17 and thinning was done at 15 days of germination to keep 20 plants per pot. The experimental units consisting of pots were arranged in factorial completely randomized block design under 16 populations screened with post-emergence application of 0.0, 0.5, 1.0 and 2.0 time of recommended dose (RD) of herbicides, *viz*. clodinafop (RD: 60 g/ha), sulfosulfuron (RD: 25 g/ha), mesosulfuron + iodosulfuron (RD: 14.4 g/ha) and pinoxaden (RD: 50 g/ha) with four replications. The herbicides were sprayed at 3-4 leaf stage {30 days after sowing (DAS)}. Plots were arranged outside the screen house and marked area was used for calculation of required quantity of herbicide corresponding to its dose. Herbicides were applied using knapsack sprayer fitted with a flat fan nozzle in 375 L water volume/ha.

Per cent control of *P. minor* was recorded at 30 days after treatment (DAT) from 0 (zero) to 100 scale (0 indicated no control, 100 = complete control of *P. minor*). GR_{50} value of different *P. minor* populations sprayed with various herbicides was calculated on basis of per cent visual control of *P. minor* under different herbicides in graded doses. Data on the per cent inhibition of the *P. minor* populations were subjected to linear regression using the probit analysis (Das *et al*. 2014) by OPSTAT software (Sheoran *et al.* 1998).

Field experiment

In order to manage resistance in *P. minor* through alternate herbicides, a field experiment was conducted at Agronomy Research Farm, CCS HAU, Hisar (Haryana) in *Rabi* (winter) 2016-17 and 2019-20. Sixteen treatments were: pendimethalin 1500 g/ha PE; metribuzin 210 g/ha PE; pendimethalin + metribuzin tank mix (TM) 1500 + 175 PE; pendimethalin + metribuzin (TM) *fb* pinoxaden 1000 +175 *fb* 60 g/ha PE *fb* PoE; pendimethalin + metribuzin (TM) *fb* mesosulfuron + iodosulfuron (RM) 1000 + 175 *fb* 14.4 g/ha PE *fb* PoE; pendimethalin + pyroxasulfone (TM) 1500+102 g/ha; pendimethalin + pyroxasulfone (TM) *fb* pinoxaden 1500+102 *fb* 60 g/ha PE *fb* PoE; pendimethalin + pyroxasulfone (TM) *fb* mesosulfuron + iodosulfuron (RM) 1500+102 *fb*14.4 g/ha PE *fb* PoE; pendimethalin + metribuzin (TM) *fb* pinoxaden 1500 + 175 *fb* 60 g/ha before sowing *fb* PoE; sulfosulfuron *fb* pinoxaden 25 *fb* 60 g/ha BI *fb* 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 check; weedy check. Evaluated in a randomized block design (RBD) replicated thrice with plot size of 6m × 6m. Wheat cv HD 2967 was sown on 20 November 2016 and 5 December 2019 and harvested on 16 April 2017 and 27 April 2020 during two seasons. The recommended dose of fertilizer (RDF), *viz.* 150 kg N/ha and 60 kg P/ha was applied in both the crop seasons. Herbicides were applied as per treatment either as pre-emergence (PE), post-emergence (PoE) at 35 days after sowing (DAS) of wheat, or PE followed by (*fb*) PoE, before sowing of wheat seeds *fb* PoE or before first irrigation (BI) at 18 DAS *fb* PoE. In weeds-free plots, weeds were removed manually as and when appeared; and no weeding was done in weedy check.

Plant dry matter, yield attributing parameters, grain and biological yield of wheat were recorded as per the standard observation and computing methods. Data on *P. minor* dry weight, total weeds dry weight and weed control efficiency (WCE) were recorded at 60 and 120 DAS, respectively. All the weeds taken with quadrate from four places selected at random from each plot for dry matter accumulation at 60 and 120 DAS. Individual weeds were separated, sun-dried and then kept in an oven at 65±5 ^{0}C till a constant weight was achieved. The dried samples of individual weeds were weighed and the final dry weight of total weeds was expressed as g/m^2. Whereas, WCE was calculated using following formula:

$$\mathrm{WCE} = \frac{(\mathrm{Wc} - \mathrm{Wt})}{\mathrm{Wc}} \times 100$$

Where, Wc = dry weight of weeds in weedy plot (g); Wt = dry weight of weeds in treated plot (g). While weed index (WI) of different treatments was calculated using formula given below and expressed in %.

$$\mathrm{WI} = \frac{(\mathrm{Yc_0} - \mathrm{Yt})}{\mathrm{Yc_0}} \times 100$$

Where, $\mathrm{Yc_0}$ = Yield obtained from weed-free plot (control plot) and Yt = Yield obtained from treatment for which WI is to be worked out

Statistical analysis

The data underwent statistical analysis using Analysis of Variance (ANOVA) *via* OPSTAT software (Sheoran *et al.* 1998). Weed dry weight data were subjected to square-root $(\sqrt{x+1})$. The responses of various treatments remained consistent across both years and passed the homogeneity test; thus, the data

Table 1. Details of *P. minor* populations collected from different locations in Haryana state under rice-wheat cropping system

P. minor Population	Village name	District	Latitude	Longitude
P_1	Nangla-1	Fatehabad	29°37'14.39"N	75°53'38.65"E
P_2	Pipaltha-1	Jind	29°45'28.38"N	76° 5'41.14"E
P_3	Nangla-2	Fatehabad	29°36'39.41"N	75°53'33.35"E
P_4	Laloda-1	Fatehabad	29°38'30.92"N	75°52'39.07"E
P_5	Pipaltha-2	Jind	29°45'42.07"N	76° 5'33.18"E
P_6	Barwala	Hisar	29°21'4.57"N	75°53'44.69"E
P_7	Pipaltha-3	Jind	29°45'51.98"N	76° 6'7.27"E
P_8	Khedi	Kaithal	29°46'49.98"N	76°29'39.13"E
P_9	Ludas	Hisar	29° 9'28.35"N	75°38'42.83"E
P_{10}	Danora	Ambala	30°29'38.66"N	77° 7'42.37"E
P_{11}	Ujhana	Jind	29°43'18.59"N	76° 7'41.49"E
P_{12}	Dhos	Kaithal	29°49'30.36"N	76°32'11.80"E
P_{13}	Danoda	Jind	29°31'7.32"N	76° 3'1.17"E
P_{14}	Samain	Fatehabad	29°37'19.98"N	75°55'25.30"E
P_{15}	Rasidan	Jind	29°43'30.55"N	76° 1'44.74"E
P_{16}	Kalwan	Jind	29°42'50.16"N	75°58'3.05"E

were statistical examination, accordingly. The significance of treatments was determined using the ‘F’ test with a least significant difference (LSD) of 5%.

RESULTS AND DISCUSSION

Dose-response bioassay for confirmation of resistance level

Sixteen populations of *P. minor* collected from different locations in Haryana state were subjected to graded doses of herbicides at 30 DAS (**Table 2**). At 30 days after treatment (DAT), averaged doses of clodinafop showed significantly least mortality in P_9 (19.9%) followed by P_2 (26.6%). At half of RD, only 5 (P_3, P_6, P_{10}, P_{13} and P_{15}) populations depicted with >80% mortality while at RD, six populations displayed >80% mortality and five (P_1, P_2, P_7, P_9 and P_{16}) showed <50% mortality. Whereas, at double of RD of clodinafop, significantly least mortality was recorded in P_9 (33.3%) followed by P_2 (43.3%). Similarly, application of sulfosulfuron resulted in significant variation in per cent mortality of *P. minor* population (**Table 2**), mean data of sulfosulfuron doses exhibited that significantly lower mortality was observed in P_9 (25.6%) followed by P_8 (41.1%). At half of RD, 8 populations depicted with >80% mortality and at RD, four populations (P_1, P_8, P_9 and P_{15}) exhibited <80% mortality. At double of RD, significantly least was recorded in P_9 (35.0%) followed by P_{15} (59.8%). Most of the tested populations were found sensitive to mesosulfuron + iodosulfuron (RM). Significantly least mortality was depicted by P_{15} (38.1%) followed by P_{16} (41.7%) under its averaged doses (**Table 2**). At half of RD, 11 populations depicted with >80% mortality. While at RD, P_{15} and P_{16} showed <50% mortality. At double of RD, significantly least mortality was recorded in P_{15} (53.3%). Similarly, under pinoxaden, significantly least mortality per cent was observed in P_{14} (38.0%) followed by P_1 (66.6%) under the averaged doses. At half of RD, 7 populations depicted with >80% mortality. While, at RD, only P_{14} witnessed least visual mortality (31.8%). At double of RD of pinoxaden, significantly least mortality was recorded in P_{14} (78.3%). Percentage mortality is an index of sensitivity of *P. minor* population over the years towards different herbicides. The resistance to herbicides can be attributed to the use of wheat monoculture in the given areas along with the repeated use of the same herbicide for a long period of time levied a persistent selection pressure resulting in resistance development (Chhokar *et al.* 2012). Clodinafop is an aryloxyphenoxypropionate type herbicide inhibiting acetyl-CoA carboxylase (ACCase) enzyme (Golmohammadzadeh *et al.* 2019). Resistance towards clodinafop is most common phenomenon of insensitivity of ACCase target site. This target site resistance in *P. minor* can appear within 10 years of its continuous application (Beckie 2006). Clodinafop is being used for more than 15 years under monocropping in the region/state (Haryana) under study. This might be the reason that nearly 62% of screened populations were observed with <80% mortality under recommended dose.

Table 2. Per cent visual mortality of different *P. minor* populations under graded doses of herbicides at 30 DAT

Population	Percent mortality (%)															
	Clodinafop				Sulfosulfuron				Mesosulfuron + Iodosulfuron				Pinoxaden			
	30 g/ha	60 g/ha	120 g/ha	Mean	12.5 g/ha	25 g/ha	50 g/ha	Mean	7.2 g/ha	14.4 g/ha	28.8 g/ha	Mean	25 g/ha	50 g/ha	100 g/ha	Mean
P_1: Nangla1	42.3	48.3	51.7	47.4	30.0	65.0	85.0	60.0	58.3	83.3	93.3	78.3	43.3	73.3	83.3	66.6
P_2: Pipaltha1	16.7	19.7	43.3	26.6	78.3	91.7	98.3	89.4	85.0	88.3	100.0	91.1	63.3	88.3	96.8	82.8
P_3: Nangla2	83.0	90.0	100.0	91.0	85.0	91.7	96.7	91.1	83.3	91.7	98.3	91.1	86.8	91.8	100.0	92.9
P_4: Laloda1	23.3	65.0	96.7	61.7	68.3	95.0	100.0	87.8	93.3	100.0	100.0	97.8	46.8	86.8	96.8	76.8
P_5: Pipaltha2	41.7	55.0	90.0	62.2	61.7	88.3	100.0	83.3	93.3	100.0	100.0	97.8	35.0	93.3	100.0	76.1
P_6: Barwala	90.0	95.0	100.0	95.0	85.0	93.3	100.0	92.8	93.3	100.0	100.0	97.8	90.0	100.0	100.0	96.7
P_7: Pipaltha3	32.7	36.7	58.3	42.6	88.3	98.3	100.0	95.6	95.0	98.0	100.0	97.7	18.3	93.3	100.0	70.5
P_8: Khedi	51.7	85.0	93.3	76.7	15.0	38.3	70.0	41.1	68.3	93.3	100.0	87.2	86.0	100.0	100.0	95.3
P_9: Ludas	4.7	21.7	33.3	19.9	16.7	25.0	35.0	25.6	50.0	81.7	98.3	76.7	88.0	100.0	100.0	96.0
P_{10}: Danora	90.0	95.0	100.0	95.0	82.3	95.0	96.7	91.3	86.7	93.3	98.0	92.7	93.0	100.0	100.0	97.7
P_{11}: Ujhana	28.3	50.0	53.8	44.0	85.0	96.7	98.3	93.3	80.0	90.1	96.7	88.9	15.0	93.3	100.0	69.4
P_{12}: Dhos	11.7	56.7	65.0	44.5	90.0	95.0	100.0	95.0	90.0	98.0	100.0	96.0	68.3	98.3	100.0	88.9
P_{13}: Danoda	85.0	100.0	100.0	95.0	90.0	95.0	100.0	95.0	88.3	96.7	100.0	95.0	96.8	100.0	100.0	98.9
P_{14}: Samain	41.7	78.3	95.0	71.7	80.5	97.5	100.0	92.7	90.0	100.0	100.0	96.7	3.8	31.8	78.3	38.0
P_{15}: Rasidan	90.0	95.0	100.0	95.0	33.3	38.3	59.8	43.8	21.7	39.3	53.3	38.1	92.0	99.0	100.0	97.0
P_{16}: Kalwan	33.3	38.3	55.0	42.2	56.7	88.3	98.3	81.1	0.0	31.8	93.3	41.7	31.8	86.8	98.3	72.3
Mean	47.9	64.4	77.2		65.4	80.8	89.9		73.5	86.6	95.7		59.9	89.7	97.1	
LSD (p=0.05)																
Population(P)	3.0				3.3				3.0				2.8			
Herbicide(H)	1.3				1.4				1.3				1.2			
PXH	5.1				5.6				5.2				4.8			

Herbicide sulfosulfuron and mesosulfuron + iodosulfuron (RM) are acetolactate synthase (ALS) enzyme inhibitors that inhibit ALS enzyme. Target site mutation in amino acid sequence of ALS is the possible cause of resistance. The earlier finding indicates that herbicides inhibiting ALS enzyme are more efficient than ACCase inhibitor herbicides for control of herbicide resistant population of *P. minor* (Kaur *et al.* 2016). However, continuous use of ALS herbicide leads to decreased efficacy towards *P. minor* population forcing farmers to apply higher doses. While, pinoxaden is ACCase inhibitors herbicide of the most recently introduced chemistry phenylpyrazolin (Linda *et al.* 2010). It was very effective against resistant populations of *P. minor*. However, being one of the costlier herbicides, though, it was used in farmers' fields at lower scale, yet, its continuous use over years under monoculture has also resulted in the raising the resistance cases towards it.

The GR_{50} values of clodinafop for seven populations (P_1, P_2, P_8, P_9, P_{11}, P_{12} and P_{16}) were more than RD (60 g/ha). Similarly, GR_{50} values of sulfosulfuron for three populations (P_8, P_9 and P_{15}) were estimated more than RD (25 g/ha) with highest in P_9 (131.8 g/ha). Whereas, GR_{50} values of mesosulfuron + iodosulfuron (RM) for two populations (P_{15} and P_{16}) were found more than RD (14.4 g/ha) with the highest value in P_{15} (24.5 g/ha). The GR_{50} value of pinoxaden for P_{14} (61.7 g/ha) was more than RD (50 g/ha). The higher dose of clodinafop to control resistant *P. minor* populations as evident from findings of study that GR_{50} value of 62% of populations estimated between 34.7-193.6 g/ha, which were 2.8 to 14.3 times higher than their most susceptible population (**Table 3**). Similarly, out of 311 populations of *P. minor* collected from Haryana and Punjab, 71 showed RF value between 2-41 for clodinafop (Das *et al.* 2014). Likewise, Chhokar and Sharma (2008) found some of the *P. minor* populations recorded with >10 times higher GR_{50} value of clodinafop than that of most susceptible one. The GR_{50} values of sulfosulfuron for *P. minor* populations were 5 g/ha before 2005 in Haryana (Yadav and Malik, 2005). Over a period of time, GR_{50} values rose up to 10-fold against sulfosulfuron (Dhawan *et al.* 2009). Similarly reduced efficacy of mesosulfuron + iodosulfuron (RM) against some populations of *P. minor* has also been reported by Kaur *et al.* (2016). Earlier researchers also documented that continuous use of pinoxaden on clodinafop resistant *P. minor* populations brought reduced sensitivity towards pinoxaden resulting in higher dose requirement for controlling *P. minor* (Chokkar *et al.* 2008). Some of the tested *P. minor* populations recorded GR_{50} value >120 g/ha towards pinoxaden and indicated progressive development of resistance in *P. minor* towards pinoxaden (Dhawan *et al.* 2010).

Present study also confirmed that population (P_1 and P_{14}) have developed cross-resistance against clodinafop (GR_{50}: 34.7-86.9 g/ha) and pinoxaden (GR_{50}: 28.2-61.7 g/ha). Also, neither clodinafop nor sulfosulfuron or pinoxaden could control P_1 population, that indicats development of multiple resistance towards ALS and ACCase inhibitor herbicides (Pieterse and Kellerman, 2002). Earlier findings also indicate that ALS and ACCase inhibitors herbicides are highly suspectable towards resistance evolution if being used continuously under monocropping (Das *et al.* 2014). However, variable resistance among the *P. minor* populations might be due to varied selection pressure across fields, crop rotation and cropping pattern; cultural practices,

Table 3. GR_{50} value (g/ha) of different herbicides against *P. minor* populations at 30 DAT

Population	Clodinafop (g/ha)	Sulfosulfuron (g/ha)	Mesosulfuron + iodosulfuron (RM) (g/ha)	Pinoxaden (g/ha)
P_1: Nangla1	86.9	19.1	5.6	28.2
P_2: Pipaltha1	193.6	5.5	4.8	18.2
P_3: Nangla2	19.0	2.3	2.2	13.2
P_4: Laloda1	44.7	10.0	2.1	25.1
P_5: Pipaltha2	41.7	11.5	2.1	28.2
P_6: Barwala	12.6	7.1	1.9	7.4
P_7: Pipaltha3	50.6	5.4	1.7	32.4
P_8: Khedi	91.2	31.6	5.9	13.1
P_9: Ludas	179.5	131.8	7.2	8.5
P_{10}: Danora	12.9	3.0	1.4	5.6
P_{11}: Ujhana	62.7	2.6	2.4	33.1
P_{12}: Dhos	72.4	5.4	2.8	18.2
P_{13}: Danoda	14.8	5.4	3.2	9.8
P_{14}: Samain	34.7	7.3	2.8	61.7
P_{15}: Rasidan	12.9	34.1	24.5	7.7
P_{16}: Kalwan	102.3	10.7	14.8	30.2

intensity and extent of herbicide usage; and the way farmers use the herbicide (Abbas *et al*. 2017).

Field experiment

Weed studies: Field experiment was carried out in a field infested with clodinafop resistant *P. minor*. The results indicated that maximum reduction in dry weight of *P. minor* at 60 and 120 DAS was recorded in sequential application of PE tank-mix pendimethalin + pyroxasulfone (1500 + 102 g/ha) *fb* PoE application of mesosulfuron + iodosulfuron (RM; 14.4 g/ha) or pinoxaden (60 g/ha) that was statistically at par with PE tank-mix pendimethalin + metribuzin (1000 + 175 g/ha) *fb* PoE mesosulfuron + iodosulfuron (RM; 14.4 g/ha) in both years. Significantly lowest total weeds dry weight and highest total WCE was observed under sequential application PE tank-mixed pendimethalin + pyroxasulfone (1500 + 102 g/ha) or pendimethalin + metribuzin (1000 + 175 g/ha) *fb* PoE mesosulfuron + iodosulfuron (RM; 14.4 g/ha) (**Table 4 & 5**). Similarly, weed index (WI) was significantly influenced by different weed control treatments. Apart from weed-free, lowest yield reduction (0.6-2.1% over weed-free) was recorded in PE pendimethalin + pyroxasulfone *fb* PoE mesosulfuron + iodosulfuron (RM) and it was statistically at par with PE pendimethalin + metribuzin *fb* PoE mesosulfuron + iodosulfuron (RM; 2.7-3.5%) and PoE mesosulfuron + iodosulfuron (RM). In contrast, significantly higher yield reduction was recorded in weedy check (29.9-34.6%) (**Table 5**). The variation in weed dry weight under different herbicides could be due to variable resistance patterns towards *P. minor*, cohorts of weeds and its composition in a different time interval. Alone pre-emergence or post-emergence herbicides recorded higher weed dry weight and least WCE compared to tank-mixed sequential application of herbicides. Among the solely applied PE herbicides, pendimethalin belongs to dinitroaniline group inhibiting cell division; and metribuzin possesses protoporphyrinogen oxidase (PPO) inhibitor activity that inhibits PSII. These two herbicides have the potential to manage herbicide resistance in *P. minor* and possess a lower risk for selection pressure (Dhawan *et al.* 2012, Kaur *et al.* 2016). Mixing PE herbicides with its compatible mixture with different alternate modes of action provided effective control of susceptible and resistant *P. minor* and other weeds (Evans *et al.* 2016). This mixture eliminates early-season weed competition pressure on the crop. PE tank mixture of pendimethalin with pyroxasulfone provides WCE of resistant *P. minor* up to 87%. This was highest among all the PE tank mix herbicides application, while pendimethalin applied alone gave only 54% control. Pyroxasulfone is a new class of chemistry known as isoxazoline that inhibits the biosynthesis of very-long-chain fatty acids in *P. minor* and other narrow-leaved weeds (Tanetani *et al.* 2011). It's mixing with pendimethalin offers a compatible mixture with alternate modes of action, reduced selection pressure, controlling weed cohorts and

Table 4. Effect of different weed control treatments on weed dry weight

Treatment	Dry weight (g/m^2)							
	P. minor				Total weeds			
	60 DAS		120 DAS		60 DAS		120 DAS	
	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20
Pendimethalin 1500 g/ha PE	3.5(11.1)	3.5(11.2)	6.3(38.9)	7.4(53.6)	3.9(14.1)	3.8(13.6)	7.2(50.8)	8.0(62.9)
Metribuzin 210 g/ha PE	3.6(12.0)	4.1(15.8)	7.3(52.2)	8.7(74.7)	4.4(18.5)	4.6(19.7)	8.8(77.3)	9.5(89.4)
Pendimethalin + metribuzin (TM) 1500 + 175 PE	2.6(5.6)	2.9(7.6)	4.8(21.9)	5.7(31.0)	3.0(8.1)	3.3(9.8)	5.7(31.8)	6.1(35.9)
Pendimethalin + metribuzin (TM) *fb* pinoxaden 1000 +175 *fb* 60 g/ha PE *fb* PoE	1.4(1.1)	1.5(1.4)	2.6(6.0)	2.0(2.9)	2.2(4.0)	2.3(4.3)	4.5(19.1)	3.5(11.3)
Pendimethalin + metribuzin (TM) *fb* mesosulfuron + iodosulfuron (RM) 1000 + 175 *fb* 14.4 g/ha PE *fb* PoE	1.0(0.0)	1.3(0.6)	1.4(1.0)	1.7(1.8)	1.2(0.5)	1.5(1.1)	2.2(3.6)	1.9(2.5)
Pendimethalin + pyroxasulfone (TM) 1500+102 g/ha	1.8(2.2)	1.9(2.6)	3.5(10.9)	3.5(11.3)	2.6(5.7)	2.6(5.8)	5.0(23.9)	5.1(25.0)
Pendimethalin + pyroxasulfone (TM) *fb* pinoxaden 1500+102 *fb* 60 g/ha PE *fb* PoE	1.0(0.0)	1.3(0.6)	1.0(0.0)	1.2(0.5)	2.0(3.2)	2.1(3.4)	3.6(11.9)	3.4(10.7)
Pendimethalin + pyroxasulfone (TM) *fb* mesosulfuron + iodosulfuron (RM) 1500+102 *fb*14.4 g/ha PE *fb* PoE	1.0(0.0)	1.0(0.1)	1.0(0.0)	1.0(0.0)	1.1(0.3)	1.1(0.2)	1.6(1.6)	1.1(0.3)
Pendimethalin + metribuzin (TM) *fb* pinoxaden 1500 + 175 *fb* 60 g/ha before sowing *fb* PoE	1.3(0.7)	1.5(1.2)	2.0(3.1)	2.0(3.1)	2.3(4.3)	2.2(4.0)	4.2(16.3)	3.9(14.0)
Sulfosulfuron *fb* pinoxaden 25 *fb* 60 g/ha BI *fb* PoE	1.1(0.3)	1.4(0.9)	1.4(1.0)	1.9(2.6)	2.0(2.9)	2.0(3.1)	4.0(14.9)	3.3(9.9)
Pinoxaden 60 g/ha PoE	1.5(1.2)	1.6(1.4)	2.4(4.9)	2.6(6.0)	3.1(8.6)	3.1(8.3)	5.7(31.1)	5.4(28.6)
Pinoxaden + metribuzin (TM) 50+120 g/ha PoE	1.5(1.3)	1.5(1.4)	2.8(7.1)	2.5(5.3)	2.2(3.9)	2.1(3.2)	4.2(16.2)	3.4(10.8)
Pinoxaden + metribuzin (TM) 50+150 g/ha PoE	1.4(0.8)	1.5(1.3)	2.4(4.8)	2.5(5.2)	1.9(2.7)	1.8(2.4)	3.3(10.2)	3.0(8.3)
Mesosulfuron + iodosulfuron (RM) 14.4 g/ha PoE	1.2(0.6)	1.4(0.9)	2.2(3.8)	2.2(4.0)	1.6(1.5)	1.7(1.7)	3.0(8.2)	2.9(7.3)
Weed-free check	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)	1.0(0.0)
Weedy check	4.4(18.4)	4.8(22.3)	8.8(76.3)	10.5(108.9)	5.6(30.4)	5.6(30.6)	10.9(117.2)	11.7(135.6)
LSD (p=0.05)	0.3	0.3	0.6	0.6	0.3	0.2	0.2	0.5

Data given in parenthesis are original values, and outside are square-root transformed value ($\sqrt{x+1}$), *fb*: followed by, PE: pre-emergence, PoE: post-emergence, and BI: before irrigation, TM: tank mix, RM: ready mix elimination of early-season weeds competitive with crop. Whereas, solely applied PoE herbicides pinoxaden and mesosulfuron + iodosulfuron (RM) control resistant *P. minor* more efficiently than PE solely applied or its tank mixture. Nonetheless, continuous application with the same herbicide or other herbicide with the same mode of action exerts more selection pressure that would be highly susceptible towards early development of resistance in *P. minor* (Das *et al.* 2014). Therefore, sequential application of tank-mixed PE herbicides followed by PoE herbicide leads to higher WCE for a longer period. Present findings showed that tank mix application of PE pendimethalin with metribuzin or pyroxasulfone followed by PoE pinoxaden or mesosulfuron + iodosulfuron (RM) provided the most efficient control of clodinafop resistant *P. minor*. However, if a field is dominated with both resistant *P. minor* and other weeds, then application of PE pendimethalin with metribuzin or pyroxasulfone followed by PoE mesosulfuron + iodosulfuron (RM) provides most efficient weed control. This was due to the fact that pendimethalin, metribuzin, pyroxasulfone and mesosulfuron + iodosulfuron (RM) provides control of broad-spectrum (narrow and broad-leaved) weeds, while, pinoxaden is very effective against narrow-leaved weeds only (Punia *et al*. 2020, Soni *et al*. 2021). Therefore, in the long run, rotational use of herbicides is recommended to minimize selection pressure. Effective control of resistant *P. minor* and other weeds with longer weed-free window provides congenial micro-climate for the crop to utilize nutrients, moisture, light and space available to crop which led to healthier crop and consequently higher yield brought least weed index (Chandana *et al*. 2019).

Crop studies: Crop growth and yield attributing parameters varied significantly with treatments (**Table 6**). Apart from weed-free plot, sequential application of pre-emergence pendimethalin + pyroxasulfone (or) pendimethalin + metribuzin followed by post-emergence application of mesosulfuron + iodosulfuron (RM) (or) pinoxaden resulted in maximum plant dry weight and yield attributes, *viz.* number of effective tillers per m^2 and grains per spike; while, least values of these parameters were obtained in weedy check followed by PE metribuzin. Similarly, the highest grain yield (5.45-6.28 t/ha) was observed under PE pendimethalin + pyroxasulfone *fb* PoE mesosulfuron + iodosulfuron (RM) with higher harvest index (48.0%) which was statistically at par with PE pendimethalin + metribuzin *fb* PoE mesosulfuron + iodosulfuron (5.37-6.15 t/ha and 47.9-48.0%). The lowest grain yield and HI were obtained in weedy check (3.91-4.14 t/ha with HI 44.6-44.7%). The improvement in crop growth, yield attributes, yield

Table 5. Effect of different weed control treatments on WCE

Treatment	WCE (%)								Weed index (%)	
	P. minor				Total weeds					
	60 DAS		120 DAS		60 DAS		120 DAS			
	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20
Pendimethalin 1500 g/ha PE	36.4	49.6	47.8	50.5	52.6	55.6	55.6	53.5	21.3	19.7
Metribuzin 210 g/ha PE	31.1	29.0	30.8	30.9	38.0	35.3	33.0	33.9	27.5	23.4
Pendimethalin + metribuzin (TM) 1500 + 175 PE	68.1	66.0	71.0	71.1	73.1	68.3	72.6	73.3	16.5	14.9
Pendimethalin + metribuzin (TM) *fb* pinoxaden 1000 +175 *fb* 60 g/ha PE *fb* PoE	93.7	93.6	92.3	97.3	86.7	85.7	83.7	91.7	12.0	11.4
Pendimethalin + metribuzin (TM) *fb* mesosulfuron + iodosulfuron (RM) 1000 + 175 *fb* 14.4 g/ha PE *fb* PoE	100.0	97.3	98.7	98.3	98.3	96.3	96.9	98.2	2.7	3.5
Pendimethalin + pyroxasulfone (TM) 1500+102 g/ha	86.5	88.4	85.5	89.4	80.8	81.0	79.4	81.5	19.5	17.7
Pendimethalin + pyroxasulfone (TM) *fb* pinoxaden 1500+102 *fb* 60 g/ha PE *fb* PoE	100.0	97.4	100.0	99.5	89.5	88.9	89.8	92.1	8.5	8.0
Pendimethalin + pyroxasulfone (TM) *fb* mesosulfuron + iodosulfuron (RM) 1500+102 *fb*14.4 g/ha PE *fb* PoE	100.0	99.6	100.0	100.0	99.1	99.2	98.7	99.8	0.6	2.1
Pendimethalin + metribuzin (TM) *fb* pinoxaden 1500 + 175 *fb* 60 g/ha before sowing *fb* PoE	95.8	94.5	96.1	97.2	86.0	86.8	86.3	89.6	14.1	10.6
Sulfosulfuron *fb* pinoxaden 25 *fb* 60 g/ha BI *fb* PoE	98.2	95.9	98.6	97.6	90.3	90.0	87.3	92.7	8.8	10.0
Pinoxaden 60 g/ha PoE	93.4	93.5	93.5	94.5	70.9	72.6	73.0	78.9	16.0	16.7
Pinoxaden + metribuzin (TM) 50+120 g/ha PoE	93.2	93.8	90.6	95.1	87.1	89.5	86.1	92.1	10.9	11.8
Pinoxaden + metribuzin (TM) 50+150 g/ha PoE	95.8	93.9	93.6	95.2	91.4	92.2	91.4	94.0	9.6	7.3
Mesosulfuron + iodosulfuron (RM) 14.4 g/ha PoE	96.9	95.7	95.1	96.3	95.2	94.3	93.1	94.7	6.3	5.5
Weed-free check	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0
Weedy check	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.6	29.9
LSD (p=0.05)	11.0	4.1	8.7	7.0	5.8	3.5	7.3	4.4	7.1	7.5

fb: followed by, PE: pre-emergence, PoE: post-emergence, and BI: before irrigation, TM: tank mix, RM: ready mix

Table 6. Effect of different weed control treatments on crop growth and yield parameters; and grain yield of wheat

Treatment	Plant dry weight (g/plant) 120 DAS		Effective tillers (no./m^2)		Grains per spike (no.)		Grain yield (t/ha)		Harvest index (%)	
	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20	2016-17	2019-20
Pendimethalin 1500 g/ha PE	14.5	13.2	386	374	47	45	4.98	4.47	47.0	46.2
Metribuzin 210 g/ha PE	14.2	12.9	378	354	46	43	4.58	4.27	45.2	45.4
Pendimethalin + metribuzin (TM) 1500 + 175 PE	15.6	13.6	384	369	48	46	5.28	4.74	46.7	46.1
Pendimethalin + metribuzin (TM) *fb* pinoxaden 1000 +175 *fb* 60 g/ha PE *fb* PoE	16.1	13.8	402	396	52	50	5.56	4.93	46.8	46.6
Pendimethalin + metribuzin (TM) *fb* mesosulfuron + iodosulfuron (RM) 1000 + 175 *fb* 14.4 g/ha PE *fb* PoE	16.7	14.3	431	415	54	52	6.15	5.37	48.0	47.9
Pendimethalin + pyroxasulfone (TM) 1500+102 g/ha	15.2	13.9	394	390	49	49	5.09	4.58	47.2	47.2
Pendimethalin + pyroxasulfone (TM) *fb* pinoxaden 1500+102 *fb* 60 g/ha PE *fb* PoE	16.4	14.2	410	402	53	51	5.78	5.13	47.6	47.2
Pendimethalin + pyroxasulfone (TM) *fb* mesosulfuron + iodosulfuron (RM) 1500+102 *fb*14.4 g/ha PE *fb* PoE	17.9	15.4	442	421	57	53	6.28	5.45	48.0	48.0
Pendimethalin + metribuzin (TM) *fb* pinoxaden 1500 + 175 *fb* 60 g/ha before sowing *fb* PoE	15.8	13.6	402	385	51	47	5.43	4.98	47.5	47.3
Sulfosulfuron *fb* pinoxaden 25 *fb* 60 g/ha BI *fb* PoE	16.0	14.1	405	404	51	48	5.76	5.01	47.7	47.3
Pinoxaden 60 g/ha PoE	15.2	13.3	380	368	48	45	5.31	4.64	47.0	46.5
Pinoxaden + metribuzin (TM) 50+120 g/ha PoE	15.0	13.4	394	386	50	46	5.63	4.91	46.4	46.7
Pinoxaden + metribuzin (TM) 50+150 g/ha PoE	15.2	13.5	412	398	52	47	5.71	5.16	46.6	46.7
Mesosulfuron + iodosulfuron (RM) 14.4 g/ha PoE	15.5	13.6	418	409	52	49	5.93	5.26	47.0	47.1
Weed-free check	17.9	15.6	445	427	57	54	6.32	5.57	48.1	48.1
Weedy check	13.2	12.2	354	341	43	40	4.14	3.91	44.7	44.6
LSD (p=0.05)	0.8	0.5	33	30	5	4	0.45	0.41	1.2	1.1

fb: followed by, PE: pre-emergence, PoE: post-emergence, and BI: before irrigation, TM: tank mix, RM: ready mix

and harvest index could be due to overall improvement in crop vigour and growth, reflected by improved dry weight/plant resulting in higher translocation of photosynthates from source to sink. This could be due to sequential application of pre- followed by post-emergence herbicides with more than one mode of action, provided efficient control of resistant *P. minor* and all other weeds in wheat field which resulted in less crop-weed competition for resources (water, nutrients, space, sunlight) and their efficient utilization for growth and development leading to higher production efficiency/productivity (Yadav *et al.* 2016, Kaur *et al.* 2019).

Conclusion

The continuous application of clodinafop, sulfosulfuron, mesosulfuron + iodosulfuron (RM) and pinoxaden herbicides year after year for the control of *P. minor* lead to the development of herbicide resistance. It was observed that out of 16 populations (collected from farmers' fields of different locations in Haryana, India); 7, 3, 2 and 1 populations recorded GR_{50} values higher than recommended for clodinafop (60 g/ha), sulfosulfuron (25 g/ha), mesosulfuron + iodosulfuron (14.4 g/ha) and pinoxaden (50 g/ha), respectively. These populations fall under resistant to highly resistant category to respective herbicides. To manage clodinafop resistance under field conditions, sequential application of tank-mixed pre-emergence pendimethalin + pyroxasulfone (1500 + 102 g/ha) (or) pendimethalin + metribuzin (1000 +175 g/ha) *fb* post-emergence pinoxaden (60 g/ha) (or) mesosulfuron + iodosulfuron (RM; 14.4 g/ha) brought 95-100% reduction in dry weight of resistant *P. minor* and total weed dry weight with higher WCE at different crop growth stages. This resulted in higher crop height, dry matter production, yield attributes, and 43-46% higher grain yield as compared to weedy check (4.0 t/ha). Application of single herbicide either as pre- or post-emergence proved ineffective for control of clodinafop resistant *P. minor* and recorded lower grain yield.

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RESEARCH ARTICLE

Efficacy of pre-emergent herbicides against diverse weed flora in wheat crop in Northern Transition Zone of Karnataka in South India

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ABSTRACT

A field experiment was carried out at All India Coordinated Wheat and Barley Improvement Project (AICW&BIP), Main Agricultural Research Station, University of Agricultural Sciences, Dharwad, Karnataka during *Rabi* season of 2021-22 and 2022-23. The weed free plot recorded significantly, higher growth and yield attributes, *viz.* plant height, lower lodging score, higher number of effective tillers, number of grains per spike, thousand grain weight, grain, straw and biological yields followed by pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix. The pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix recorded significantly lower total number of weeds (5.66, 6.96 and 4.57/m^2), total dry weight of weeds (2.26, 6.24 and 10.38 g/m^2), higher weed control efficiency (74.68, 62.48 and 61.07%) at 30, 60 and 90 DAS, respectively and lower weed index (2.64%) as compared to weedy check plot.

Key words: Economics, Pre-tank mix herbicides, Weed control efficiency, South India, Wheat, Yield

INTRODUCTION

Wheat (*Triticum aestivum* L.) holds the position of the second most crucial cereal crop in India, playing a vital role in ensuring food and nutritional security. Being widely cultivated worldwide, wheat stands out as the most popular staple food among grain crops, contributing significantly to human consumption. In India, diverse environmental conditions and dietary preferences support the cultivation of bread, durum and dicoccum wheat varieties. Bread wheat dominates production with a substantial 95%, followed by durum wheat at four percent and dicoccum at nearly one percent. Wheat serves as a vital carbohydrate source and is globally recognized as the primary source of vegetable protein in human diets, boasting a protein content of around 13%. This protein, gluten, is crucial for the baking process.

Globally, wheat is cultivated in an area of 222 Mha with a production of 779 Mt and having the productivity of 3510 kg/ha (Anon. 2022). In India, the estimated area 31.61 Mha with production of 109.52 Mt and productivity of 3464 kg/ha (Anon. 2021). Uttar Pradesh has the highest area (9.85 M ha) and production (35.50 Mt) followed by Madhya Pradesh (6.39 Mha, 17.62 Mt). Punjab has the highest average productivity of 4.86 t/ha followed by Haryana with 4.84 t/ha (Anon. 2021). Karnataka is unique in cultivation of three species, namely, bread, durum and dicoccum wheat. In Karnataka, the area under wheat is 1.67 lakh ha with annual production of 1.79 Mt and productivity of 1.20 t/ha.

Wheat is a key component of various cropping systems in different regions worldwide. Globally, the rice-wheat and cotton-wheat cropping systems collectively occupy 60% of the cultivated wheat area. In the state of Karnataka, groundnut-wheat, greengram-wheat and soybean-wheat cropping systems play a crucial role, where wheat is cultivated as either a rainfed or irrigated crop during the *Rabi* season. Weeds emerge as major contributors to decreasing crop productivity in these wheat-based cropping systems. They disrupt crop production practices and result in substantial yield and quality losses. The composition of weed flora is strongly influenced by factors such as soil types, cultivation systems and agronomic practices in different cropping systems.

Continuous growing of same crop in a cropping system results in the prevalence of the best-suited weeds. For instance, rice-wheat cropping system favoured *Phalaris minor, Chenopodium album,*

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Avena fatua, Rumex dentatus. Moreover, soybean-wheat-greengram cropping system favoured *Medicago denticulata, Chenopodium album* and *Phalaris minor,* whereas, *Echinochloa crus-galli, Eleusine indica, Commelina benghalensis, Amaranthus viridis, Abutilon indicum* were favoured by maize–wheat cropping system (Singh *et al.* 2017a). Similarly, groundnut-wheat cropping system favoured *Cynodon dactylon, Echinochloa colonum, Euphorbia hirta, Commelina benghalensis, Alternanthera sessilis* and *Cyperus rotundus* weeds (Agasimani *et al.* 2010).

At present, global pesticide consumption stands at approximately 2 million metric tons, with herbicides accounting for 47.5%, insecticides for 29.5%, fungicides for 17.5% and other pesticides for 5.5% of the total usage (Pathak *et al.* 2022). The leading countries in pesticide consumption worldwide are China, the USA, Argentina, Thailand, Brazil, Italy, France, Canada, Japan and India. Specifically, India reported a pesticide usage of 62,193 metric tons in the 2020-21 period, with insecticides comprising 51%, herbicides 16%, fungicides 32% and others 1% of the total (Shekhawat *et al.* 2022).

In India, herbicides are employed on more than 20 million hectares, constituting approximately 10% of the total cropped area in the country. Notably, wheat, rice, soybean and sugarcane are the major crops where herbicides find extensive use, accounting for approximately 28%, 20%, 9% and 7% of herbicide application, respectively. According to Rao *et al.* (2018), the highest consumed herbicides in India were Butachlor (6032 tons) and Glyphosate (6003 tons), followed by Paraquat (2068 tons), Pretilachlor (2418 tons) and Pendimethalin (1444 tons). The states with the highest herbicide consumption were reported to be Punjab, followed by Uttar Pradesh, Andhra Pradesh, Maharashtra and West Bengal.

Weeds pose a substantial threat to wheat cultivation in India, leading to significant annual productivity losses in various regions (Harrington *et al.* 1992). Weed infestation stands out as a major factor that hampers crop productivity. To unlock the full genetic yield potential of the crop, proper weed control becomes an indispensable component. Weeds not only diminish the overall yield but also complicate the harvesting process. Therefore, to sustain food grain production and meet the needs of the ever-growing population, effective weed management is crucial in wheat cultivation.

The primary objective of this study was to evaluate the efficacy of pre-emergent herbicides against diverse weed flora in wheat crop in Northern Transition Zone of Karnataka.

MATERIALS AND METHODS

Experimental site and design

A field experiment was conducted at All India Coordinated Wheat and Barley Improvement Project (AICW&BIP), Main Agricultural Research Station, University of Agricultural Sciences, Dharwad, Karnataka during *Rabi* season of 2021-22 and 2022-23 to assess the efficacy of pre-emergent herbicides against diverse weed flora in wheat crop in Northern Transition Zone of Karnataka. The soil type of experimental site was medium deep black with clay loam texture. Soil was neutral in reaction (pH 7.6) with normal electrical conductivity (EC 0.27 dS/m), medium in organic carbon content (0.58%), low in available nitrogen (174.23 kg/ha) and higher in available phosphorous (31.17 kg/ha) and potassium (291.14 kg/ha) content. The experiment was laid out in randomized block design with three replications. The experiment consists of twelve treatments, *viz.* pendimethalin 1000 g/ha PE, pendimethalin 1500 g/ha PE, pyroxasulfone 127.5 g/ha PE, pendimethalin + pyroxasulfone 1250 + 127.5 g/ha PE tank mix, pyroxasulfone 127.5 g/ha + metsulfuron 4 g/ha PE, pyroxasulfone 127.5 g/ha EPoE, pyroxasulfone + metsulfuron 127.5 + 4 g/ha EPoE tank mix, metribuzin 300 g/ha PE, pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix, pendimethalin + metribuzin 127.5 + 280 g/ha PE tank mix, weedy check and weed free. Each experimental plot had dimensions of 8.0 × 1.80 = 14.40 square meter in size. The sowing process utilized a seeding rate of 150 kg/ha, with a row spacing of 20 cm. The recommended doses of fertilizer (RDF) at 150: 75: 50 kg N:P:K /ha were applied. Nitrogen was applied in two equal splits, *i.e.* at sowing as basal application and 30 days after sowing. Entire quantity of phosphorus and potassium was applied as basal dose at the time of sowing along with 1/2rd nitrogen and the remaining was applying 1/3rd and 2/3rd nitrogen as 1/3rd at first irrigation and 2/3rd at second irrigation. The other package of practices was adopted to raise the wheat as for University of Agricultural Science, Dharwad. Irrigation was administered in accordance with the crop's water requirements using the check basin method. Pre-emergent herbicides were administered immediately after sowing on adequately moistened soil, while early post-emergence (EPoE) herbicides were administered at 21 days after sowing (DAS). Spraying was done by manually operated knapsack sprayer.

Crop sampling

Five plants were selected and harvested for subsequent analysis. The grains were then carefully separated from the spikes and enumerated. The average number of grains per spike was calculated for each treatment. Average value of number of effective tillers m^{-2} were counted from each net plot at harvest. The wheat crop was harvested manually, leaving two border rows unharvested in both directions and 0.5 m in the longitudinal direction. The harvested wheat grain was collected and then oven-dried at 65–70°C for 48 h. The dried grain was weighed to determine the economic yield. The crop harvesting was done from net plot and the yield was expressed in kg/hectare.

Lodging score

To score lodging the per cent area of plant that lodged was estimated and the angle of stem lodging was estimated (Wiersma *et al.* 2011).

$$Lodging\ score = \frac{\%\ area\ lodging\ \times Angle\ of\ lodging\ from\ vertical}{90}$$

Weed count

The number of weeds present in one m^2 area in each plot was counted at 30, 60 and 90 DAS.

Dry weight of weeds (g/m²)

Dry weight of weeds was recorded at 30, 60 and 90 DAS. The weeds were uprooted from the sampling area of 0.5 m^2 each time and oven dried to a constant weight 60 to 70°C and the dry weight of weeds was expressed as g/m^2.

Weed control efficiency (%)

Weed control efficiency (WCE) = [(X-Y)/X] × 100

Where,

X = Dry weight of weeds in weedy check

Y = Dry weight of weeds in the treatment

Weed index (%)

Weed index (Wp!) = [(X-Y)/X] × 100

Where,

X = Yield of weed free plot.

Y = Yield of treated plot.

Statistical analysis

All the data recorded were processed in Microsoft excel 2016 and analysed with ANOVA at 5% level of significance.

RESULTS AND DISCUSSION

Weed flora

The predominant weed flora observed in the experimental plots during the period of experimentation consisted of grassy weeds, sedges and broad-leaved weeds. Among the grassy weeds, *Echinochloa colona, Dinebra retroflexa, Digitaria sanguinalis, Brachiaria eruciformis* and *Cynodon dactylon.* Among broad-leaved weeds, *Lagascea mollis, Euphorbia geniculata, Ageratum houstonianum, Convolvulus arvensis, Alternanthera sessilis, Parthenium hysterophorus, Amaranthus viridis, Physalis minima, Phyllanthus niruri, Commelina diffusa, Portulaca oleracea.* Among sedges, *Cyperus rotundus* was noticed.

Effect on plant height and lodging score

Plant height of wheat as influenced by various weed management practices is illustrated in (**Table 1**). There are significant differences in plant height of wheat were identified as a result of various weed management practices through different herbicides application. Though the weed free plot has shown significantly higher plant height (80.33 cm). The weedy check treatment recorded significantly lowest plant height (69.93 cm). Improved weed control in the mentioned treatments likely led to more efficient utilization of light, water and nutrients compared to other treatments. The decreased plant height observed in the weedy check can be attributed to the suppressive impact of weeds on crop plants, as noted by Chander *et al.* (1997). The substantial competition from weeds resulted in reduced nutrient uptake by the crop, as evidenced by the lowest plant height observed in the weedy check, as reported by Balasubramanian (1985).

Significantly lower lodging score was recorded in weed free check (2.47%) followed by pendimethalin 1250 g/ha + metribuzin 280 g/ha PE tank mix (2.75%) and pendimethalin 1500 g/ha PE (2.77%). The weedy check recorded significantly higher lodging score (3.93%) (**Table 1**). This might be due to better weed control in the above treatments which resulted in weed-free plot supports lodging control in wheat by minimizing competition for resources, enhancing air circulation, facilitating effective fungicide application, preventing host plants for pests, optimizing plant density, improving nutrient utilization and eliminating lodging-prone weed species. These results in similarity with the findings of Chaudhari *et al.* (2017).

There is no significant difference was recorded in number of days taken for maturity of wheat were identified as a result of various weed management practices through different herbicides application. Though, the weed free check has shown numerically lower number of days take for maturity of wheat (105.67 days) followed by pendimethalin 1250 g/ha + metribuzin 280 g/ha PE tank mix (105.83 days). The weedy check recorded higher number of days taken for maturity of wheat (112.33 days) (**Table 1**). This might be due to better weed control in the above treatments which resulted in weed-free plot supports early maturity in wheat by minimizing competition for resources, enhancing nutrient availability, improving water use efficiency, reducing allelopathic effects, optimizing light exposure, preventing weed-induced stress, promoting crop uniformity and facilitating easier harvesting.

Effects on yield and yield attributes

The significantly, higher number of effective tillers and number of grains per ear head was recorded in weed free check (396.33/m^2 and 54.00) followed by pendimethalin 1250 g/ha + metribuzin 280 g/ha PE tank mix (385.33/m^2 and 52.00) and pendimethalin 127.5 g/ha + metribuzin 280 g/ha PE tank mix (375.00 m^2 and 51.47) (**Table 1**). The weedy check recorded significantly, lowest number of effective tillers and number of grains per ear head (303.83/m^2 and 43.43). The observed increase in the number of ear head productions per square meter in crops under effective weed control treatments could be attributed to reduced competition between the crop and weeds, leading to better conservation of soil moisture, nutrients and space. These findings align with the results reported by Chaudhari *et al.* 2017.

The statistically higher thousand grain weight (47.38 g) was recorded in weed free check followed by pendimethalin 1250 g/ha + metribuzin 280 g/ha PE tank mix (46.31 g). While, significantly lowest thousand grain weight was recorded in weed check plot (37.91 g) (**Table 2**). Improved weed control in the aforementioned treatments likely led to a more efficient utilization of light, water and nutrients compared to the other treatments. These outcomes align with the discoveries made by (Meena and Singh 2011).

The significantly, higher grain, straw and biological yields of wheat (4.74, 8.55 and 13.30 t/ha, respectively) were recorded in weed free plot than other treatments. The next best treatment was pendimethalin 1250 g/ha + metribuzin 280 g/ha PE tank mix (4.62, 8.51 and 13.13 t/ha, respectively) closely followed by pendimethalin 127.5 g/ha + metribuzin 280 g/ha PE tank mix (4.50, 8.34 and 12.85 t/ha, respectively). The weedy check recorded significantly lower grain, straw and biological yields of wheat (2.978 5.99 and 8.97 t/ha, respectively) among all the treatments as shown in (**Table 2**). The observed higher yield and associated attributes, such as the number of ear heads, number of grains per ear head and thousand grain weight, in the aforementioned treatments suggest improved

Table 1. Growth and yield attributes of wheat as influenced by different pre- and early pre-emergence tank mix herbicides application

Treatment	Plant height (cm) at 80 DAS			Lodging score (%)			No. of days taken for maturity			No. of effective tillers per m^2			No. of grains per ear head		
	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled
Pendimethalin 1000 g/ha PE	73.0	72.3	72.7	3.07	2.77	2.92	111.0	102.7	106.8	257.7	368.0	312.8	44.4	48.3	46.4
Pendimethalin 1500 g/ha PE	77.0	78.7	77.8	2.80	2.73	2.77	111.3	104.0	107.7	301.3	351.7	326.5	48.0	48.7	48.3
Pyroxasulfone 127.5 g/ha PE	73.9	77.5	75.7	3.13	2.80	2.97	108.0	104.7	106.3	295.0	384.3	339.7	44.8	49.3	47.1
Pendimethalin + pyroxasulfone 1250 + 127.5 g/ha PE tank mix	71.8	78.7	75.2	4.20	3.60	3.90	110.7	104.0	107.3	287.7	401.0	334.3	48.8	51.0	49.9
Pyroxasulfone 127.5 g/ha + metsulfuron 4 g/ha PE	74.5	80.0	77.2	3.07	2.77	2.92	109.7	103.0	106.3	291.3	407.0	349.7	46.0	49.3	47.7
Pyroxasulfone 127.5 g/ha EPoE	74.5	81.4	78.0	3.03	3.17	3.10	110.0	102.7	106.3	309.7	390.7	350.7	44.6	45.7	45.1
Pyroxasulfone + metsulfuron 127.5 + 4 g/ha EPoE tank mix	75.1	79.5	77.3	3.43	2.73	3.08	109.0	104.0	106.5	307.7	416.3	362.0	45.6	51.3	48.5
Metribuzin 300 g/ha PE	73.5	80.8	77.1	3.67	3.03	3.35	110.3	104.7	107.5	310.0	394.0	352.0	44.4	50.7	47.5
Pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix	74.3	79.8	77.0	2.83	2.67	2.75	108.3	103.3	105.8	324.7	446.0	385.3	50.0	54.0	52.0
Pendimethalin + metribuzin 127.5 + 280 g/ha PE tank mix	75.2	81.1	78.2	3.50	3.33	3.42	110.0	104.7	107.3	316.0	434.0	375.0	49.6	53.3	51.5
Weedy check	64.9	75.0	69.9	4.30	3.57	3.93	117.0	107.7	112.3	286.7	321.0	303.8	39.2	47.7	43.4
Weed free	78.8	81.9	80.3	2.70	2.23	2.47	109.3	102.0	105.7	330.0	462.7	396.3	51.3	56.7	54.0
LSD (p=0.05)	8.6	11.5	7.9	0.72	0.78	0.68	2.0	2.0	1.3	42.0	96.1	50.1	8.2	8.8	4.7

PE: pre-emergence; EPoE: early post-emergence; DAS: day after sowing performance compared to other treatments. These findings closely align with the results reported by Pisal and Sagarka (2013).

Harvest index of wheat as influenced by various weed management practices through different herbicide application is shown in (**Table 2**). Though the weed free check and pendimethalin 1250 g/ha + metribuzin 280 g/ha PE tank mix has shown higher harvest index (37 and 37%, respectively). While, lower harvest index was recorded in weedy check plot (33%). This might be due to support higher harvest index in wheat, allowing the crop to utilize resources efficient and reach its full potential. These results are in agreement with (Meena and Singh, 2011)

Effects on weeds

The treatment with effective weed control exhibited significantly lower total weed population and total weed dry weight, along with higher weed control efficiency and a lower weed index across all stages, compared to the other treatments. Among other weed management practices through different herbicides application, pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix recorded significantly lower weed population (5.66, 6.96 and 4.57 no./m), total weed dry weight (2.26, 6.24 and 10.38 g/m), higher weed control efficiency (76.84, 64.18 and 61.85) at 30, 60 and 90 DAS, respectively and lower weed index (2.64%) than other treatments and it was on par with pendimethalin + metribuzin 127.5 + 280 g/ha PE tank mix. However, weedy check plot recorded significantly higher total weed population (52.38, 63.86 and 56.91 no./m), total weed dry weight (8.91, 16.62 and 26.68 g/m) at 30, 60 and 90 DAS, respectively and weed index (37.23%) (**Table 3** and **4**). The observed effects are likely attributed to the herbicidal properties of pendimethalin, which specifically targets annual grass and small-seeded broadleaf weeds. Pendimethalin's mode of action involves entering grasses through the coleoptile and shoot of the seedling below the ground, as described by Vencill (2002). This herbicide effectively reduces weed competition in the initial stage and controls late-emerged weeds through sequential spray applications, leading to lower weed density and reduced weed dry matter. The efficacy of pendimethalin in controlling grasses is further supported by its pre-emergent action against annual grass weeds and small-seeded dicot weeds for approximately a month, as highlighted by Byrd and York, 1987. The rapid depletion of carbohydrate reserves in weeds through accelerated respiration, as proposed by Prakash *et al.* 1999, may contribute to the overall effectiveness of pendimethalin in weed control. The weed management practices in these treatments have controlled weeds efficiently throughout the growing season ultimately improving the yield of crop, which resulted in lower weed index. This resulted into satisfactory control over both broad-leaf as well and grassy weeds, respectively and ultimately reducing total weed count in respective treatments. The better performance of these herbicides might be due to the effective control of all type of weeds. This study provides further evidence to support the conclusions of Veeraputhiran and Srinivasan (2015) and Gnanavel and Babu (2008).

Table 2. Yield and yield attributes of wheat as influenced by different pre- and early pre-emergence tank mix herbicides application

Treatment	Thousand grain weight (g)			Grain yield (t/ha)			Straw yield (t/ha)			Biological yield (t/ha)			Harvest index (%)		
	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled	2021-22	2022-23	Pooled
Pendimethalin 1000 g/ha PE	41.83	43.20	42.52	3.53	3.91	3.72	6.53	7.56	7.05	10.06	11.47	10.77	33	34	35
Pendimethalin 1500 g/ha PE	42.11	43.70	42.90	3.65	4.09	3.87	6.41	8.41	7.41	10.06	12.50	11.28	36	33	34
Pyroxasulfone 127.5 g/ha PE	42.53	43.42	42.97	3.76	4.15	3.95	6.19	9.18	7.69	9.95	13.33	11.64	38	31	34
Pendimethalin + pyroxasulfone 1250 + 127.5 g/ha PE TM	43.92	45.80	44.86	3.91	4.91	4.41	6.28	9.06	7.67	10.19	13.97	12.08	36	35	35
Pyroxasulfone 127.5 g/ha + metsulfuron 4 g/ha PE	43.05	43.74	43.40	3.97	4.78	4.38	6.51	9.23	7.87	10.48	14.01	12.25	38	34	36
Pyroxasulfone 127.5 g/ha EPoE	42.19	46.78	44.48	3.70	4.20	3.95	7.01	9.12	8.06	10.72	13.32	12.02	35	32	33
Pyroxasulfone + metsulfuron 127.5 + 4 g/ha EPoE TM	43.35	45.49	44.42	3.97	4.77	4.37	6.75	8.35	7.55	10.72	13.12	11.92	36	35	35
Metribuzin 300 g/ha PE	44.20	44.86	44.53	3.73	4.65	4.19	7.29	8.50	7.90	11.02	13.15	12.08	34	35	35
Pendimethalin + metribuzin 1250 + 280 g/ha PE TM	45.14	47.48	46.31	4.01	5.23	4.62	7.50	9.52	8.51	11.51	14.75	13.13	35	35	35
Pendimethalin + metribuzin 127.5 + 280 g/ha PE TM	42.90	46.46	44.68	4.00	5.01	4.50	7.23	9.46	8.34	11.23	14.46	12.85	37	36	37
Weedy check	37.72	38.09	37.91	2.77	3.18	2.98	5.34	6.65	5.99	8.11	9.83	8.97	34	32	33
Weed free	46.21	48.55	47.38	4.26	5.23	4.74	7.56	9.54	8.55	11.82	14.77	13.30	38	35	37
LSD (p=0.05)	6.02	6.74	4.57	0.73	1.06	0.72	1.44	1.98	1.05	1.44	1.85	1.67	0.3	0.3	0.2

*Note: PE: pre-emergence; EPoE: early post-emergence; DAS: day after sowing; TM: tank mix

Table 3. Mean weed count and total weed dry weight at different growth stages of wheat as influenced by different pre- and early pre-emergence tank mix herbicides application

Treatment	Mean weed count (no./m)									Total weed dry weight (g/m^2)					
	2021-22			2022-23			Pooled			2021-22			2022-23		
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS
Pendimethalin 1000 g/ha PE	4.16 (16.3)	4.41 (18.5)	4.59 (20.1)	3.90 (14.2)	4.41 (18.4)	4.80 (22.0)	4.03 (15.3)	4.41 (18.4)	4.70 (21.1)	2.83 (7.0)	3.89 (14.1)	4.69 (21.0)	2.77 (6.7)	3.85 (13.8)	4.63 (20.4)
Pendimethalin 1500 g/ha PE	3.33 (10.1)	3.91 (14.3)	3.88 (14.1)	3.64 (12.2)	3.96 (14.7)	4.03 (15.2)	3.49 (11.1)	3.93 (14.5)	3.96 (14.7)	2.79 (6.8)	3.80 (13.4)	4.52 (19.4)	2.75 (6.6)	3.74 (13.0)	4.48 (19.1)
Pyroxasulfone 127.5 g/ha PE	3.30 (9.9)	3.55 (11.6)	3.70 (12.7)	3.07 (8.4)	3.59 (11.9)	3.59 (11.9)	3.19 (9.2)	3.57 (11.7)	3.65 (12.3)	2.69 (6.2)	3.76 (13.1)	4.42 (18.6)	2.64 (6.0)	3.72 (12.9)	4.37 (18.1)
Pendimethalin + pyroxasulfone 1250 + 127.5 g/ha PE TM	2.85 (7.1)	3.20 (9.2)	2.65 (6.0)	3.00 (8.0)	3.29 (9.8)	2.82 (6.9)	2.93 (7.6)	3.25 (9.5)	2.73 (6.5)	2.19 (3.8)	2.93 (7.6)	3.61 (12.0)	2.07 (3.3)	2.86 (7.2)	3.56 (11.7)
Pyroxasulfone 127.5 g/ha + metsulfuron 4 g/ha PE	2.92 (7.5)	3.30 (9.9)	2.74 (6.5)	2.98 (7.9)	3.35 (10.2)	2.83 (7.0)	2.95 (7.7)	3.33 (10.1)	2.79 (6.8)	2.37 (4.6)	3.35 (10.2)	3.83 (13.6)	2.30 (4.3)	3.27 (9.7)	3.76 (13.2)
Pyroxasulfone 127.5 g/ha EPoE	3.21 (9.3)	3.39 (10.5)	2.88 (7.3)	3.35 (10.2)	3.45 (10.9)	3.01 (8.1)	3.28 (9.8)	3.42 (10.7)	2.94 (7.7)	2.75 (6.6)	3.64 (12.3)	4.27 (17.2)	2.72 (6.4)	3.59 (11.9)	4.24 (17.0)
Pyroxasulfone + metsulfuron 127.5 + 4 g/ha EPoE TM	2.78 (6.7)	3.00 (8.0)	2.62 (5.9)	2.85 (7.1)	3.08 (8.5)	2.65 (6.0)	2.82 (6.9)	3.04 (8.24)	2.63 (5.9)	2.47 (5.1)	3.58 (11.8)	4.09 (15.8)	2.42 (4.9)	3.50 (11.2)	4.04 (15.3)
Metribuzin 300 g/ha PE	2.98 (7.9)	3.18 (9.1)	3.06 (8.3)	3.01 (8.0)	2.85 (7.1)	3.13 (8.8)	2.99 (7.9)	3.02 (8.1)	3.09 (8.6)	2.63 (5.9)	3.49 (11.2)	3.95 (14.6)	2.50 (5.2)	3.44 (10.9)	3.91 (14.3)
Pendimethalin + metribuzin 1250 + 280 g/ha PE TM	2.50 (5.2)	2.79 (6.8)	2.26 (4.1)	2.66 (6.1)	2.85 (7.1)	2.46 (5.0)	2.58 (5.7)	2.82 (7.0)	2.36 (4.6)	1.84 (2.4)	2.73 (6.5)	3.39 (10.5)	1.77 (2.1)	2.65 (6.0)	3.36 (10.3)
Pendimethalin + metribuzin 127.5 + 280 g/ha PE TM	2.68 (6.2)	2.82 (7.0)	2.53 (5.4)	2.78 (6.7)	3.00 (8.0)	2.58 (5.7)	2.73 (6.5)	2.91 (7.5)	2.56 (5.5)	1.94 (2.8)	2.80 (6.8)	3.57 (11.7)	1.92 (2.7)	2.75 (6.5)	3.53 (11.5)
Weedy check	7.84 (60.5)	8.68 (74.3)	8.13 (65.1)	6.72 (44.2)	7.38 (53.4)	7.05 (48.7)	7.31 (52.4)	8.06 (63.9)	7.61 (56.9)	3.09 (8.6)	4.18 (16.4)	5.23 (26.3)	3.20 (9.2)	4.22 (16.8)	5.29 (27.0)
Weed free	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00 (0.0)	1.00 (0.0)	1.00 (0.0)	1.00 (0.0)	1.00 (0.0)	1.00 (0.0)
LSD (p=0.05)	2.56	2.83	2.75	2.49	2.89	2.87	1.98	1.96	2.28	1.59	2.85	2.72	1.84	1.88	2.62

PE-Pre-emergence; EPoE-Early post emergence; DAS- Day after sowing *Figures in the parentheses represent original values Data subjected for transformation using ($\sqrt{x+1}$), where x is weed count

Table 4. Total weed dry weight, WCE and weed index at different growth stages of wheat as influenced by different pre- and early pre-emergence tank mix herbicides application

Treatment	Total weed dry weight (g/m^2) Pooled			Weed control efficiency (%)									Weed index (%)		
				2021-22			2022-23			Pooled					
	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	30 DAS	60 DAS	90 DAS	2021-22	2022-23	Pooled
Pendimethalin 1000 g/ha PE	2.80 (6.8)	3.87 (14.0)	4.66 (20.7)	18.4	13.6	20.4	28.1	17.5	24.5	23.2	15.6	22.5	17.1	25.2	21.6
Pendimethalin 1500 g/ha PE	2.77 (6.7)	3.77 (13.2)	4.50 (19.3)	20.5	17.9	26.2	28.9	22.4	29.3	24.8	20.2	27.8	14.3	21.8	18.5
Pyroxasulfone 127.5 g/ha PE	2.66 (6.1)	3.74 (13.0)	4.40 (18.3)	27.9	20.1	29.6	35.3	23.3	32.8	31.7	21.7	31.2	11.6	20.7	16.7
Pendimethalin + pyroxasulfone 1250 + 127.5 g/ha PE TM	2.13 (3.5)	2.90 (7.4)	3.59 (11.9)	55.8	54.0	54.2	64.8	57.3	56.7	60.2	55.7	55.5	8.2	6.2	7.1
Pyroxasulfone 127.5 g/ha + metsulfuron 4 g/ha PE	2.33 (4.4)	3.31 (10.0)	3.80 (13.4)	46.3	37.7	48.1	54.0	42.5	51.2	50.2	40.1	49.7	6.8	8.5	7.8
Pyroxasulfone 127.5 g/ha EPoE	2.73 (6.5)	3.62 (12.1)	4.26 (17.1)	23.3	25.3	34.5	31.1	29.3	36.9	27.3	27.3	35.7	13.0	19.7	16.7
Pyroxasulfone + metsulfuron 127.5 + 4 g/ha EPoE TM	2.45 (5.0)	3.54 (11.5)	4.07 (15.5)	40.5	28.0	40.1	47.7	33.0	43.3	44.1	30.6	41.7	6.6	8.8	7.8
Metribuzin 300 g/ha PE	2.57 (5.6)	3.47 (11.0)	3.93 (14.4)	30.9	31.9	44.6	43.3	35.2	47.1	37.3	33.6	45.9	12.4	11.1	11.7
Pendimethalin + metribuzin 1250 + 280 g/ha PE TM	1.80 (2.3)	2.69 (6.2)	3.37 (10.4)	72.3	60.7	60.3	76.8	64.2	61.8	74.7	62.5	61.1	5.8	0.1	2.6
Pendimethalin + metribuzin 127.5 + 280 g/ha PE TM	1.93 (2.7)	2.77 (6.7)	3.55 (11.6)	67.5	58.5	55.5	71.1	61.0	57.5	69.4	59.7	56.5	6.1	4.3	5.1
Weedy check	3.15 (8.9)	4.20 (16.6)	5.26 (26.7)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.9	39.1	37.2
Weed free	1.00 (0.0)	1.00 (0.0)	1.00 (0.0)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	0.0	0.0	0.0
LSD (p=0.05)	1.30	1.96	2.59	18.5	17.6	9.9	19.7	11.2	9.5	14.49	12.1	9.37	2.11	2.35	3.25

PE: pre-emergence; EPoE: early post-emergence; DAS- day after sowing; TM: tank mix; Figures in the parenthesis represent original values; Data subjected for transformation using ($\sqrt{x+1}$), where x is weed count

Table 5. Relative economics of wheat as influenced by different pre- and early pre-emergence tank mix herbicides application

Treatment	Cost of cultivation (₹/ha)	Gross returns (₹/ha)	Net returns (₹/ha)	B:C ratio
Pendimethalin 1000 g/ha PE	48895	137917	89022	2.82
Pendimethalin 1500 g/ha PE	49145	143535	94390	2.92
Pyroxasulfone 127.5 g/ha PE	48945	146880	97935	3.00
Pendimethalin + pyroxasulfone 1250 + 127.5 g/ha PE tank mix	49545	162752	113207	3.28
Pyroxasulfone 127.5 g/ha + metsulfuron 4 g/ha PE	49095	161852	112757	3.30
Pyroxasulfone 127.5 g/ha EPoE	48945	147192	98247	3.01
Pyroxasulfone + metsulfuron 127.5 + 4 g/ha EPoE tank mix	49095	161393	112298	3.29
Metribuzin 300 g/ha PE	48745	155267	106522	3.19
Pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix	49345	171027	121682	3.47
Pendimethalin + metribuzin 127.5 + 280 g/ha PE tank mix	48805	166785	117981	3.42
Weedy check	48445	110857	62412	2.29
Weed free	53770	175482	121712	3.26
LSD (p=0.05)	-	6820	4766	-

PE-Pre-emergence & EPoE-Early post emergence

Table 6. Phytotoxicity symptoms of herbicides on succeeding soybean (pooled)

Treatment	Germination (%)	yellowing					stunting				
		1	3	5	7	10	1	3	5	7	10
Pendimethalin 1000 g/ha PE	87.59	0	0	0		0	0	0	0	0	0
Pendimethalin 1500 g/ha PE	86.75	0	0	0		0	0	0	0	0	0
Pyroxasulfone 127.5 g/ha PE	88.25	0	0	0		0	0	0	0	0	0
Pendimethalin + pyroxasulfone 1250 + 127.5 g/ha PE tank mix	87.36	0	0	0		0	0	0	0	0	0
Pyroxasulfone 127.5 g/ha + metsulfuron 4 g/ha PE	87.00	0	0	0		0	0	0	0	0	0
Pyroxasulfone 127.5 g/ha EPoE	87.36	0	0	0		0	0	0	0	0	0
Pyroxasulfone + metsulfuron 127.5 + 4 g/ha EPoE tank mix	87.71	0	0	0		0	0	0	0	0	0
Metribuzin 300 g/ha PE	89.64	0	0	0		0	0	0	0	0	0
Pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix	88.66	0	0	0		0	0	0	0	0	0
Pendimethalin + metribuzin 127.5 + 280 g/ha PE tank mix	89.60	0	0	0		0	0	0	0	0	0
Weedy check	89.60	-	-	-	-	-	-	-	-	-	-
Weed free	89.97	-	-	-	-	-	-	-	-	-	-
LSD (p=0.05)	NS	-	-	-	-	-	-	-	-	-	-

Influenced on relative economics of wheat

Significantly higher cost of cultivation of wheat was recorded in weed free plot (₹ 53,770/ha). Where, as significantly higher gross returns, net returns and benefit cost ratio was recorded under pendimethalin + metribuzin 1250 + 280 g/ha PE tank mix. While, lower cost of cultivation of wheat was recorded in weedy check plot (₹ 48,445 /ha) but yield was to low shown in (**Table 5**). This might be due to higher labour was require for removing weeds from weed free plot as compared to weedy check plot. Similar results were also obtained by Singh *et al.* 2020.

Among various weed management practices through different herbicide application the weed free check recorded significantly higher gross return, net return and statistically higher benefit cost ratio (₹ 175482, ₹ 121712 and 3.26/ha, respectively), followed by pendimethalin 1250 g/ha + metribuzin 280 g/ha PE tank mix (₹ 171027, ₹ 121682 and 3.47/ ha, respectively) and pendimethalin 127.5 g/ha + metribuzin 280 g/ha PE tank mix (₹ 166785, ₹ 117981 and 3.42/ha, respectively). Weedy check treatment recorded significantly lower gross return, net return and benefit cost ratio (₹ 110857, ₹ 62412 and 2.29/ ha, respectively) as compared to other treatments (**Table 5**). The higher economics in the above-mentioned treatments can be attributed to higher yield of the respective treatments. The higher yield was achieved to better yield contributes and growth parameters. These parameters were results of efficient management of weeds in those treatment, which resulted in higher yield with better quality ultimately fetching more returns. Similar results were also obtained by Singh *et al.* 2020.

There is no phytotoxicity symptoms on succeeding crop of soybean

The current study definitively concluded that the pendimethalin + metribuzin at the rate of 1250 + 280 g/ha PE tank mix effectively managed a diverse weed flora in wheat, leading to enhanced grain yield and improved economic returns for wheat cultivation. Importantly pendimethalin + metribuzin PE tank mix was not shown any observable phototoxicity symptoms on the germination, root length, shoot length and seedling vigour index of the succeeding crop of soybean.

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RESEARCH ARTICLE

Integrated nutrient and weed management effect on greengram under new alluvial zone of West Bengal

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ABSTRACT

Field experiment was undertaken during summer season of 2020 and 2021 to evaluate the effect of various different nutrient and weed management options for higher productivity of greengram under new alluvial zone of West Bengal. The experiment was laid out in a split plot design with three replications and 28 treatment combinations. The treatments comprised with four main plot treatment, which includes nutrient management, *viz.* 100% RD_{NPK}, 100% RD_{PK} +75% RD_N + 25% N (vermicompost), 100% RD_{PK} +75% RD_N + 25% N (FYM), and 75 % RD_{NPK} + *Rhizobium* + PSB and seven weed control measures, *viz.* pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS, pendimethalin 1.25 kg/ha *fb* hoeing at 25 DAS, pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, pendimethalin 1.25 kg/ha *fb f*enoxaprop-p-ethyl 100 g/ha, weed check and weed free. Dry weight of weeds at 60 DAS lower observed with the 100% RD_{PK} + 75% RD_N + 25% N through vermicompost and was statistically better to other treatments. Whereas, it was lowest under pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha and was at par with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha and pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS and significantly superior to other integrated treatments. More seed yields was found with 100% RD_{PK} +75% RD_N + 25% N (vermicompost) and was at par with all other main plot treatments except 100% RD_{PK} +75% RD_N + 25% N (FYM). Highest stover production was observed with 100% RD_{NPK} which was at par with 100% RD_{PK} +75% RD_N + 25% N (vermicompost). Per cent increase in seed yield in main plot due to treatment, 100% RD_{PK} +75% RD_N + 25% N (vermicompost), 100% RD_{NPK} and 75% RD_{NPK} + *Rhizobium* + PSB was 52.48, 47.03 and 44.09 %, respectively compared to 100% RD_{PK} +75% RD_N + 25% N (FYM). The corresponding increase in straw yield under these treatments were 74.91, 79.01 and 48.11% as against the lowest recorded in 100% RD_{PK} +75% RD_N + 25% N (FYM). More seed and straw yield of greengram was recorded in weed free treatment followed by pre- and post-emergence application of pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha. Data revealed per cent increase in seed yield due to weed free and pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, which was 158.1 and 139.35%, respectively compared to weedy check. More return (₹ 50,052) and B:C ratio (2.27) was observed with 100% RD_{PK} +75% RD_N + 25% N (vermicompost) closely followed by 75 % RD_{NPK} + *Rhizobium* + PSB and 100% RD_{NPK}. With weed control measures, more return (₹ 46,584) and B: C ratio (2.23) was observed with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha and quizalofop-ethyl 50 g/ha.

Keywords: Greengram, Nutrient management, Weed control, Yield and economics

INTRODUCTION

Among the pulses, greengram (*Vigna radiata* L.) is one of the most important and extensively cultivated crops in India, which, is cultivated in arid and semi-arid region. Greengram is locally known as "moong". It contains about 25% protein, 1.3% fat, 3.5% mineral, 4.1% fiber and 56.7% carbohydrate. Despite the significance of this crop in our daily diet, the average productivity of this crop remains notably low in India. It thrives in locations with low and unpredictable rainfall, light textured soils with limited water holding capacity, and is also drought-resistant. With a short duration for growth, it adapts effectively to various multiple and intercropping systems. It is cultivated over an area of approximately 4.5 million hectares having a production of 2.64 million tons, with a productivity rate of 555 kg/ha (Anonymous, 2020-21). The primary reason for the crop's low production is attributed to inadequate nutrient supply and competition with weeds (Mukherjee 2022). Despite its wide adaptation in India, the crop faces a challenge of significantly low productivity, exacerbated by the intensive use of agrochemicals during the green revolution, negatively impacting soil health. To address this issue, there is substantial potential for growers to adopt an integrated nutrient management (INM) approach, emphasizing the use of organic amendments as an alternative or supplement to agrochemicals (Meena 2015). Noteworthy progress has been made in recent years,

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particularly in utilizing vermicompost and implementing seed inoculation with *Rhizobium* and PSB for INM. Furthermore, effective weed control measures are crucial for enhancing productivity, as weeds compete for essential resources during the early growth period. In addition to reducing crop yield by up to 70%, weeds increase production costs, harbor insect pests and diseases, degrade the quality of farm produce, and diminish land value. Weeds are resilient, easily spreading due to their prolific seed production, and once established, they are challenging to eradicate. Aligning with the type of weed and crop-weed competition, it is reported that weed interference can significantly reduce crop yield (Mukherjee 2015). The integrated use of farmyard manure (FYM), vermicompost, crop residues, and green manure can be employed to maximize the benefits of INM (Ghosh *et al.* 2021). In this context, it is of paramount importance to evolve the strategies for integrated nutrient and weed management. Considering the miserably low amount of organic matter, low fertility status of these soils, low purchasing power of farmers for fertilizers, a study was undertaken with specific objectives of identifying appropriate integrated nutrient and weed management treatments, to sustain greengram yields and soil productivity.

MATERIALS AND METHODS

The field experiment was conducted at District Seed Farm (AB Block), Kalyani under Bidhan Chandra Krishi Viswavidyalaya, West Bengal during *pre-Kharif* season of 2020 and 2021 in an upland situation with the objective to study the performance of different nutrients along with suitable weed management in greengram (*Vigna radiata* (L.) Wilczek). The farm is situated at approximately 22^{o} 56´ N latitude and 88^{o} 32´ E longitude with an average altitude of 9.75 m above mean sea level (MSL). The soil was sandy loam with a slightly acidic pH of 7.1. The available nitrogen (N), phosphorus (P), and potassium (K) levels were reported as 198.7 kg/ha, 19.72 kg/ha, and 187.52 kg/ha, respectively (Subbiah and Asija 1956, Olsen *et al.* 1954, Jackson 1973). The experiment was laid out in a split plot design with three replications and 28 treatment combinations. The treatments comprised four main plot treatments, which includes nutrient management, *viz.* 100% RD_{NPK}, 100% RD_{PK} +75% RD_{N} + 25% N (vermicompost), 100% RD_{PK} +75% RD_{N} + 25% N (FYM), and 75% RD_{NPK} + *Rhizobium* + PSB and seven weed control measures, *viz.* pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS, pendimethalin 1.25 kg/ha *fb* hoeing at 25 DAS, pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, pendimethalin 1.25 kg/ha *fb* fenoxaprop-p-ethyl 100 g/ha, weed check and weed free. Pendimethalin was applied as pre-emergence 3 DAS (days after sowing) and imazethapyr, quizalofop-ethyl, and fenoxaprop-p-ethyl were applied as post emergence weed control at 25 DAS. All the fertilizer applied as per treatment. The greengram crop (cv. *Meha*) was raised during summer season with a seed rate of 25 kg/ha, with plant to plant spacing of 10 cm and row to row spacing of 30 cm. The nutrients were applied using urea, single superphosphate, and muriate of potash. The N content in organic manures was 1.54 to 1.59% in vermicompost and 0.59 to 0.66% in farmyard manure (FYM), respectively. Knapsack sprayer (16 litres' capacity) with flat fan nozzles was used for herbicide application and the spray volume was 500 L/ha. Thinning was done at 15 DAS (days after sowing) to maintain uniform crop stand. Observations on different growth parameters like plant height, dry matter accumulation, crop growth rate, number and dry weight of nodules were recorded at 30, 45 and 60 DAS and yield attributing characters and yield were noted at the time of harvest. Crop sample were analyzed for uptake of nitrogen, phosphorous and potash as per standard laboratory procedure (Jackson 1973). Benefit: cost ratio (B:C) was obtained by dividing the gross income with cost of cultivation. The effect of treatments was evaluated on pooled analysis basis on yield attributes and yields. Data obtained from the 2 years were pooled and statistically analyzed using the F test as per the procedure given by Gomez and Gomez (1984). The experimental data were analyzed statistically by applying the technique of analysis of variance (ANOVA) prescribed for the design to test the significance of overall difference among treatments by the F test and conclusions were drawn at 5% probability level.

RESULTS AND DISCUSSION

Weed flora

Sixteen weed species were observed in experimental field; among them, grasses were four, sedges one and remaining weed flora were from broad-leaf category. The predominant weed species were *Digitaria sanguinalis*, *Cynodon dactylon*, *Eleusine indica*, *Echinochloa colona* among grasses; *Cyperus rotundus* among the sedges and the broad-leaf weeds were *Cleome viscose*, *Convolvulus arvensis*, *Eclipta alba*, *Amaranthus viridis*, *Euphorbia hirta*, *Digeria arvensis*, *Trianthema* *portulacastrum*, *Tribulus terrestris* and *Physalis minima*.

Weed density and weed dry weight

Different nutrient and weed management treatments had significant effect on all the growth and yield attributing characters (**Table 1** and **2**). All the weed control treatments significantly reduced the density of narrow and BLW. At 30 DAS, lowest grasses and BLW density was observed with the 75 % RD_{NPK} + *Rhizobium* + PSB, and was at par with 100% RD_{PK} +75% RD_N + 25% N through vermicompost for grasses only, and significantly better to other treatments. Lowest sedges density was observed with 100% RD_{PK} +75% RD_N + 25% N through vermicompost which was statistically better to all other main plot treatments. Total number of less weeds were observed with 75% RD_{NPK} + *Rhizobium* + PSB which were significantly superior to other treatments. However, higher number of weeds population was observed with the 100% RD_{PK} +75% RD_N + 25% N through FYM, which might be due to more invasion of weed via compost. At 30 DAS, lowest grassy and BLW population observed with pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS with various sub-plot treatments, which was at par only with pendimethalin 1.25 kg /ha *fb* hoeing at 25 DAS. This was statistically better to all other treatments except weed free situation. Least sedges population was observed with pendimethalin 1.25 kg/ha *fb* hoeing at 25 DAS, which was at par with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha and one hand weeding at 25 DAS. Total weed density was observed lowest at 30 DAS with pendimethalin 1.25 kg/ha *fb* one hand weeding at 25 DAS, which showed parity only with pendimethalin 1.25 kg/ha *fb* hoeing at 25 DAS and was statistically superior to all other treatment except weed free treatments. This corroborates with the earlier finding of Mukherjee (2021) and Verma *et al.* (2015). At 60 DAS, less density of weeds observed with 100% RD_{PK} +75% RD_N + 25% N through vermicompost, and was statistically better to all other main plot treatments. This was closely followed by 75% RD_{NPK} + *Rhizobium* + PSB and 100% $RD_{NPK.}$ Whereas, less number of all category of weed observed with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha and was at par with pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha for grasses only and it was statistically better to all other subplot treatments except weed free situation. The total weed density in pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha and pendimethalin 1.25 kg/ha *fb* fenoxaprop-p-ethyl 100 g/ha was 8.27, 10.2 and 11.56/m^2, respectively as against 17.67/m^2 in weedy check plot.

Lowest dry weight of BLW and sedges was observed with 75 % RD_{NPK} + *Rhizobium* + PSB and was at par with 100% RD_{PK} +75% RD_N + 25% N through FYM for BLW and 100% RD_{PK} +75% RD_N + 25% N through vermicompost for sedges, and notably better to all other treatments for reducing weed population. Less total dry weight of weed at 30 DAS observed with 75 % RD_{NPK} + *Rhizobium* + *PSB* was at par only with 100% RD_{PK} + 75% RD_N + 25% N through vermicompost to check dry weight of weed. Lowest dry weight of narrow and BLW observed with pendimethalin 1.25 kg/ha *fb* one hand weeding at 25 DAS was at par with pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha and pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha for grasses, and was statistically superior to all other treatments except weed free treatment. Least total dry weight observed with pendimethalin 1.25 kg/ha *fb* one hand weeding at 25 DAS was found comparable to pendimethalin 1.25 kg/ha *fb* one hand weeding at 25 DAS and pendimethalin 1.25 kg/ha *fb* hoeing at 25 DAS (**Table 1** and **2**).

Lowest dry weight of grasses at 60 DAS observed with 100% RD_{PK} +75% RD_N + 25% N through vermicompost was comparable with all other main plot treatments except 100% RD_{PK} +75% RD_N + 25% N through FYM. Further, observation on subplot treatments revealed less dry biomass of narrow-leave weeds with pendimethalin 1.25 kg /ha *fb* quizalofop-ethyl 50 g/ha which was at par with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha and one hand weeding at 25 DAS which was significantly superior to other treatments except weed free situation. Post-emergence application of quizalofop-ethyl 50 g/ha resulted significantly less narrow-leaved weed density and dry biomass over all other treatments. Better response of quizalofop-ethyl in controlling narrow-leaved weeds might be due to the fact that aryloxyphen - oxypropionates (AOPP) class to which this herbicide belongs is readily absorbed and translocated to meristematic region and exert herbicide activity. It acts by inhibiting the enzyme Acetyl Coenzyme–A carboxylase (ACCase) in susceptible species (Burton *et al.* 1997). Acetyl coenzyme catalyzes, the first committed step of fatty acid biosynthesis, is adenosine triphosphate dependent carboxylation of acetyl Co A to malonyl Co A. Grass species have a eukaryotic type ACCase in the chloroplasts which is sensitive to ACCase

Table 1. Effect of different treatments on weed density of weeds at 30 and 60 DAS in greengram (pooled data of two years)

Treatment	Weed density at 30 DAS (no./m^2)				Weed density at 60 DAS (no./m^2)			
	Grasses	BLW	Sedges	Total	Grasses	BLW	Sedges	Total
Nutrient management								
100% RD_{NPK}	4.56** (20.25)*	6.42 (40.66)	4.19 (17.03)	8.86 (77.94)	5.64 (31.26)	7.73 (59.33)	6.45 (41.15)	11.5 (131.7)
100% RD_{PK} +75% RD_N + 25% N (vermicompost)	3.85 (14.33)	5.62 (31.08)	3.49 (11.66)	7.59 (57.07)	4.87 (23.23)	6.17 (37.63)	4.97 (24.2)	9.25 (85.06)
100% RD_{PK} +75% RD_N + 25% N (FYM)	5.01 (24.64)	6.1 (36.74)	4.47 (19.44)	9.02 (80.82)	7.74 (59.36)	7.2 (51.36)	7.1 (49.98)	12.7 (160.7)
75 % RD_{NPK} + *Rhizobium* + PSB	3.44 (11.36)	4.38 (18.65)	3.85 (14.36)	6.7 (44.37)	5.92 (34.58)	6.98 (48.25)	5.79 (33.05)	10.79 (115.9)
LSD (p=0.05)	0.41	0.64	0.57	0.79	0.55	0.73	0.64	0.77
Weed management								
Pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS	3.03 (8.66)	3.75 (13.56)	3.71 (13.25)	5.84 (33.58)	5.64 (31.36)	7.41 (54.35)	5.46 (29.36)	10.75 (115.1)
Pendimethalin 1.25 kg/ha *fb* hoeing at 25 DAS	3.41 (11.15)	4.38 (18.69)	3.44 (11.36)	6.6 (43.09)	6.79 (45.65)	6.44 (41.02)	5.71 (32.15)	10.92 (118.8)
Pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha	4.71 (21.66)	4.57 (20.36)	4.24 (17.45)	7.74 (59.47)	4.96 (24.12)	5.26 (27.19)	4.68 (21.36)	8.27 (67.91)
Pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha	4.32 (18.2)	5.76 (32.69)	4.31 (18.11)	8.34 (69.00)	4.46 (19.36)	6.68 (44.11)	5.99 (35.36)	10.2 (103.6)
Pendimethalin 1.25 kg/ha *fb* fenoxaprop-p-ethyl100 g/ha	3.85 (14.36)	6.69 (44.25)	4.57 (20.36)	8.91 (78.97)	5.58 (30.65)	7.32 (53.06)	7.06 (49.36)	11.56 (133.3)
Weed check	7.18 (51.06)	9.73 (94.25)	5.64 (31.26)	13.3 (176.6)	10.5 (109.23)	11.2 (125.36)	8.81 (77.16)	17.67 (311.8)
Weed free	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
LSD (p=0.05)	0.53	0.74	0.60	1.26	0.61	0.91	0.73	1.27

*Figure in parentheses are original values. **Square root transformed value" (x+0.5)

Table 2. Effect of different treatments on dry weight of weeds at 30 and 60 DAS in greengram (pooled data of two years)

Treatment	Dry weight of weeds at 30 DAS (g/m^2)				Dry weight of weeds at 60 DAS (g/m^2)			
	Grasses	BLW	Sedges	Total	Grasses	BLW	Sedges	Total
Nutrient management								
100% RD_{NPK}	2.42 (5.36)	4.67 (21.32)	3.97 (15.26)	6.51 (41.94)	5.27 (27.26)	7.86 (61.21)	5.58 (30.69)	10.94 (119.2)
100% RD_{PK} +75% RD_N + 25% N (vermicompost)	2.18 (4.25)	4.09 (16.25)	3.43 (11.25)	5.68 (31.75)	4.48 (19.54)	6.87 (46.65)	5.48 (29.54)	9.81 (95.73)
100% RD_{PK} +75% RD_N + 25% N (FYM)	3.2 (9.74)	3.97 (15.25)	4.23 (17.39)	6.55 (42.38)	6.14 (37.16)	7.69 (58.58)	6.31 (39.32)	11.64 (135.1)
75 % RD_{NPK} + *Rhizobium* + PSB	2.2 (4.36)	3.46 (11.46)	3.22 (9.88)	5.12 (25.71)	5.24 (26.93)	6.06 (36.26)	5.26 (27.12)	9.52 (90.31)
LSD (p=0.05)	0.49	0.52	0.67	1.09	0.76	1.02	0.93	1.21
Weed management								
Pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS	1.87 (2.98)	2.85 (7.65)	3.26 (10.12)	4.54 (20.13)	4.66 (21.21)	6.34 (39.66)	6.85 (46.36)	10.38 (107.2)
Pendimethalin 1.25 kg/ha *fb* hoeing at 25 DAS	2.77 (7.15)	3.69 (13.11)	3.14 (9.33)	5.49 (29.59)	4.31 (18.05)	7.09 (49.75)	6.76 (45.23)	10.66 (113.0)
Pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha	2.04 (3.65)	3.88 (14.56)	3.97 (15.28)	5.83 (33.49)	4.56 (20.32)	5.73 (32.36)	4.97 (24.25)	8.79 (76.93)
Pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha	1.69 (2.36)	4.22 (17.35)	4.22 (17.32)	6.18 (37.65)	4.22 (17.32)	6.59 (42.98)	4.44 (19.21)	8.94 (79.55)
Pendimethalin 1.25 kg/ha *fb* fenoxaprop-p-ethyl100 g/ha	2.61 (6.32)	4.78 (22.36)	4.78 (22.36)	7.18 (51.04)	4.95 (24.02)	5.59 (30.78)	5.46 (29.26)	9.19 (84.06)
Weed check	4.46 (19.36)	6.46 (41.23)	4.97 (24.25)	9.24 (84.84)	7.93 (62.33)	10.5 (109.15)	7.68 (58.49)	15.18 (230.0)
Weed free	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)	0.71 (0.00)
LSD (p=0.05)	0.67	0.57	0.91	1.19	0.97	1.03	0.99	1.51

inhibitors. Whereas most broad-leaved species have a prokaryotic type of ACCase, which is not sensitive to ACCase inhibitors (Incledon and Hall 1997). Less BLW biomass found with pendimethalin 1.25 kg/ha *fb* fenoxaprop-p-ethyl 100 g/ha was at par with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha *fb q*uizalofop-ethyl 50 g/ha and pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS. Less dry weight of sedges with pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha showed parity with pendimethalin 1.25 kg /ha *fb* imazethapyr 100 g/ ha.

Growth parameters

Observations on different growth parameters revealed more plant height with 100% RD_{NPK}, which was notably better than other main plot treatments (**Table 3**). Among weed control measures, more plant height found with weed free treatment was statistically improved to all other subplot measures except weedy check plot. Further, **Table 3** revealed that LAI failed to give any statistical difference at 30 DAS either in main plot or subplot treatments, however at 45 and 60 DAS, more LAI observed with 100% RD_{PK} +75% RD_N + 25% N (vermicompost) was significantly better to all other treatment except 100% RD_{NPK}. With different subplot treatments, more LAI at 45 and 60 DAS was observed with pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha and was at par with all the treatments except pendimethalin 1.25 kg/ha *fb* hoeing at 25 and 50 DAS and weedy check and statistically superior to other treatments.

Plant dry biomass production failed to give any response at 30 DAS with different nutrient management options. Moreover, among subplot treatments, more plant biomass was seen with weed free which showed parity with pendimethalin 1.25 kg/ha *fb* one hand weeding at 30 DAS which was statistically superior to other subplot treatments. At 45 and 60 DAS, more plant biomass production was observed with 100% RD_{PK} +75% RD_N + 25% N and 100% RD_{NPK}, respectively. They were at par to each other and statistically better to all other main plot treatments. With subplot treatments, increased dry biomass at 45 DAS found with pendimethalin 1.25 kg/ha *fb* hoeing at 25 and 50 DAS was significantly better to all other treatments. At 60 DAS, more crop biomass found with weed free treatment was at par only with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, which was statistically superior to all other weed management treatments.

Increased number of branches per plant seen with 75% RD_{NPK} + *Rhizobium* + PSB was at par with all the treatments except 100% RD_{PK} +75% RD_N + 25% N (FYM), which gave least number of branches per plant. Moreover, more branches per plant observed with pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha was at par with pendimethalin 1.25 kg/ha *fb* one hand weeding 30 DAS and weed free situation.

More nodules per plan more found with 100% RD_{NPK} was significantly better to all other treatments at 30 DAS. However, at 45 and 60 DAS, more nodule per plant observed with 75% RD_{NPK} + *Rhizobium* +

Table 3. Effect of different treatments on different growth parameters of greengram (pooled data of two years)

Treatment	Plant height (cm) (60 DAS)	Leaf area index (DAS)			Dry biomass production (g/m^2)			Branches/plant (no.)	Nodules/plant (no.)			Dry weight of nodules (g/plant)		
		30	45	60	30	45	60		30	45	60	30	45	60
Nutrient management														
100% RD_{NPK}	49.16	3.03	4.32	3.11	27.8	132.4	342.8	4.29	18.63	38.41	25.25	0.047	0.077	0.06
100% RD_{PK} +75% RD_N + 25% N (Vermicompost)	47.39	3.00	4.41	3.61	27.4	137.4	321.6	4.19	16.34	34.65	25.09	0.046	0.081	0.067
100% RD_{PK} +75% RD_N + 25% N (FYM)	46.11	2.87	3.21	3.52	26.1	124.2	234.8	3.17	13.53	38.44	21.61	0.032	0.059	0.041
75 % RD_{NPK} + *Rhizobium* + PSB	46.98	2.89	3.44	3.13	28.1	136.2	264.6	4.38	17.69	40.24	30.33	0.035	0.078	0.068
LSD (p=0.05)	1.04	NS	0.70	0.58	NS	9.9	25.2	0.44	0.46	1.65	1.36	0.007	0.011	0.010
Weed management														
Pendimethalin 1.25 kg /ha *fb* one hand weeding 25 DAS	48.23	2.75	4.01	3.54	30.3	144.0	224.5	4.32	19.09	41.03	31.29	0.031	0.089	0.062
Pendimethalin 1.25 kg /ha *fb* hoeing at 25 DAS	46.38	2.92	3.63	3.11	28.3	161.4	256.2	4.02	14.37	36.53	28.75	0.049	0.061	0.057
Pendimethalin 1.25 kg /ha *fb* imazethapyr 100 g/ha	49.25	3.11	4.08	3.02	28.1	121.5	366.5	4.11	16.03	38.78	20.51	0.054	0.087	0.051
Pendimethalin 1.25 kg /ha *fb* quizalofop-ethyl 50 g/ha	46.25	2.98	4.11	3.98	27.6	129.4	287.9	4.65	17.89	42.39	27.81	0.032	0.081	0.068
Pendimethalin 1.25 kg/ha *fb* fenoxaprop-p-ethyl100 g/ha	45.69	3.02	4.03	3.41	25.1	134.7	301.8	3.85	18.69	34.74	21.54	0.041	0.065	0.044
Weed check	44.32	2.63	3.06	2.73	22.5	91.6	211.8	3.13	11.36	29.92	17.11	0.020	0.049	0.033
Weed free	51.66	3.06	4.7	3.69	31.2	144.9	381.5	4.23	19.44	42.46	31.63	0.051	0.09	0.069
LSD (p=0.05)	1.36	NS	0.68	0.59	2.3	10.2	16.1	0.34	0.87	1.98	1.69	0.003	0.012	0.005

PSB was significantly better to all other main plot treatments. With different weed management treatments, increased parameters observed with weed free plot showed parity only with pendimethalin 1.25 kg/ha *fb* one hand weeding 30 DAS at all stages, and pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha at 45 DAS only (**Table 3**).

Data on dry weight of nodule revealed more value obtained with 100% $RD_{NPK,}$ which was at par with 100% RD_{PK} +75% RD_{N} + 25% N (vermicompost) and significantly better to other treatments. At 45 and 60 DAS, more dry weight observed with 100% RD_{PK} +75% RD_{N} + 25% N (vermicompost) was at par with all the main plot treatments except 100% RD_{PK} +75% RD_{N} + 25% N (FYM). At 60 DAS, increased dry weight of nodule observes with 75% RD_{NPK} + *Rhizobium* + PSB was closely followed by 100% RD_{PK} +75% RD_{N} + 25% N (vermicompost) and 100% RD_{NPK}, and they were at par with each other. Among various subplot treatments, more nodule dry weight at 30 DAS, observed with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha was at par with weed free treatment. At 45 and 60 DAS, more dry weight of nodule observed with weed free showed parity only with pendimethalin 1.25 kg/ha *fb* one hand weeding at 30 DAS, pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha and pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha at 45 DAS (**Table 3**).

Yield and yield attributing characters

Yield attributing character revealed significant difference with diverse main and subplot treatments. Increased number of pods/plant and seeds/plant, observed with 100% RD_{NPK} was at par with all the treatments except 100% RD_{PK} +75% RD_{N} + 25% N (FYM). With different subplot treatments, added pods/plant was found with weed free treatment and showed parity with pendimethalin 1.25 kg /ha *fb* imazethapyr 100 g/ha and pendimethalin 1.25 kg /ha *fb* hoeing at 25 DAS (**Table 4**). Additional number of seed per pod established with weed free was closely followed by pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha and pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, and was statistically better to other treatments. The increase in growth and yield attributes under these treatments might be attributed due to the reduction in weed competitiveness with the crop which ultimately favoured better environment for growth and development of crop, while, weedy check recorded significantly lowest values for growth, yield attributes and yields of greengram crop.

Increased seed yield realized with 100% RD_{PK} +75% RD_{N} + 25% N (vermicompost) was at par with all other main plot treatments except 100% RD_{PK} +75% RD_{N} + 25% N (FYM). Highest stover production observed with 100% $RD_{NPK\ was}$ at par with 100% RD_{PK} +75% RD_{N} + 25% N (vermicompost), notably better to other main plot treatments. Per cent increase in seed yield in main plot due to treatments was 52.48, 47.03 and 44.09% in 100% RD_{PK} +75% RD_{N} + 25% N (vermicompost), 100% RD_{NPK} and 75 % RD_{NPK} + *Rhizobium* + PSB, respectively compared to 100% RD_{PK} +75% RD_{N} + 25% N (FYM). The corresponding increase in straw yield under these treatments was 74.91, 79.01 and 48.11% as against the lowest recorded in 100% RD_{PK} +75% RD_{N} + 25% N (FYM). Increased vegetative growth and balanced C: N ratio led to higher carbohydrate synthesis, enhancing yield attributing characters in greengram due to combined organic and inorganic fertilizer application (Mukherjee and Mandal 2017). Improved nutrient supply from both sources and weed control treatments boosted seed and straw yields significantly. Maintaining a weed-free environment during critical growth stages reduced crop-weed competition, fostering better growth and development, resulting in higher seed and stover yields. It was found that the highest seed and straw yield of greengram was recorded in weed free treatment followed by pre- and post-emergence application of pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha. They were at par to each other and significantly better to other treatments. The highest yield under weed free treatment due to the fact that this treatment controlled early as well as late flushes of weeds and provided weed free environment to the crop during critical period of crop weed competition. The results are in conformity with the findings of Verma *et al.* (2015) and Singh and Singh (2020). On the other hand, pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha had significantly controlled grassy weeds and the most dominated broad-leaved weed and saved the crop efficiently from its infestation and it reflected in terms of significant increase in growth and yield attributes which ultimately resulted into higher yield of crop. This result indicated that appreciable increase in seed yield and decrease total dry weight of weeds were recorded under these treatments are also responsible for better seed and stover yield of greengram. These findings are accordance with the finding of Chhodavadia *et al.* (2014). Lowest seed yield observed with weedy check and was statistically poor to all the treatments. Increased stover production found with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha was statistically at par with the weed free and pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, and significantly better to other subplot treatments. Data revealed per cent increase in seed yield due to weed free, pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS and pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, was 158.1, 139.35, 111.41 and 108.61%, respectively compared to weedy check. The corresponding increase in straw yield under these treatments was 123.36, 131.21, 100.77 and 119.43% as against the lowest recorded in weedy check. More harvest index observed with 100% RD_{PK} +75% RD_N + 25% N (FYM) showed parity only with 75% RD_{NPK} + *Rhizobium* + PSB and was statistical better to all other main plot treatments. Further with different weed management treatments, more harvest index found with pendimethalin 1.25 kg /ha *fb* hoeing at 25 DAS was at par only with weed free and significantly better to other treatment.

Nutrient uptake

Nutrient uptake by crop significantly influenced with different nutrient and weed management option. Increased crop nutrient uptake was recorded with the application of 100% RD_{PK} +75% RD_N + 25% N (vermicompost) and showed at par result with all major nutrient uptake with 100% $RD_{NPK,}$ and nitrogen and potassium uptake with 75% RD_{NPK} + *Rhizobium* + PSB, and significantly better to other treatments (**Table 4**). With different subplot treatments, increased nitrogen uptake observed with weed free treatments was at par with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha, pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, and pendimethalin 1.25 kg/ha *fb* one hand weeding 25 DAS which was statistically better to other treatments. This corroborates with the finding of Chhodavadia *et al.* (2013). Phosphorus uptake more found with weed free and significantly better to all other treatments of weed management options. Further, more potassium uptake with weed free showed parity with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha and pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha, which was significantly better to other treatments.

Economics

The economics of greengram was varied with the variation in the treatment impact of different nutrient and weed management practices applied to the crops (**Table 4**). The total treatment cost in greengram has varied with the difference in the cost for nutrient and weed management. Economics revealed that with different nutrient management measures, more return (₹ 50,052) and B:C ratio (2.27) was observed with 100% RD_{PK} +75% RD_N + 25% N (vermicompost) and was closely followed by 75 % RD_{NPK} + *Rhizobium* + PSB and 100% RD_{NPK} (**Table 4**). With subplot treatments, more net return was observed with weed free (₹ 56044) followed by pendimethalin 1.25 kg /ha, *fb* imazethapyr 100 g/ha (₹ 46,584) and pendimethalin 1.25 kg/ha *fb* quizalofop-ethyl 50 g/ha (₹ 43,099). However, with weed management options, more B:C ratio was observed with pendimethalin 1.25 kg/ha *fb* imazethapyr 100 g/ha (2.26) which was closely followed by weed free treatment (2.23).

Table 4. Effect of different treatments on yield attributes, yield and economics of greengram (pooled data of two years)

Treatment	Pods/ plant (no.)	Seeds/ pod (no.)	Test weight (g)	Seed yield (t/ha)			Stover yield (t/ha)	Harvest index (%)	Nutrient uptake (kg/ha)			Cost of cultivation (x10^3 `/ha)	Net returns (`/ha)	B:C ratio
				2020	2021	Pooled			N	P	K			
Nutrient management														
100% RD_{NPK}	25.05	11.09	31.08	0.91	1.06	0.99	2.81	26.03	88.51	13.14	78.63	41.49	46.51	2.12
100% RD_{PK} +75% RD_N + 25% N (vermicompost)	23.39	10.03	32.19	104	1.01	1.02	2.74	27.20	90.47	14.01	85.11	39.28	50.05	2.27
100% RD_{PK} +75% RD_N + 25% N (FYM)	18.66	8.34	28.06	0.71	0.64	0.67	1.57	30.01	61.21	10.15	65.64	37.15	17.35	1.46
75 % RD_{NPK} + *Rhizobium* + PSB	22.87	9.33	29.39	102	0.91	0.97	2.32	29.41	81.41	11.31	75.96	36.06	43.29	2.20
LSD (p=0.05)	2.32	1.01	0.73	0.07	0.07	0.07	1.60	0.93	12.19	1.31	11.36			
Weed management														
Pendimethalin 1.25 kg /ha *fb* one hand weeding 25 DAS	22.36	9.48	32.42	0.98	0.98	0.98	2.47	27.68	85.38	12.63	83.81	42.26	39.66	1.93
Pendimethalin 1.25 kg /ha *fb* hoeing at 25 DAS	23.05	9.05	31.83	1.01	0.88	0.94	2.25	30.42	78.44	12.54	72.84	40.57	33.89	1.83
Pendimethalin 1.25 kg /ha *fb* imazethapyr 100 g/ha	24.36	11.55	34.64	1.09	1.14	1.11	2.85	28.06	93.41	13.03	90.65	36.85	46.58	2.26
Pendimethalin 1.25 kg /ha *fb* quizalofop-ethyl 50 g/ha	20.365	10.97	28.19	1.02	0.92	0.97	2.71	26.35	91.63	12.11	87.11	35.95	43.10	2.19
Pendimethalin 1.25 kg/ha *fb* *f*enoxaprop-p-ethyl100 g/ha	19.311	8.45	30.01	0.64	0.77	0.71	2.25	23.99	68.53	11.94	64.57	36.58	37.50	2.02
Weed check	22.36	6.25	22.74	0.50	0.43	0.46	1.23	27.37	45.39	8.84	39.65	31.95	18.32	1.57
Weed free	25.68	11.89	33.9 8	1.20	1.19	1.20	2.75	30.36	98.32	13.91	95.43	45.31	56.04	2.23
LSD (p=0.05)	2.89	1.24	0.97	0.08	0.08	0.08	0.19	1.18	14.35	1.29	10.02			

Conclusion

It can be stated that need based application of nutrient and weed management method should be advocated for greengram. On the basis of experimental finding, application of 100% RD_{PK} +75% RD_N + 25% N (vermicompost) along with pendimethalin 1.25 kg /ha *fb* imazethapyr 100 g/ha become very effective for higher productivity of greengram under new alluvial zone.

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RESEARCH ARTICLE

Comparative evaluation of agronomical, mechanical and chemical management of weeds and their impact on sugarcane productivity

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ABSTRACT

Weeds are opportunistic plants causing serious yield reduction in sugarcane production, so management of unwanted vegetation is of paramount importance for sugarcane cultivation. With this objective, an experiment was planned at Navsari Agricultural University, Navsari (Gujarat) to assess the various weed management strategies including agronomical, mechanical/physical and herbicides on weeds and yield of sugarcane (*Saccharum officinarum*). The experiment comprised of 14 treatments (two control *i.e.* weedy check and weed free along with herbicides, *viz*. atrazine, pendimethalin, metribuzin. 2,4-D Na salt and 2,4-D amine salt and their combination in-between as well as with cultural practices) laid out in randomized complete block design replicated thrice. The weed flora of experimental site during *Kharif* season was alienated with 60% broad-leaf weeds and 40% grassy weeds. Among broad-leaf weeds, *Phyllanthus maderaspatensis, Alternanthera sessilis, Euphorbia hirta, Digera arvensis, Physalis minima, Convolvulus arvensis* and *Trianthema portulacastrum* were found as dominant. While, among grassy weeds *Eragrostis major, Brachiaria reptans, Echinochloa colonum, Cynodon dactylon, Digitaria sanguinalis* and *Commelina benghalensis,* were the major weeds, whereas there was only one dominating sedge *i.e. Cyperus rotundus*. The results showed all the weed management practices significantly produced higher sugarcane yield over weedy check and HW at 30, 60 and 90 DAP + IC at 45 and 90 DAP was found significantly superior, being at par with application of pre-emergence herbicides *i.e.* atrazine or metribuzin *fb* HW+IC at 60 DAP which recorded lowest weed density, weed dry matter, weed index and maximum weed control efficiency. The presence of weeds reduced cane yield about 49.8% in comparison to HW+IC (weed free). In addition to this, application of pre-emergence herbicides followed by post-emergence herbicides or smoother crop (sunnhemp) was also found remunerative.

Keywords: 2,4-D Amine salt, 2,4-D Na salt, Atrazine, Integrated Weed Management, Pendimethalin, Metribuzin, Sugarcane

INTRODUCTION

Sugarcane (*Saccharum* spp. hybrid complex), a key cash crop cultivated from 8°N to 30°N latitude covering diversity of climate and soil of India, having the second largest sugar making in the world (Patel *et al*. 2018). Sugar industry, located in rural areas of India is next to agro based industry after textiles (Lokhande *et al*. 2018). In India, s'cane is cultivated in an area of 4.85 million hectares with a cane production of 397.66 million tonnes and average productivity of 81.98 tonnes/ha. Gujarat is one of the prominent states in sugarcane and sugar production, where, sugarcane is cultivated in 1.83 lakh hectares with a production of 13.62 million tonnes. Highest cane yield produced by farmers for sugarcane was 261 t/ha, however, the average yield of state is about 74.53 t/ha. Thus, there is a wide gap amongst the usual yields and potential yield and production potential can be attained by adopting good agronomical practices of crop production (Anonymous 2021).

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Many factors are responsible for the declining sugarcane yield. Weed infestation and poor agronomic practices proved fatal and caused heavy yield reductions. Sugarcane being a perennial crop having invasion of all sorts of weeds; seasonal, annual and perennials (Das 2009). The antagonism triggered through weeds is a main restrictive factor for sugarcane production. Heavy infestation of weeds comprising grasses, broad leaf weeds and sedges poses a big challenge for sugarcane production because its planted with a moderately wider row spacing, initial growth is very slow as it takes about 30 to 45 days for complete emergence and additional 60-75 days for developing full canopy cover, besides plentiful water and nutrient supply again provides ample opportunities for weeds to occupy the vacant space that is easily available between rows and thus, it offers serious competition to crop. The occurrence of weeds in the sugarcane fields and no control has also led to a decrease in sugar yield (Roshan *et al.* 2006, Kanchan 2009) in proportion of sucrose, purity and brix (Rathika 2023). Generally, the increase in weed growth by one kilogram corresponds to a reduction in one kilogram of crop dry matter. Sugarcane crop faces tough competition with weeds between 60 to 120 days of its planting which causes heavy reduction ranging from 40-67 per cent (Chauhan and Srivastava 2002). Weed competition can decrease millable stalks by 32%, stalk thickness by 15% and sugar yield by 31% compared to weed-free plots (El-Shafai, *et al.* 2010). The reduction in cane yields due to weeds ranged from 40 to 60% noted by Kadam *et al.* (2011), about 24 to 52% were also noted by Khan (2015) and Fontenot *et al.* (2016). In India, weeds which sprout at later stages and twine around clumps affect cane growth and cause yield losses range from 12 to 72 per cent, could go up to 17.5 t/ha. Further, the total cane yield loss in the country per annum is around 25 million tonnes (equivalent to 2.5 million tons of sugar) valued around rupees 1500 crores (Takim *et al.* 2014). Besides, weeds act as host of certain pests and disease caused incidental losses. Bermuda grass (*C. dactylon*) cogan grass (*I. cylindrica*) and other grassy weeds are identified as alternate hosts to Ratoon Stunting Disease (RSD) of sugarcane (Walia 2003). Besides, *Ipomoea* spp. is a serious weed is many sugarcanes cultivating areas, escalating cost of farming, too decreasing cane yields. Weeds drain sizable amount of moisture, nutrients, solar radiations, capture space and may produce allele-chemicals (Abbas *et al.* 2017) that damage the crops and decrease the yield (Christoffoleti *et al.* 2006, Huang *et al.* 2018). Weeds uptake 4 times of N and P and 2.5 times of K compared to sugarcane within first seven-week period (Anusha and Rana 2016). So, management of weeds is not only essential task for gainful sugarcane production but also imperative for reduction in exhaustion of nutrient and water resources from soil.

Different kinds of socioeconomic and environmental aspects influence on the choice of weed management methods. Manual, biological, mechanical, and chemical methods are the usual ways of treating weeds. Manual weed control is challenging because it takes longer, is weather-dependent, and can cause a bad smell when weeds are uprooted. Mechanical weed control carries the risk of crop plant injury, as well as the distribution of weed seeds in fields and potential soil erosion issues (McErlich and Boydston 2013). One has to avail the excellent quality herbicides that have a great promise in controlling all kinds of weeds in sugarcane. Herbicides are being extensively used for weed control in many sugarcane growing countries of the world for the following reasons 1) Labour is becoming scarce and overpriced 2) Conventional approaches are inefficient 3) Early weed growth cannot be controlled by conventional methods 4) Well-timed weeding is becoming tough, time taking and expensive. Pre-emergence application of triazine molecules (atrazine, simazine *etc.*) resulted high mortality of weeds in sugarcane fields (Bimbraw and Kaur, 2004; Smith, *et al.* 2011). A large number of trials across the nation have directed that for sole crop of sugarcane, atrazine is the most reliable herbicide at dosages ranging from 1.25 to 2.0 kg/ha. Besides, 2,4-D at 1.0 to 1.5 kg/ha (sprayed on weeds between 20 and 40 days) has been found highly effective in controlling most of the broad-leaved weeds. Atrazine, metribuzin and 2,4-D have become very popular herbicides throughout the country in sugarcane. They give a more or less complete weed free condition for about 50 to 60 days. Moreover, post-emergence application of Paraquat dichloride and Glyphosate applied between the rows as directed spray on weeds can control wide variety of weeds suggested by Hameed *et al.* (2017). Especially glyphosate being translocated herbicide has a great promise in controlling pernicious weeds like *Cynodon dactylon* and *Cyperus* spp., in widely spaced cane crop (Singh and Kaur 2004). A hood should be used especially when Paraquat and Glyphosate is applied to target/kill only weeds and to safeguard the crop, as such, a protection on the nozzle avoids spray drift reaching the crop. For controlling twining weeds such as *Ipomoea* spp. and *Convolvulus* spp., application of atrazine (1.0 kg/ha) or metribuzin (1 kg/ha) may be done between the cane rows after final earthing up. Weed control through chemicals is comparatively more resourceful and reasonable due to entrance of novel chemistry and herbicides (Kahramanoglu and Uygur 2010, Khan 2015). Thus, it is important to know and select a compound that is the most effective in controlling weeds in sugarcane in order to reduce the operational cost of weed management. Sometimes single approach does not give satisfactory results to combat weeds below threshold or the selectively of herbicides with weed flora can limit the control of weeds. Hence, integrated weed management concept found more appropriate especially combination of chemical, physical and cultural methods.

Overall, a weed free environment during the germination and tillering phase is important for attainment higher yield. This can be accomplished by the introduction of effective herbicides that has revolutionised the weed control in sugarcane. Selection of appropriate herbicides along with accurate dose and time of application is the key to success for controlling weeds. Consequently, keeping in view of these perspectives, the current study aims to: (1) conduct a survey on weed species that are present in sugarcane fields, (2) assess the efficacy of herbicides to control the weeds in sugarcane and (3) study the effect of weed management strategies on sugarcane yield.

MATERIALS AND METHODS

Description of the study area: A field experiment was conducted for three years *i.e.* 2014-15, 2015-16 and 2017-18 at Instructional Farm, N.M. College of Agriculture, Navsari Agricultural University, Navsari on *Vertisols*. The experimental site was located at the longitude of 20.9229° N, 72.8882° E latitude with 10 m altitude, from mean sea level.

Edaphic and climatic conditions: Before conducting the field trial, soil samples (0-30 cm depth) were collected randomly with the help of auger from the experimental area at the time of field lay out. All samples were mixed to form one composite sample to characterize its physical and chemical properties. The soil physical property of the study area was sand (14.30%), silt (19.56%) and clay (63.89%) means that soil of the experimental field was clay (deep black) in texture, organic carbon (0.53 %), pH (7.80) with EC of 0.419 dS/m shows the reaction of soil was slightly alkaline. The available N (248 kg/ha) and P (50.8 kg/ha) status of the soil was medium whereas available K (364 kg/ha) contents were in high range. The total rainfall received during the crop season was 1655, 1720 to 1585 mm in 49, 55 and 48 rainy days with annual average maximum and minimum temperatures of 39.85°C and 18.43°C, and mean temperature of 29.14°C. Out of total rainfall, most of the rainwater was received from the South-West monsoon period (June- September), however unexpected rain during off-season are very common. The mean relative humidity of the area was 77.5%, ranging from average maximum of 90% to minimum of 61%.

Treatments and experimental design: The experiment was laid out in randomised block design (RCBD), keeping with fourteen weed management strategies with three replications. The treatments included two control *i.e.* weedy check (allowed weed infestation throughout crop period) and weed free (kept weed free for season long) and the rest twelve treatments included herbicides (atrazine, pendimethalin, metribuzin. 2,4-D Na salt and 2,4-D Amine salt) and their integration in-between as well as with cultural practices. The details of the treatments are given in **Table 1**. Each plot was 7.2 m × 6.0 m (43.20 m^2) in size. There were eight-planting furrows of 6.0 m length spaced at 0.90 m distance. The distance between blocks, (replications) was 2.0 m and between plots was 1.5 m, so herbicides drifting could be avoided.

Crop husbandry: The field was prepared following the mechanical tillage (deep disc ploughing for removal of hardpan of the soil and harrowing for preparation of seedbed) practices to facilitate sugarcane setts plantation. Land was levelled and furrowed precisely. In accordance with the

Table 1. Weed management treatment details (trade name, active ingredient, formulation, herbicides doses and its time of application, other weed management strategies investigated)

Symbol	Treatment	Trade name	a.i. (%)	Formulation	Dose (kg/ha)	Application time
W_1	Weedy check	--	--	--	--	--
W_2	Three HW + two IC	--	--	--	--	at 30, 60 & 90 and 45 & 90 DAP
W_3	Atrazine	Atrataf	50	WP	2.0	Pre- emergence (PE)
W_4	Atrazine *fb* HW and IC	Atrataf	50	WP	2.0	PE and at 60 DAP
W_5	Pendimethalin *fb* HW and IC	Stomp	30	EC	1.0	PE and at 60 DAP
W_6	Metribuzin *fb* HW and IC	Sencor	70	DF	1.0	PE and at 60 DAP
W_7	Atrazine *fb* 2,4-D Na salt	Atrataf, Heera Super	50, 80	WP, WP	2.0 +1.0	PE and at 60 DAP
W_8	2,4-D Na salt *fb* Paraquat	Heera Super, Gramoxone	80, 24	WP, SL	1.0 + 0.5	At 30 *fb* 60 DAP
W_9	2,4-D Amine salt *fb* Paraquat	Zura, Gramoxone	58, 24	WSC, SL	1.0 + 0.5	At 30 *fb* 60 DAP
W_{10}	2,4-D Amine salt *fb* Metribuzin	Zura, Sencor	58, 70	WSC, WP	1.0 + 0.5	At 30 *fb* 60 DAP
W_{11}	2,4-D Amine salt *fb* Atrazine	Zura, Atrataf	58, 70	WSC, WP	1.0 + 1.0	At 30 *fb* 60 DAP
W_{12}	Pendimethalin + sunnhemp (smother crop)	Stomp	30	EC	1.0	PE *fb* at 60 DAS
W_{13}	Metribuzin + sunnhemp (smother crop)	Sencor	70	DF	1.0	PE *fb* at 60 DAS
W_{14}	Atrazine + sunnhemp (smother crop)	Atrataf	50	WP	1.0	PE *fb* at 60 DAS

* **a.i.** : Active ingredient**, WP :** Wettable powder**, EC**: Emulsifiable concentrate, **DF**: Dry Flowables, **SL**: Soluble Liquide, **WSC**: Water-Soluble Concentrates, **HW:** Hand Weeding, **IC**: Inter-cultivation, **PE**: pre-emergence and **DAP**: Days after planting

specifications of the design, a field layout was prepared. After furrow adaptation, disease-free, well-fertilized seed canes were chopped. Healthy three budded sugarcane cultivar (Co. 99004) setts were collected and used for planting. Carbendazim (1 g /1 litre of water) was used to prevent the disease transmission at the time of cutting and chopping. Sugarcane chopping knife was also sterilized with Dettol before chopping. The dry method of sugarcane planting was used and done by manual labour in flat bed method, eventually irrigation was applied. Setts were planted by overlapping three budded setts in the furrows and covered them with soils. Planting was done on first half of December and harvested after fourteen months during all the three seasons of experiments. All plots were uniformly received 250-125-125 kg NPK/ha + FYM 10 t/ha on area based. Before application of FYM, it was blended with bio-fertilizer (*Acetobacter* + PSB 12.5 lit/ha) and Trichoderma as prophylactic measure. Half dose of phosphorus, full dose of potash and ¼ dose of nitrogen were used during crop sowing while remaining dose of nitrogen was used in to 3 equal portions; ¼ at germination completion, ¼ at tillering and remaining ¼ nitrogen and ½ phosphorus at final earthing up. Total 13-irrigations were given according to crop requirement by tube well. All other cultural practices except weed management followed the sugarcane production guidelines.

Herbicides treatments: Five herbicides were tested *i.e.* atrazine, pendimethalin, metribuzin. 2,4-D Na salt and 2,4-D Amine salt. These herbicides were applied at different rates using the hand operated knapsack sprayer (15 litter capacity) fitted with flat fan nozzle covered by a spray hood to avoid unnecessary drifting towards neighbour plots. A spray volume of 495 lit. of water was used per hectare. The hand weeding operations were carried out with the help of "*Khurpi*" and intercutting was carryout with bled harrow as per the treatments, while, control plots were treated by water only.

Weed species survey: Weed species survey was conducted randomly from one-meter square from each plot of experimental field. Green weed plants were pulled out from the soil. The weed species that were easy to identify were recorded in the field, those species which could not be identified in the field were brought to the laboratory and were identified using the weed identification guide (Naidu 2012). Weeds were then identified and classified into three groups *i.e.* monocot, dicot and sedges.

Observation on weeds: Weeds from one-meter square were taken from the quadrate from each plot by hand pulling of weeds. Weeds were separated and air-dried followed by oven dried at 65^{0}C ±2 for 48 hrs. and weighed. The effect of tested herbicide on density (no./m^2) and dry weight of grass weeds (g/m^2) was recorded at 60 DAP and at final earthing up of the crop and the data were subjected to log transformation by adding 0.5 to original value prior to statistical analysis. Same data were used to know the reduction percentage in the dry weight and calculate the weed control efficacy (WCE) by using formula given by Mani *et al.* (1973) as followed.

$$\text{WCE (\%)} = \frac{\text{WDc - WDt}}{\text{WDc}} \text{ X } 100$$

Where, WDc = Dry weight of weed in control, and

WDt = Dry weight of weed in treatment

Further, weed index is defined as the extent of yield reduction due to incidence of weeds in comparison with weed free condition. In other sense, it expresses the competition offered by weeds that measured as per cent reduction in yield owing to their occurrence in the field. To know the losses caused by weeds in sugarcane, weed index was computed as procedure given by Gill and Kumar (1969) using the following formula:

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

Whereas, X = Yield from weed free plot (hand weeding)

Y= Yield of plot for which WI is calculated

Observation on crop: Data on millable canes yield was taken at the time of harvest per plot, finally converted in to tonnes per hectare. The primary data generated through observations and laboratory analysis during the investigation was statistically analysed and the differences among the treatment means were tested for their significance (P=0.05) as described by Gomez and Gomez (1984).

RESULT AND DISCUSSION

Weed composition

Since, sugarcane is long duration crop, a diverse weed flora was observed from the investigational plots and the major were *Cyperus rotundus* from sedge; *Echinochloa colonum*, *Cynodon dactylon* *Commelina benghalensis* and *Digitaria sanguinalis* were dominated weeds belongs to monocot; whereas *Phyllanthus maderaspatensis*, *Alternanthera sessilis*, *Digera arvensis*, *Trianthema portulacastrum* and *Convolvulus arvensis* were major weeds from dicot. In addition to the aforementioned species, other weeds were also observed in relatively low densities. Overall, seven of these weeds were classified as monocots (44%), eleven as dicots (46%), and two as sedges (10%). Results are in conformity with Suwanarak (1994) and Singh *et al.* (2012).

Weed density

The impact of weed management techniques on weed density, categorized by species, was observed at 60 days after planting (DAP) and at the final earthing up stage. The results, as presented in **Table 2**, indicate that the treatments applied to sugarcane field had a significant influence on the weed density. The weedy check treatment recorded a higher count of monocot, dicot, and sedge weeds, which was significantly greater than the other weed management strategies that were successful in weed knockdown.

Monocots: At sixty (60) days after planting, pre-emergence application of Atrazine, and hand weeding + inter-cultivation significantly reduced the monocot density followed by pre- emergence spraying of metribuzin and pendimethalin. Further, application of Paraquat significantly minimized the monocot count, which was statistically followed by three hand weeding+ two inter-cultivations, and postemergence application of herbicides *i.e.* Atrazine and Metribuzin as well as smoother cropping with sunnhemp at final earthing-up.

Dicots: Hand weeding thrice in combination with inter-cultivation twice recoded significantly lower dicot weeds density at 60 DAP and at earthing-up, application of herbicides *viz*. Atrazine, metribuzin and 2,4-D (Na salt or amine salt) were found equally effect at 60 DAP.

Sedges: Application of 2,4-D (Na salt or amine salt) and HW+IC found superior by reducing the sedges weed density at 60 DAP. Further, at earthing-up, adaptation of HW thrice + IC twice significantly curtailed the sedges count and recorded significantly the lower sedges, being at par with 2,4-D (Na salt or amine salt) *fb* Paraquat application.

Total weeds density: Removed the weeds through three hand weeding + two inter-cultivation recorded significantly the lowest density of weeds at both 60 DAP and at earthing-up. Moreover, other weed management combinations also significantly minimized the total weed density compared to weedy check, however failed to compete with HW+IC method of weed removal.

The data on weed count (**Table 2**) respond by weed management option including herbicide sprayed either pre or post-emergence shows significant reduction in density of monocot, dicot, sedge weeds ultimately reflected in total weed density at all crop growth stages compared to weedy condition. However, none of the herbicides as well as integrated weed management treatments were found as effective as hand weeding + inter-cultivation observed for weed density reduction. Rana and Singh, (2004), Tomar *et al.* (2005) also concluded that the density of the weeds likely to increase with progress in crop age up to ninety days and decline thereby irrespective of the treatments, because at start the needs of weeds remains low that permits the new weeds to establish, while at a later stage intra-weed competition resulted in exclusion of later germinated weed plants and also due to slow initial growth of cane that gives more chance to weeds for

Table 2. Monocot, dicot and sedge count at 60 days after planting and at erthing-up in sugarcane as influenced by various weed management strategies (pooled over 3 years)

Treatment	Monocot (no./m^2)		Dicot (no./m^2)		Sedge (no./m^2)		Total weed (no./m^2)	
	60 DAP	At earthing up	60 DAP	At earthing up	60 DAP	At earthing up	60 DAP	At earthing up
Weedy check	8.19(67.1)	10.87(118.3)	7.64(58.9)	6.57(43.2)	2.78(7.8)	3.19(10.2)	11.5(133.8)	13.1(171.8)
Three HW + two IC	4.10(17.2)	5.14(26.9)	3.73(14.2)	3.76(14.4)	1.55(2.6)	1.47(2.2)	5.82(34.0)	6.53(43.2)
Atrazine	4.55(20.8)	7.34(54.2)	5.51(30.7)	5.75(33.6)	2.32(5.4)	2.73(7.6)	7.52(56.9)	9.74(95.3)
Atrazine *fb* HW and IC	4.14(18.3)	7.14(51.1)	4.94(24.7)	4.98(25.0)	2.35(5.6)	2.44(6.0)	6.94(48.6)	9.05(82.1)
Pendimethalin *fb* HW and IC	4.82(23.6)	7.04(49.7)	5.29(28.2)	4.87(24.2)	2.37(5.7)	2.64(7.0)	7.57(57.4)	8.98(80.9)
Metribuzin *fb* HW & IC	4.41(19.8)	6.94(48.9)	4.89(24.3)	4.85(23.7)	2.42(5.9)	2.68(7.3)	7.06(50.0)	8.90(79.9)
Atrazine *fb* 2,4-D Na salt	4.00(16.8)	5.66(32.3)	4.95(24.7)	4.33(18.9)	2.39(5.8)	1.94(3.9)	6.83(47.2)	7.42(55.1)
2,4-D Na salt *fb* paraquat	7.81(61.1)	5.04(25.6)	3.95(15.9)	4.62(21.6)	1.63(2.8)	1.62(2.7)	8.92(79.8)	7.05(49.8)
2,4-D Amine salt *fb* paraquat	7.72(59.7)	5.09(26.1)	3.93(15.8)	4.62(21.4)	1.71(3.0)	1.57(2.7)	8.85(78.4)	7.08(50.2)
2,4-D Amine salt *fb* metribuzin	7.64(58.9)	5.05(25.8)	3.90(15.7)	4.63(21.7)	1.65(2.9)	2.10(4.6)	8.76(77.4)	7.20(52.0)
2,4-D Amine salt *fb* atrazine	7.42(55.3)	5.08(25.9)	4.10(17.1)	4.60(21.3)	1.52(2.4)	2.14(4.8)	8.64(74.9)	7.21(52.0)
Pendimethalin + sunnhemp	4.62(21.9)	5.06(25.7)	4.53(20.6)	5.31(28.3)	2.11(4.6)	2.37(5.7)	6.84(47.0)	7.72(59.7)
Metribuzin + sunnhemp	4.62(21.7)	5.58(31.3)	5.17(26.9)	5.37(29.0)	2.20(5.0)	1.99(4.1)	7.30(53.6)	8.01(64.4)
Atrazine + sunnhemp	4.82(23.4)	5.61(31.6)	5.09(26.4)	5.40(29.2)	2.18(4.8)	2.07(4.3)	7.38(54.7)	8.06(65.1)
LSD (p=0.05)	0.56	0.48	0.55	0.44	0.26	0.30	0.50	0.48

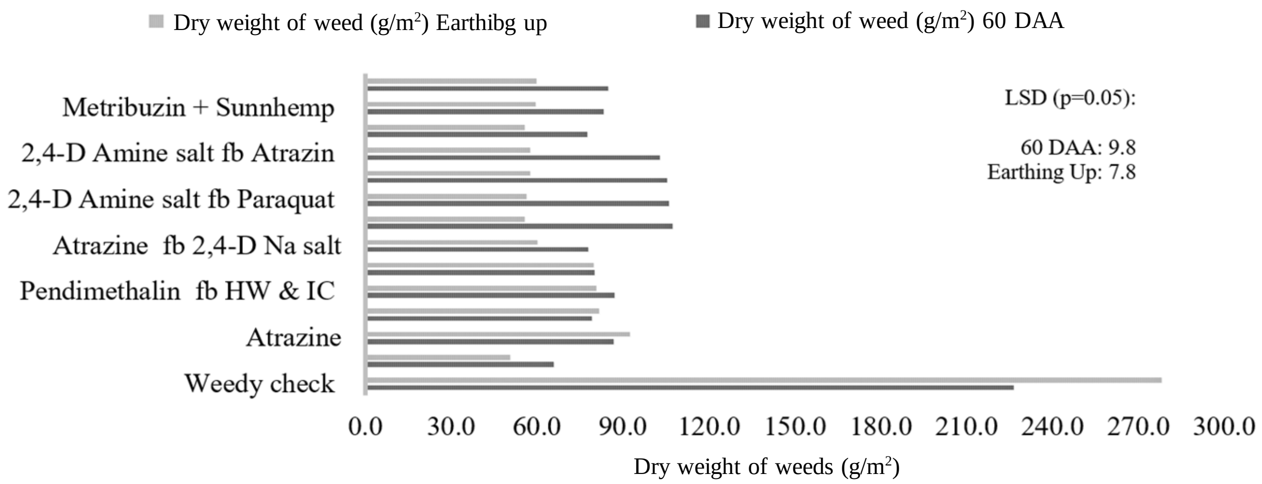


Figure 1. Weeds dry weight influenced by weed management (pooled of 3 years)

emergence, while it deceased afterword due to smothering effects of sugarcane. Srivastava *et al.* (2005), Tomar *et al.* (2005), Lal *et al.* (2006) and Singh *et al.* (2013) also concluded that inter-culturing at 30-45 days' interval is most effective in reducing weed density. Further application of herbicides (pre and post) caused highest reduction in density of all types of weeds, might be due to fact that most of the weeds at initial stage were actively growing and herbicide was effectively absorbed by roots and moved with transpiration stream and caused toxicity at the site of action of different weed. The more density of monocots was observed in plots treated with 2, 4-D because its a selective herbicide that eliminates dicots without harming monocots (Song 2014). Whereas, application of atrazine and metribuzin significantly reduced the weed density in sugarcane reported by Mishra *et. al* (2012) and Singh *et.al* (2012).

Overall response of different treatments was also justified with the results reported by Singh *et al.* (2013) as they all documented clearly that the treated plots significant minimized the density of weeds compared to weedy plot due to phytotoxicity or mortality of weed by various management techniques. The response was found more superior in HW+IC, because periodical removal of weeds physically and mechanically destroyed the three flushes of weeds from the sugarcane filed.

Dry weight of weeds

The data on dry weight of total weeds (**Figure 1**) varied in different weed management treatments, might be due to variable density of weeds. Perusing of the data also revealed that, the biomass buildup of weeds increased with progression of crop stage up to 90 days and dropped subsequently regardless of the treatments. The maximum decrease in total weed dry weight was noted under hand weeding (30, 60 and 90 120 DAP) + inter cultivation (45 and 90 DAP). The next better treatments were application of 2,4-D Na salt *fb* Paraquat, 2,4-D amine salt *fb* Paraquat, 2,4-D amine salt *fb* metribuzin, 2,4-D amine salt *fb* atrazine and pendimethalin + sunnhemp as smoother crop, that also reduced the dry matter accumulation significantly compared to weedy check. The minimum decline in dry weight of weeds was recorded with the application of atrazine because single application of herbicide only killed initial germinating weeds and failed to cause phytotoxicity on later emerged weeds. Decrease in weed dry matter, attributed to physical and mechanical weed management, has also been noticed by Singh *et al.* (2012) and Kumar *et al.* (2014).

Paraquat is classified as a contact herbicide and is not translocated extensively throughout the plant. It acts quickly with no selectively, and is lethal to all plant cells it comes in contact with. Atrazine is a pre- and post-emergence, slowly acting herbicide, that moves within the plant's structure (Heri *et al.* 2008). The effectiveness of both herbicides in controlling weed density and weed biomass showed gradual declines and disappeared within 30 to 60 days after application. Increases in weed biomass at 60 DAA were attributed to the successful growth of some weed species up to the reproductive stage, which completes the life cycle, particularly within a single herbicide application. As expected, the sequential applications of herbicides resulted in better check on re-growth of weeds (**Table 2 and Figure 1**). Shade-tolerance was another characteristic characterized by the most common weed species in sugarcane fields observed due to smothering effect. The methods used to control the dominant weed species are, therefore, dependent on species, environment, and soil type; as well as the dissipation of toxicity at 30 to 60 DAA. While, maximum weed biomass was noticed under weedy check because weed species were free to germinate, reach maturity, and successfully completed its entire lifespan without facing any hurdles and management aspect.

Weed control efficiency (%): Data pertaining to the effect of various weed management treatments on weed control efficiency (%) calculated in terms of percentage at final earthing-up are furnished in **Figure 2**. Highest weed control efficiency of 81.8 per cent was found under the treatment three HW (30, 60 and 90 DAP) + two IC (45 and 90 DAP), whereas lowest weed control efficiency *i.e.* 66.83 per cent observed in single application of Atrazine at earthing-up. The weed control obtained under various treatments was in the order of W_2>W_{12}>W_8>W_9>W_{10}e”W_{11}>W_{13}> W_{14}e”W_7>W_6>W_5>W_4>W_3.

The maximum control efficiency was noticed with three HW+ two IC, might be due periodical removal of weeds that curtailed the unwanted vegetation frequently leads maximum weed control efficiency. Moreover, application of pre- emergence herbicides killed the weeds at the times of germination or just after germination that provided sufficient time and space to emergence and establishment of crops seedlings for next thirty to thirty-five days, whereas, later emerged weeds destroyed with application of post emergence herbicides lead to comparable weed control efficacy. Similarly, integration of different weed management *i.e.* chemicals, physical, cultural methods appreciably control the weeds compared to weedy check and alone application of atrazine because either weeds was freely established or only one flush was removed in single application of herbicide.

Sugarcane yield: The data furnished in **Figure 3** indicated that all the weed management practices significantly improved the sugarcane production compared to weedy check. Significantly higher cane yield of 129.64 t/ha was recorded with three HW (at 30, 60 and 90 DAP) + two IC (at 45 and 90 DAP), being at par with metribuzin (PE) *fb* HW and IC (at 60 DAP) and atrazine (PE) *fb* HW and IC (at 60 DAP) that produced 99.1, 91.6 and 85.9 per cent higher than weedy check. Presence of weeds in weedy check compete badly for inputs and resources with the sugarcane plants throughout the year, in due course reduced the cane yield by 49.8%. Overall, mechanical weeding or integration of pre-emergence with mechanical weeding found significantly superior. Moreover, sequential application of pre and/ or post emergence herbicides was not significantly comparable with superior treatment combinations, however produced significantly higher cane yield (62.6%, on an average) than weedy check. Additionally, pre-emergence application of herbicides with agronomical practices *i.e.* smoother cropping also produced significantly higher yield (47.3%, on an average) than control and proved it efficacy.

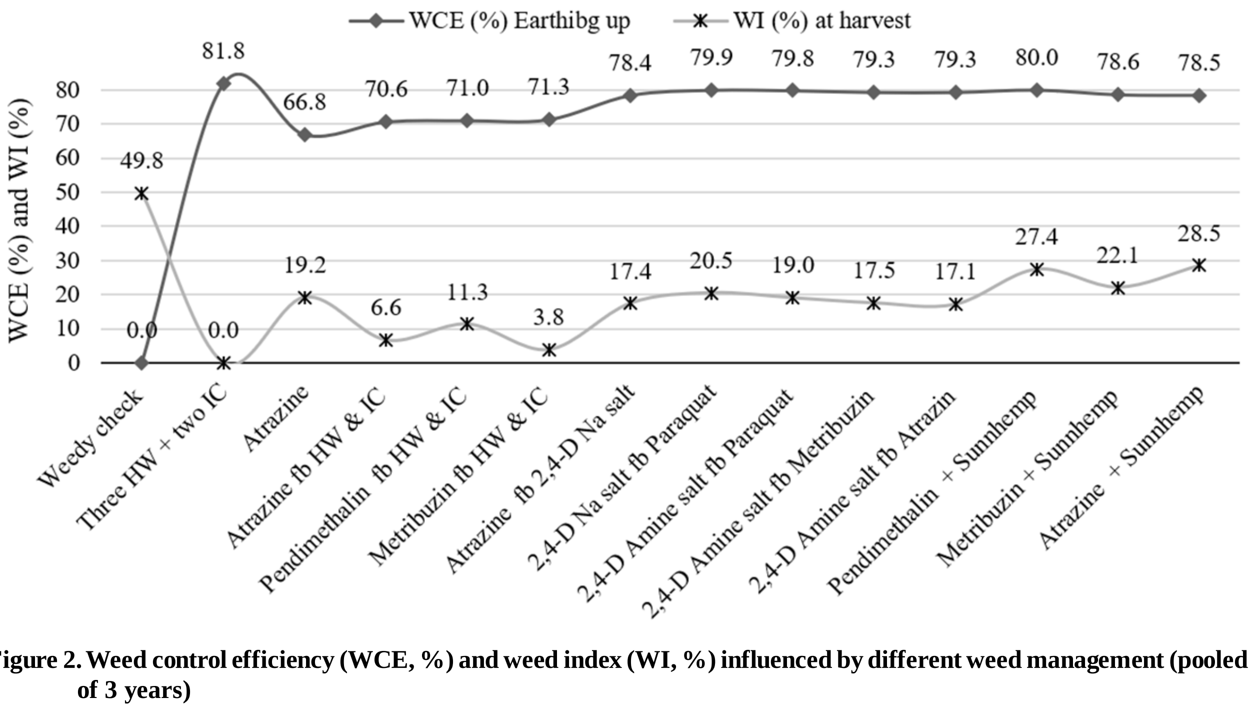
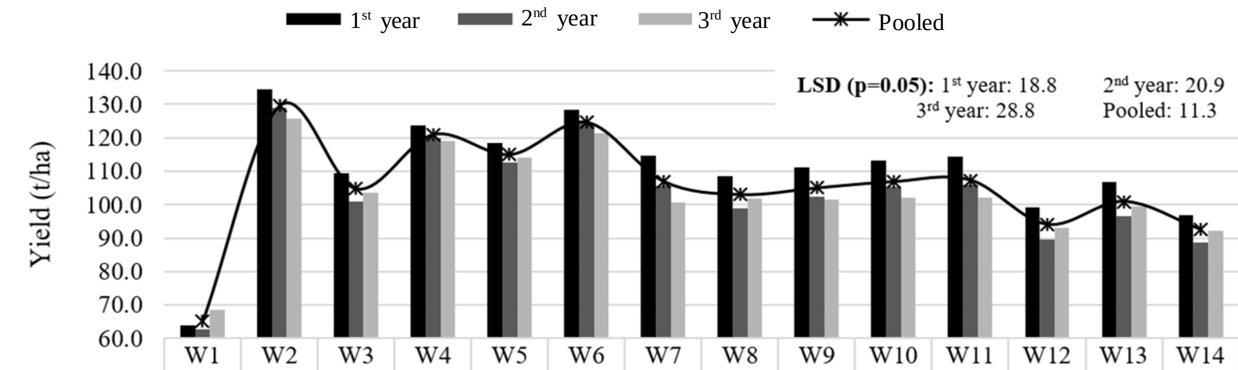


Figure 2. Weed control efficiency (WCE, %) and weed index (WI, %) influenced by different weed management (pooled of 3 years)



	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1st year	63.8	134.4	109.3	123.8	118.4	128.4	114.7	108.5	111.1	113.1	114.3	99.2	106.8	96.8
2nd year	62.8	128.9	101.1	120.0	112.5	124.2	105.5	98.9	102.5	105.3	106.0	89.7	96.7	88.6
3rd year	68.6	125.7	103.7	119.1	114.1	121.5	100.7	101.7	101.5	102.2	102.0	93.2	99.6	92.2
Pooled	65.1	129.6	104.7	121.0	115.0	124.7	107.0	103.0	105.0	106.9	107.4	94.1	101.0	92.6

Figure 3. Yield of sugarcane as influenced by weed management (individual years and in pooled)

Removal of weeds by any means, definitely minimized the weed infestation considerably that ensued higher sugarcane yield, however the yield increments was directly correlated with weed management methods, its timing and selectivity of herbicides employed for weed removal.

Residue analysis

The reports on soil and plant samples analysis for herbicides residue reflected that the residues of different herbicides were in below detectable levels *i.e.* 0.05 µg/ml, it revealed that herbicides can be applicable for sugarcane crop.

Conclusion

Weeds become a serious threat for sugarcane crop production that caused 49.8 per cent yield reduction. Cane yield can be increase significantly with any of the weed management practices. Thus, HW (30, 60 and 90 DAP) + IC (40 and 90 DAP) found to be effective weed management strategy as it produced higher cane yield with maximum weed control efficiency. Pre-emergence application of atrazine or metribuzin effectively reduced the weed menace during early slow growth period of sugarcane while the HW+IC at 60 DAP eradicated later emerged weed flora from the field, hence integrated approach of chemical followed by mechanical weed control proved effective.

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RESEARCH ARTICLE

Herbicides for weed management in onion and analysis of herbicide residues using liquid chromatography tandem mass spectrometry

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ABSTRACT

Management of weeds is the major challenge to the success of onion. Chemical weed control has been intensively used to reinforce crop yield; however, even selective herbicides can potentially interfere with biochemical and physiological changes in onion. A field experiment was conducted to evaluate the efficacy of different herbicides pendimethalin, oxyfluorfen and quizalofop-ethyl individually and in combinations on weed control efficiency, yield attributes, changes in photosynthetic pigments, membrane injury and persistence of herbicides in onion. The combined application of oxyfluorfen and quizalofop-ethyl efficiently influenced the weed density and biomass causing higher yield and net returns. The application of oxyfluorfen recorded highest weed control efficiency, while a decline in photosynthetic pigments caused lesser yield. The results of QuEChER method of liquid chromatography tandem mass spectrometry (LC-MS/MS) revealed that herbicide residue did not find in both leaves and bulb in any treatment.

Key words: Chlorophyll, Herbicide residue, Liquid chromatography, Onion, QuEChER, Tandem mass spectrometry, Weeds

INTRODUCTION

Onion (*Allium cepa* L.) is an important commercial vegetable crop worldwide and India is the second largest producer of onion after China. In India, Maharashtra state is the leading onion producing state with an area of 4.81 mha, production 37.34 mt and productivity of 14.0 t/ha (National Horticultural Research and Development Foundation 2016-17). In Maharashtra, Nashik is the leading district in area and production of onion (Indian Horticulture Database 2017). Low productivity of onion in the country might be the resultant of a number of factors like poor yielding genotypes, non-availability of quality seeds and poor agronomic practices. Among the agronomic factors, proper weed management may be a serious issue. Onion is a slow growing plant with narrow upright leaves and non-branching habit due to which crop cannot compete well with weeds. In onion crop, weeds not only compete vertically and horizontally for space, but also consume essential nutrients, much needed water and acts as a reservoir for several pathogenic pests and insects due to which yield loss have estimated to the 40-58% (Channapagoudar and Biradar 2007) or even ranging from 40-80% depending upon the type of weed flora and their competitiveness (Prakash *et al.* 2000). There are a number of methods available by which weeds can be controlled effectively like manual methods and chemical weed control. Unlike, the horticultural developed countries, use manual weeding techniques which are time consuming and costly. At the earlier stages of crop weed infestation significantly reduces the bulb yield, the pre-emergent herbicides application may not control the weed population long enough. To optimize the bulb yield, post emergence herbicides control weed population effectively. Therefore, proper weed control is the prime need and essential to obtain maximum productivity and under such circumstances chemical method of weed control has shown good promise.

Improper herbicide application causes phytotoxicity and high dosages causes alterations in biochemical and physiological changes that leads to the formation of reactive oxygen species causing oxidative stress, which has been identified as a consequence of different abiotic stresses including herbicides usage in crops for weed management (Song *et al.* 2007). Although, the reactive oxygen species are inevitable products of plant metabolism under normal circumstances, yet coordinated

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antioxidant defence mechanisms inside plant cells maintain a balance between their synthesis and scavenging (Mittler 2002). While, in severe conditions the damage due to reactive oxidative stress cannot overcome (Langaro *et al.* 2017). Under such circumstances, one of the protection mechanisms is the enzymatic antioxidant defence mechanism, which operates with sequential and simultaneous actions of several anti-oxidative enzymes including superoxide dismutase, ascorbate peroxidase and catalase. In the non-enzymatic antioxidant system includes phenolic compounds like ascorbic acid, glutathione, chlorophylls, carotenoids, proteins and amino acids. Carotenoids pigments are responsible for the photo protection of the photosynthetic membranes, acting as auxiliary pigments. The carotenoids also act in the dissipation of the excited state of chlorophyll and neutralization of reactive oxygen species (Kreslavski *et al.* 2009).

Farmers are using wide range of herbicides in onion growing pockets, among these pendimethalin, oxyfluorfen and quizalofop-ethyl are very new chemical substances in Nashik region of India. Due to improper application of these herbicides, the chemical residue may persistent in bulb may become an important issue in major onion growing and export zone of India. Different herbicides detected in some food products and estimated its concentration by Gas chromatography (GC) due to its high selectivity and high sensitivity for thermo-stable and volatile molecules (Xin *et al.* 2009). However, it is limited because nowadays commonly used pesticides are polar, less volatile and /or thermo-labile compounds, which are not directly traceable by GC (Fernandez *et al.* 2001). Most of these polar pesticides like fungicides, carbamates and herbicides in vegetables can be efficiently separated by liquid chromatography (LC) without a preceding laborious risk. Recent developments in the detection and separation by LC have extended its application in pesticide residue analysis (Choi *et al.* 2001). High performance liquid chromatography and Tandem mass spectrometry (LC-MS/MS) and QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe) sample extraction method was used to determinate herbicides for fruits and vegetables (Wilkowska and Biziuk 2011). It was found that it is the best method for determination of herbicides in some food products in terms of high recovery, short time of analysis, low cost and safety (Renata 2014). Therefore, in this study, we evaluated optimised and validated by the QuEChERS procedure for the determination of three herbicides residues in onion. The study was supposed to provide scientific evidence and implement recommendations with chemicals for management of weeds in onion with minimum toxic effects and environmental safety.

MATERIALS AND METHODS

The present investigation was carried out at the research farm of Regional Research Station, National Horticultural Research and Development Foundation (NHRDF), Nashik, Maharashtra, India, during *Kharif* 2015, 2016 and 2017. The experimental site is located at an altitude of about 492 m above sea level, latitude of 20’ N and has longitude of 73º 57’ E. The agro-meteorological data of experimental site during the cropping period has given in **Figure 1**. The experiment was laid out in randomized block design with three replications. The fifty days old seedlings of onion variety ‘*Agrifound Dark Red*’ developed and released by NHRDF were transplanted in mid of August during three seasons under drip irrigation system. Three herbicides were used in this experiment, which includes pre-emergence herbicide pendimethalin [N-(1-ethylpropyl)-3, 4-dimethyl 1-2,6 dinitrobenzenamine], pre- and post-emergence herbicide oxyfluorfen [2-chloro-4 (trifloromethyl) phenyl-3-oxy-4- nitrophenol ether] and post-emergence herbicide quizalofop-ethyl [(R)-2-[4-(6-chloroquinoxaline -2- phenoxy]-ethyl propionate] with different combinations as tank mixture and applied to the onion crop two times, the first application was done at pre-transplanting (pre-emergence of weed and second application was done 30 days after transplanting (DAT). The treatments includes oxyfluorfen 23.5% EC 1.5ml/l of water at pre-transplanting and second at 30 DAT, oxyfluorfen 23.5% EC1.5 ml/l of water at pre-transplanting + quizalofop-ethyl 5% EC 3.0 ml/l of water at 30 DAT, combined spray of oxyfluorfen23.5% EC 1.0 ml + quizalofop-ethyl 5% EC 2.0ml/l of water at pre-transplanting and second at 30 DAT, pendimethalin 30% EC 5.0 ml/l of water at transplanting and second at 30 DAT, pendimethalin 30% EC 5.0 ml/l of water at pre-transplanting + quizalofop-ethyl 5% EC 3.0 ml/l of water 30 DAT, combined spray of pendimethalin 30% EC 3.0 ml + quizalofop-ethyl 5% EC 2.0 ml/l of water at pre-transplanting and second at 30 DAT, weed free check (three times manual weeding was done at 25, 40 and 55 DAT) and weedy check (No manual weeding and no herbicide application throughout cropping period - kept as control). The required quantity of herbicides was dissolved in water and sprayed with the help of a knapsack sprayer fitted with flat fan nozzle. Soil of the experimental area was deep heavy clay with pH- (7.6), organic carbon (0.75%), available N (374 kg/ha), available P (49.05 kg/ha), available K (414.4 kg/ha), water holding capacity (62.8%), field capacity (38.9%) and permanent wilting point (24.6%).

Data collection and analysis

During the course of the study, data was recorded on various parameters such as weed density (number of weeds/m²) counted based on quadrate of size 1.0 x 1.0 m placed randomly at three sites per plot and weeds growing within this quadrate were counted, fresh weeds biomass (fresh weight of weeds collected from one m² area), for dry weeds biomass (dry weight of weeds collected from one m² area), when fresh weeds were kept in electric oven at 66˚C for 72 ± hr then weighed. Weed control efficiency (WCE) denotes the magnitude of weed reduction due to weed control treatment was calculated by using formula suggested by Mani *et al.* (1973) and expressed in percentage *i.e.* $WCE = \frac{DW_1 - DW}{DW_1} \times 100$ where; DW_1 is dry weight of un-weeded control and DW is dry weight of treatments. Weed index (WI) was determined by the formula given by Gill and Vijayakumar (1969), *i.e.* $WI = \frac{X - Y}{X} \times 100$, where; X = Total yield from the weed free check, Y = Total yield from the treatment.

Biochemical parameters

The photosynthetic pigments were extracted at 35 DAT (after 5 days of post-emergence herbicide application) and 60 DAT (bulb developing stage) by the method described by Gunes *et al.* (2007) using dimethyl sulphoxide (DMSO). Twenty-five mg of leaf tissue was placed in a vial containing 3 ml DMSO at room temperature till the tissue became chlorophyll free (12-16 h). The extract was transferred to a graduated tube and absorbance was read at 665, 645 and 454 nm as described by Kaloyereas (1958) on a computer aided spectrophotometer (CHEMITO Spectro Scan UV 2700 – Double Beam UV VIS Spectrophotometer) running a multiple wave length programme. Calculations for different pigments were made according to the formulae given by Lichtenthaler (1987). Quantities of these pigments were calculated in mg/g fresh weight (FW) of tissue. Membrane stability was assessed by the method of Vanstone and Stobbe (1977). Leaf samples were collected from control as well as herbicide sprayed plants, from these 100 mg of leaf tissue was taken separately in 20 ml test tubes containing 10 ml of de-ionized water. These samples were incubated for 24 hr at 4˚C. The conductance of decanted liquid containing efflux electrolytes was determined at 25˚C with a conductivity meter and designated as Ec a (before boiling). Then the samples were subjected to heating at 100 ˚C in a water bath for 10 min. After cooling, the electrical conductivity of the solutions was measured and designated as Ec b (after boiling). The electrolyte leakage was expressed as membrane stability was assessed by the following formula; Membrane stability $= \frac{Ec\ a}{Ec\ b} \times 100$.

Data were analysed using randomized block design and all the parameters were compared using critical difference (CD) at 5% level of significance. Data were analysed analyses of variance (ANOVA).

Liquid chromatography and mass spectroscopy (LC MS/MS) analysis

The ≥96% purity certified pesticide reference materials and HPLC acetonitrile solvent were obtained from Dr. Ehrenstorfer GmbH, Augsburg, Germany and J T Baker, USA, respectively. The analytical grade with ≥97% purity of Ammonium formate, acetic acid,

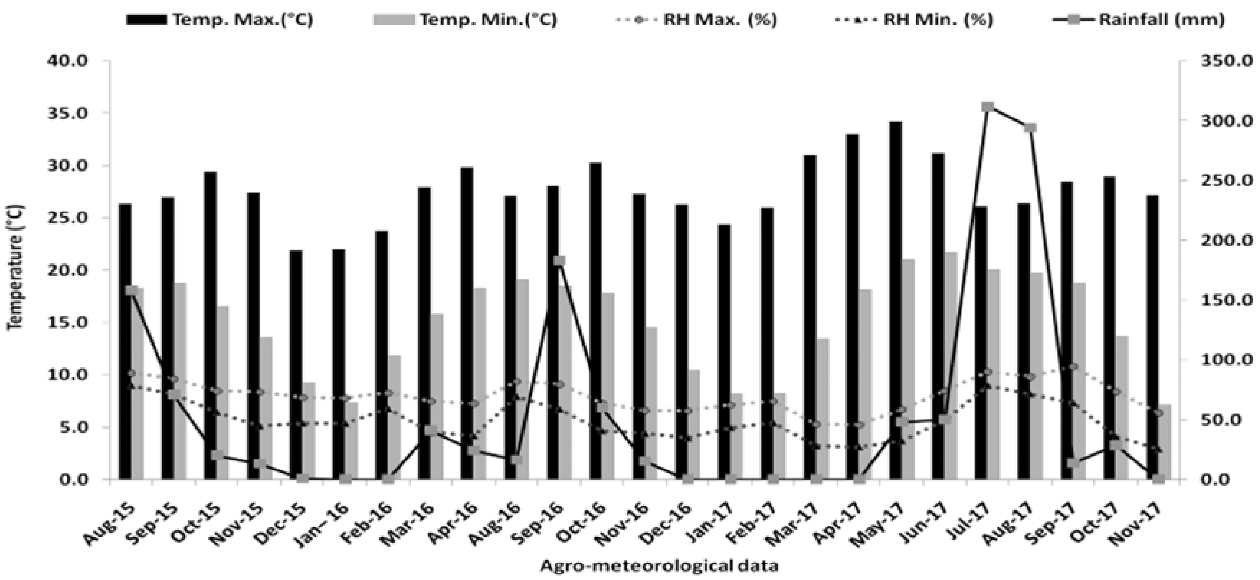


Figure 1. Agro-meteorological data during crop growing *Kharif* season of 2015, 2016 and 2017

diethylene glycol, magnesium sulphate and sodium sulphate anhydrous were from Merck India Ltd. The stock solutions of each analytes prepared with the concentration of 1000 mg/kg by dissolving standard in acetonitrile. The HPLC, Shimadzu, Japan equipped with DGU-20 degasser, 20-AD pumps A and B, SIL-20 AC HT auto sampler, and CTO-20 AC oven. The separation was performed by 10 µl sample injecting on reverse phase zorbaxelipse C-18 column (4.6 id × 100 mm, 5 µm, Agilent) maintained at 30˚C. The triple quadrupole system an API 4000 Q TRAP (ABSCIEX, CA, USA) LC-MS/MS spectrometer fitted with an electro spray ionization interface and operated in positive polarity mode. The analytical method validation parameters have given in **Table 1** as standardized by Yadav *et al.* (2017).

Modified QuChERS method for extraction of onion bulbs for LC MS/MS analysis Anastassiades *et al.* (2003). Onion bulbs separated at neck region very close to the bulb from the leaves and were separately blended and homogenized at speed of 3000 rpm for 1 min, for bulbs 1:1w/v ratio and 1:5 w/v for leaves were prepared by adding of water. The 10 g sample from these, centrifuged and extracted 10 ml of acetonitrile, after added magnesium sulphate anhydrous and sodium acetate. Finally, the sample was homogenized and centrifuged for phase separation. The 50 g of primary secondary amine added to 4 ml of acetonitrile and centrifuged at 10000 rpm. The supernatant layer of 2 ml quantity was evaporated with 200 µl 10% diethylene glycol in methanol. The 2 ml of residues were dissolved and reconstituted with methanol and 0.1% acetic acid (1:1 v/v) and filtered with 0.22 µm polyvinyl idene fluoride filter and injected 10 µl quantity in to LC-MS/MS (Yadav *et al.* 2017).

RESULTS AND DISCUSSION

Effects on weeds population

In the present investigation important monocot weeds and dicot weeds are described in **Table 2**. The *Cyperus Rotundus* and *Cynodon dactylon* from monocot and *Portulaca oleracea* and *Scoparia dulcis* form dicot were major weeds. All the treatments for weed control were effective in reducing both monocot and dicot weed population as compared to weedy check. The lowest monocot weed density and dicot weed density were recorded in combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT followed by combined spray of pendimethalin 3.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT and pendimethalin 5.0 ml/l at transplanting + quizalofop-ethyl 3.0 ml/lat30 DAT. Among the herbicide treatments, the lowest dicot weed density was recorded in oxyfluorfen 1.5ml/l at transplanting and second at 30 DAT. The reduction in weed population in these treatments could be attributed due to the effect pre-emergence and post emergence herbicide applications. Oxyfluorfen acts as a contact herbicide and kills weeds by destroying cell membranes by inhibiting the enzyme protopor-phyrinogen oxidase within leaves and shoots. At lower rates act as a contact herbicide, though it has good pre-emergence activity at higher rates and also has post emergence activity at lower rate. The combine application of pre and post emergence herbicide is one of the options to the farmers to eliminate monocot and dicot weed population at the early and later stages of the crop and to achieve higher weed control efficiency. The herbicide treatments caused significant reduction in weed

Table 1. Analytical method validation parameters of herbicides recovery, precision, accuracy, LOD, LOQ, linearity and uncertainty

Herbicide	Recovery (10 µg/kg)								
	1	2	3	4	5	6	Average	Standard deviation	Relative standard deviation
Pendimethalin	8.81	9.42	8.80	9.93	9.48	9.85	9.38	0.45	4.75
Oxyfluorfen	10.36	11.69	9.89	10.95	10.99	10.99	10.81	0.56	5.21
Quizalofop-ethyl	9.55	10.08	8.90	10.03	9.18	9.27	9.50	0.44	4.58
	Precision (10 µg/kg)								
Pendimethalin	10.15	10.30	9.57	10.04	9.77	9.69	9.92	0.26	2.64
Oxyfluorfen	8.70	11.74	11.78	10.25	8.37	11.44	10.38	1.40	13.51
Quizalofop-ethyl	9.36	9.60	9.24	9.44	9.52	8.87	9.34	0.24	2.55
	Accuracy (10 µg/kg)								
Pendimethalin	9.02	10.07	9.73	10.04	9.51	10.13	9.75	0.39	4.03
Oxyfluorfen	8.51	9.76	8.73	9.55	9.44	9.18	9.20	0.45	4.85
Quizalofop-ethyl	49.72	56.86	56.28	54.02	51.54	57.59	54.33	2.88	5.31
	LOD		LOQ		Linearity		Uncertainty		
Pendimethalin	10.0 µg/kg		5.0 µg/kg		0.9985		± 4.509 at 20.0 µg/kg		
Oxyfluorfen	10.0 µg/kg		5.0 µg/kg		0.9988		± 2.330 at 20.0 µg/kg		
Quizalofop-ethyl	10.0 µg/kg		5.0 µg/kg		0.9958		± 3.336 at 20.0 µg/kg		

population compared with the weedy check, in weedy check highest weed plants competition impact on plant growth. The magnitude of reduction in density varied with different treatments can be attributed to the fact that the herbicides which could kill most of the weed population more effective. The results are similar with the findings of Chattopadhyay *et al.* (2016) and Singh *et al.* 2017. Application of herbicides is sufficient to reduce the weed population at early stage of crop growth, but at later stages there might be degradation of herbicide in the root or by volatilization or leaching effect. Hence, there was increase in weed population at bulb development stage. In manual weeding also some weed population was recorded was due to weekly manual weeding allowed sufficient light, space and received adequate nutrients for remaining buried weed seeds to geminate. Application of quizalofop-ethyl at 30 DAT is the most effective selective herbicides for controlling *Chenopodium album*, *Parthenium hysterophorus* and *Cyperus rotundus* on the basis of weed relative density, while *Cyperus rotundus* could not be controlled completely by any of these herbicides. Quizalofop-ethyl inhibits the acetyl CoA carboxylase (ACCase) activity which is inhibiting the lipid biosynthesis could be possible due to better weed control. The results are in similar line with the results of Dhawan *et al.* (2010). Effectiveness of various herbicides against different weed species in onion crop has been previously reported by Tripathi *et al.* (2013), Vishnu *et al.* (2015) and Singh *et al.* (2017).

Effects on weed biomass, weed control efficiency and weed index

The biomass of monocot and dicot weed population is the index to determine the efficiency of herbicides to control the weeds in onion. The biomass of both monocot and dicot were significantly affected by different treatments had the marked effect on fresh and dry biomass. Among the herbicide treatments, lower monocot fresh and dry biomass were recorded in combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT followed by combined spray of pendimethalin 3.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT and pendimethalin 5.0 ml/l at transplanting + quizalofop-ethyl 3.0 ml/L at 30 DAT, while in manual weeding treatment, the lowest monocot fresh and dry biomass were recorded. These results are in line with those reported by Kalhapure and Shete (2013), Vishnu *et al.* (2015) and Chattopadhyay *et al.* (2016). Recording of WCE under particular treatment can be useful to understand the competition stress of weeds on crop. The maximum WCE was recorded in manual weeding, however among herbicide treatments, the highest WCE was recorded in oxyfluorfen 1.5ml/l at transplanting and second at 30 DAT followed by combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT and pendimethalin 5.0 ml/l of water at transplanting + quizalofop-ethyl 3.0 ml/l at 30 DAT (**Table 3**). It is obvious from the results that those treatments which inhibits weed population growth and had lesser weed dry matter resulted in higher WCE. At 60 DAT, weed density and dry matter were maximum as compared to that at harvesting stage. But, in case of WCE it was found higher at 60 DAT than at harvesting. It might be due to various fate of herbicides like leaching, volatile movement and decomposition which ultimately decrease their efficiency with passage of the time. The results are in close conformity with the findings of Vishnu *et al.* (2015) and Chattopadhyay *et al.* (2016). Weed index also indicates that the yield reduction caused would be due to competition of

Table 2. Common monocot and dicot weed population found in experimental area of onion field

Sr. No.	Dominant weeds details				
	Common name	Botanical name	Family	Habit	Reproduction
		Sedge			
1	Purple nut sedge	*Cyperus rotundus*	Cyperaceae	Perennial	Vegetative
		Monocot			
2	Bermuda grass	*Cynodon dactylon*	Poaceae	Perennial	Seed
3	Viper grass	*Dinebra retroflexa*	Poaceae	Annual	Seed
4	Tropical spiderwort	*Commelina banghalensis*	Commelinaceae	Annual	Seed
6	Jungle rice	*Echinochloa colona*	Poaceae	Annual	Seed
		Dicot			
7	Asthma herb	*Euphorbia hirta*	Compositae	Annual	Seed
8	Slender amaranth	*Amaranths viridis*	Amaranthaceae	Annual	Seed
9	Parthenium	*Parthenium hysterophorus*	Compositae	Annual	Seed
10	Common purslane	*Portulaca oleracea*	Portulacaceae	Annual	Seed
11	Sunberry	*Physalis minima*	Solanaceae	Annual	Seed
12	Licorice weed	*Scoparia dulcis*	Scrophulariaceae	Perennial	Seed
13	Lambs quarter	*Chenopodium album* L.	Chenopodiaceae	Annual	Seed
14	Field bindweed	*Convolvulus arvensis*	Convolvulaceae	Perennial	Seed

major weeds under weedy check. The maximum reduction in weeds and increase in yield was recorded in combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT. This could be described that under these treatments, there was a lower impact of weeds on yield. The findings are in close proximity to that of Chattopadhyay *et al.* (2016).

Effects on morphological characters

The growth parameters such as plant height, number of leaves and neck thickness were influenced significantly by all weed control treatments. Plant height and number of leaves are one of the most important phenological characters of the plant growth and development, maximum plant height and number of leaves were recorded in combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT which was followed by manual weeding and combined spray of pendimethalin 3.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT. While, the poor growth and development was recorded in weedy check followed by oxyfluorfen 1.5ml/l at transplanting and second at 30 DAT. All the herbicide treatments significantly increased the plant growth and development over weedy check. The superior plant growth and development could be due to lower weed population count, moisture and nutrient competition and higher exposure to sunlight. The inferior plant growth and development in treatment of weed check was due to prolonged competition of weeds caused by poor exposure to sunlight and emulation for nutrient and water. The findings are in agreement with earlier results reported by Ghadage *et al.* (2006), Channappagoudar and Biradar (2007), Vishnu *et al.* (2015) and Chattopadhyay *et al.* (2016).

Effects on yield and yield attributes

The bulb yield is the final index of the experiment indicates the success or failure of any herbicide treatments. It is evident from results that highest gross yield as well as marketable yield were recorded in treatment of manual weeding and the yield was found at par with treatment of combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT and in the same treatment highest benefit ratio (3.07) recorded (**Table 4**). This is due to the strenuous growth of the crop by control of weeds resulting into poor weed competition from the transplanting stage to maturity stage and thus enhanced availability of moisture, nutrient, light and space which hastening the photosynthetic rate thereby quacking the supply of carbohydrates and overall improvement in vegetative growth, which favourably influenced the bulb development and ultimately resulted into increased bulb yield. Results are supported by the earlier findings of Warade *et al.* (2008). While in weedy check reverse happened and weeds seriously affected average bulb weight and drastically reduced yield to the tune of 62.2% and these variabilities were due to effectiveness of weed control. The results clearly indicated the adverse impact of weed infestations in onion crop, which in term affected the bulb yield. The results are in agreement with Tripathi *et al.* (2013), Vishnu *et al.* (2015), Chattopadhyay *et al.* (2016) and Singh *et al.* (2017).

Table 3. Efficacy of different herbicides on various monocot and dicot weed population in onion

Treatment	Monocot population / m^2	Dicot /population / m^2	Monocot		Dicot		Weed control efficiency (%)	Weed index
			Fresh weight (g/m^2)	Dry weight (g/m^2)	Fresh weight (g/m^2)	Dry weight (g/m^2)		
Oxyfluorfen 1.5ml/L of water at transplanting and second at 30 DAT	15.21	1.97	84.81	40.66	39.92	11.39	86.41	20.96
Oxyfluorfen 1.5 ml/L of water at transplanting + quizalofop-ethyl 3.0 ml/L of water at 30 DAT	13.16	3.04	93.86	48.95	120.9	63.31	41.57	17.33
Combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/L of water at transplanting and second at 30 DAT	11.79	2.89	58.79	20.66	85.62	25.95	73.65	9.78
Pendimethalin 5.0 ml/L of water at transplanting and second at 30 DAT	15.67	5.83	95.87	67.04	184.14	69.78	32.38	14.25
Pendimethalin 5.0 ml/L of water at transplanting + quizalofop-ethyl 3.0 ml/L of water 30 DAT	14.17	3.44	72.03	56.65	90.87	30.75	70.72	20.83
Combined spray of pendimethalin 3.0 ml + quizalofop-ethyl 2.0 ml/L of water at transplanting and second at 30 DAT	12.08	3.52	71.57	51.5	147.5	42.68	57.75	14.09
Weed free check (three hand weeding at 25, 45 and 60 DAT)	6.33	0.99	28.28	14.03	26.65	8.25	91	0
Weedy check	29.65	8.76	659.09	236.4	325.48	94.43	0	62.18
LSD (p=0.05)	3.26	0.69	12.59	16.63	39.12	11.53	7.38	2.80
Year								
2014	18.25	3.92	126.46	88.33	167.13	32.42	58.49	18.92
2015	15.25	4.25	163.51	50.68	169.13	48.7	68.84	16.94
2016	15.15	3.25	163.51	50.68	159.13	48.7	68.84	20.94
LSD (p=0.05)	8.02	0.42	7.71	10.19	23.96	7.06	4.52	1.72

Photosynthetic pigments and membrane permeability

The effect of herbicidal treatments on photosynthetic pigments content in foliage of onion at 35 DAT and 60 DAT showed variable results. Amongst the early physiological responses after herbicide applications in crop as well as weed plants included stunted growth, leaf chlorosis and increase in cell membrane were highest chlorophyll-a content recorded. Due to herbicide treatments a small decline was observed, however minute difference (3.37%) was observed in combined spray of oxyfluorfen and quizalofop-ethyl (**Figure 2a**), while individual spray of oxyfluorfen caused highest decline (14.98%) at 35 DAT and the same treatment efficiently controlled both monocot and dicot weed population with higher WCE, however due to reduction in photosynthetic pigments a small decline in yield. Similar trend was observed in chlorophyll-b content (**Figure 2b**). The small decline was observed in total chlorophyll content in all the treatments including weed check at 35 DAT and 60 DAT over weed free check in the range of 3.80 (%) to 16.79 (%) and 7.97 (%) to 27.70 (%) at 35 DAT and 60 DAT, respectively (**Figure 2c**). The similar results were observed in decline of photosynthetic pigments after herbicide treatments by Vanstone and Stobbe (1977), Bhasker *et al.* (2015) and Langaro *et al.* (2017). The oxyfluorfen is a potential inhibitor of protoporphyrinogen oxidase and has a direct effect on chlorophyll synthesis route, it may interfere with photosynthesis. Therefore, the decline of these compounds may compromise photosynthetic pigments. Due to less toxic effect on onion by various herbicide treatments has checked most of the weeds and thus allowed the crop to grow more vigorously, resulting in higher yield. A small decline in carotenoid content was observed in all herbicidal treatments (**Figure 2d**). The ratio of chlorophyll-a and chlorophyll-b showed mixed results (**Figure 3a**) and the ratio of chlorophyll- a and carotenoid showed declining trend, whereas chlorophyll-b and carotenoid showed increasing trend over weed check. The increase in ratio of chlorophyll-b and carotenoid indicates that carotenoid involved in oxidative defence mechanism (**Figure 3b**), as carotenoids plays an important role in plants protect the photosynthetic apparatus from oxidative stress. The results are in line with the results of Wahid and Ghazanfar (2006) under abiotic stress condition.

Lipid peroxidation is one of the most investigated consequences of the actions of reactive oxygen species on membrane structures, being one of the first responses to damage induced by stress in plant tissues (Amri and Shahsavar 2010). Due to herbicide injury on leaf membrane ion efflux increased in all treatments sprayed with herbicide,

Table 4. Morphological and yield attributing characters under various herbicidal treatments in onion (pooled data)

Treatment	Plant height (cm)	No. of leaves/ plant	Neck thickness (cm)	Gross yield (t/ha)	Marketable yield (t/ha)	Cost: Benefit ratio
Oxyfluorfen 1.5ml/L of water at transplanting and second at 30 DAT	47.0	6.91	1.22	15.93	14.66	2.68
Oxyfluorfen 1.5 ml/L of water at transplanting + quizalofop-ethyl 3.0 ml/L of water at 30 DAT	49.49	7.29	1.22	16.69	15.33	2.78
Combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/L of water at transplanting and second at 30 DAT	53.27	7.58	1.23	18.11	16.73	3.07
Pendimethalin 5.0 ml/L of water at transplanting and second at 30 DAT	48.47	7.07	1.18	17.51	15.90	2.89
Pendimethalin 5.0 ml/L of water at transplanting + quizalofop-ethyl 3.0 ml/L of water 30 DAT	50.0	6.96	1.23	15.75	14.68	2.66
Combined spray of pendimethalin 3.0 ml + quizalofop-ethyl 2.0 ml/L of water at transplanting and second at 30 DAT	50.07	7.18	1.22	17.08	15.93	2.92
Weed free check (three hand weeding at 25, 45 and 60 DAT)	51.96	7.40	1.17	19.58	18.55	2.40
Weedy check	41.64	5.58	0.98	8.86	7.01	1.32
LSD (p=0.05)	1.22	0.33	0.07	1.36	1.43	-
Year						
2014	51.31	7.90	1.31	16.07	14.81	2.60
2015	47.83	6.54	1.12	16.25	14.87	2.59
2016	47.83	6.54	1.12	16.25	14.87	2.87
LSD (p=0.05)	0.75	0.20	0.04	0.83	0.88	-

Table 5. List of herbicides and MRM parameters in liquid chromatography tandem mass spectrometer

Name of herbicide	Class of chemical	RT (min)	Q	Q1[a]	DP(V)[a]	CE(V)[a]	CXP(V)[a]	Q2[b]	DP(V)[b]	CE(V)[b]	CXP(V)[b]
Pendimethalin	Triazine	8.9	216	174	54	26	14	104	54	45	6
Oxyfluorfen	Nicotinoid	5.8	223	126	60	27	7	56	60	35	3
Quizalofop-ethyl	Organophosphorus	2.5	184	143	48	14	5	125	48	29	4

RT, retention time; Q, protonated parent ion; Q1, quantifier ion; Q2, qualifier ion; DP, de-clustering potential; CE, collision energy; CXP, collision cell exit potential; [a] quantifier (1st transition) mass parameter; [b] qualifier (2nd transition) mass parameter

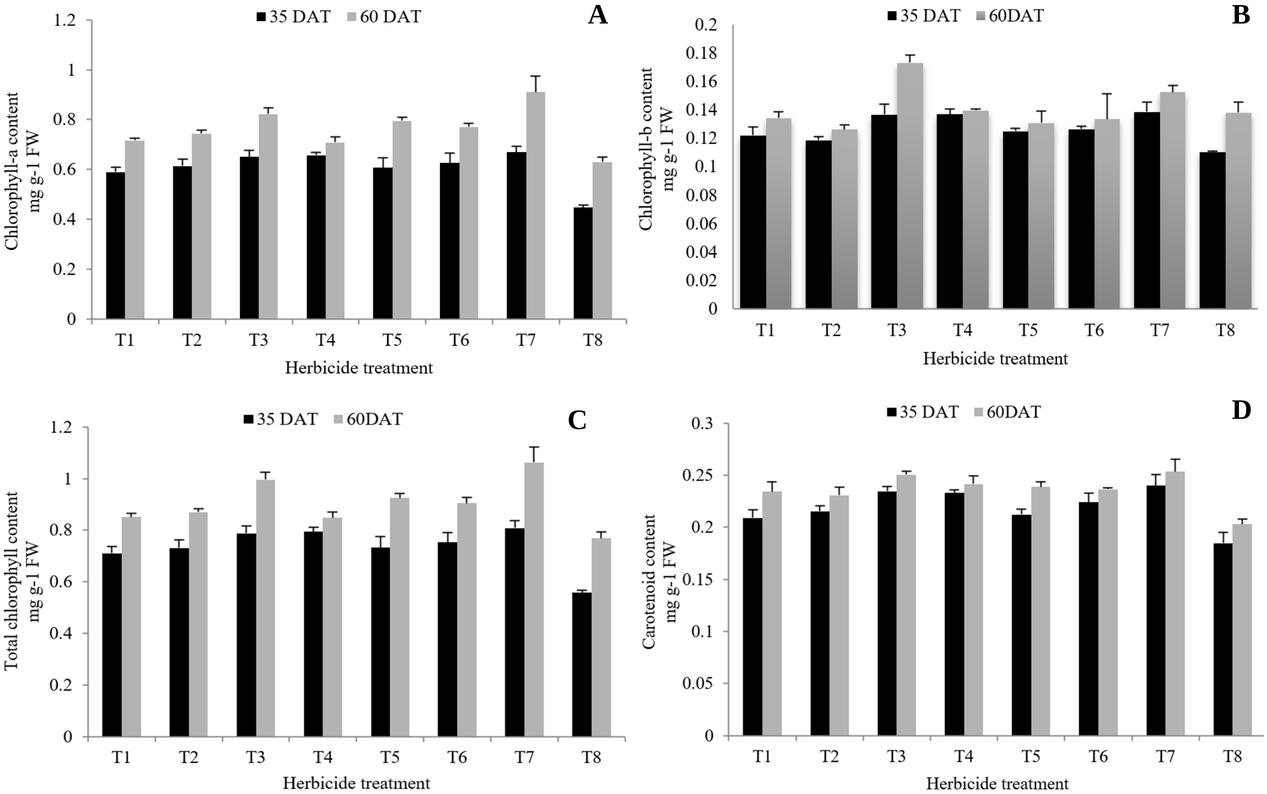
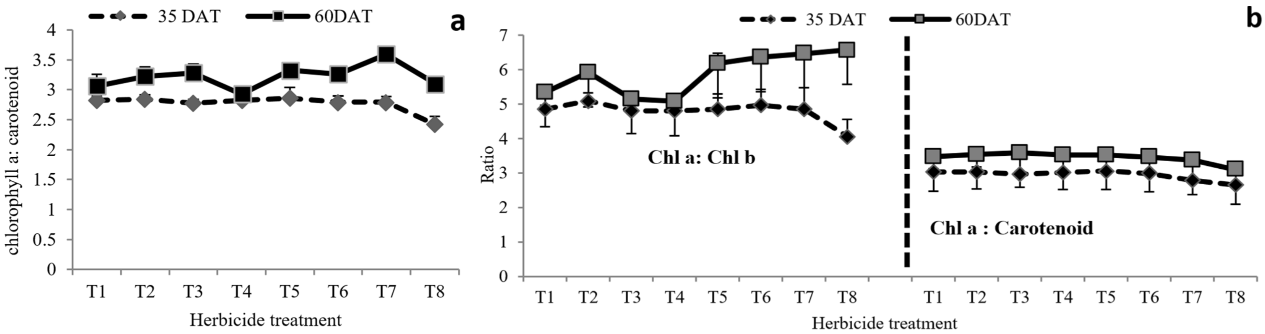


Figure 2. Changes in chlorophyll-a (a), chlorophyll-b (b), total chlorophyll (c) and carotenoid (d) content in onion leaves as affected by different herbicide treatments



Note for figure 2, 3 and 4:- T1: Oxyfluorfen 1.5ml/L of water at transplanting and second at 30 DAT; T2: Oxyfluorfen 1.5 ml/L of water at transplanting + quizalofop-ethyl 3.0 ml/L of water at 30 DAT; T3: Combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/L of water at transplanting and second at 30 DAT; T4: Pendimethalin 5.0 ml/L of water at transplanting and second at 30 DAT; T5: Pendimethalin 5.0 ml/L of water at transplanting + quizalofop-ethyl 3.0 ml/L of water 30 DAT; T6: Combined spray of pendimethalin 3.0 ml + quizalofop-ethyl 2.0 ml/L of water at transplanting and second at 30 DAT; T7: Weed free check (three hand weeding at 25, 45 and 60 DAT); T8: Weedy check

Figure 3. Changes in chlorophyll a: chlorophyll b (a) and chlorophyll a: carotenoid and chlorophyll b: carotenoid (b) in onion leaves affected by different herbicide treatments

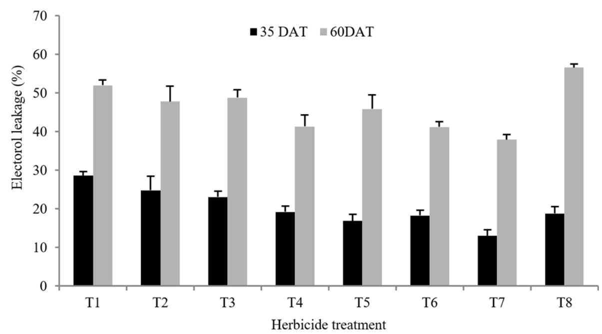


Figure 4. Changes in membrane injury of leaves in onion affected by different herbicide treatments

highest leakage was recorded at 35 DAT in individual spray of oxyfluorfen at 30 DAT, while in weed check at 60 DAT maximum leakages was recorded (**Figure 4**) due to high weed infestation causes poor development of leaf and competes for space, nutrients and water results highest ion leakage.

LC-MS/MS method optimization

The method is designed to detect and quantify the herbicides in a single run. The herbicides chosen in this experiment were applied to the onion crop to control the weed population. The Liquid chromatography (LC), gradient elution program was run in binary gradient solvent of LC i.e. methanol - water (20:80, v/v) with 5 mM ammonium formate and methanol-water (90:10, v/v) with 5 mM ammonium formate with the following programme of 0-1 min, 20% B, 1-8 min 20% - 100% B, 8-16 min. 100% B, 16-17 min 100% - 20% B, 17-20 min 20% B as reported by Yadav *et al.* (2017). The rate of flow kept at 0.6 mlmin^{-1} and all the solvents were on-line degassed with a degasser. The targeted three herbicides i.e. pendimethalin, oxyfluorfen and quizalofop-ethyl chromatographically well separated with good retention time (**Figure 5**). The herbicide residue detection and quantification were performed in schedule multi reaction mode. The mass dependent specific parameters of target herbicides were mentioned in **Table 5**, revealed that the three herbicides presenting different retention, *viz*. pendimethalin 8.9 min, oxyfluorfen 5.8 min and quizalofop-ethyl 2.5 min, in theses ranges there was no detection was recorded in both the leaves and bulb. The precursor and herbicide quantification and confirmation ion pairs, the de-clustering potential and collision energies are summarised in **Table 5**. The optimized method was applied for the analysis onion bulbs and leaves and limit of quantification for three herbicides was 0.01 mg/kg and standard and sample chromatograms summarized in chromatograms. This was conducted for all trails and from results, it was concluded that no any plant part contains residue of these herbicides. Islam *et al.* (2017) reported that by using the similar QuEChERs method followed by LC-MS/MS detected herbicide residues in fruits and vegetables.

Conclusion

Field experiment conducted during *Kharif*, 2015, 2016 and 2017 on onion variety '*Agrifound Dark Red*' revealed that manual weeding practice throughout growing season of the crop controlled all monocot and dicot weed population, which resulted in highest yield, but it is the most laborious and un-economical method to control all weeds may be replaced with chemical weed management practises. Applications of herbicides are effective in the control of monocot and dicot weeds. The combined spray of oxyfluorfen 1.0 ml + quizalofop-ethyl 2.0 ml/l at transplanting and second at 30 DAT with different weed control spectrum were beneficial in reducing weed population and improving the onion growth and also these herbicides had no harmful effect on crop and it was free of any residue.

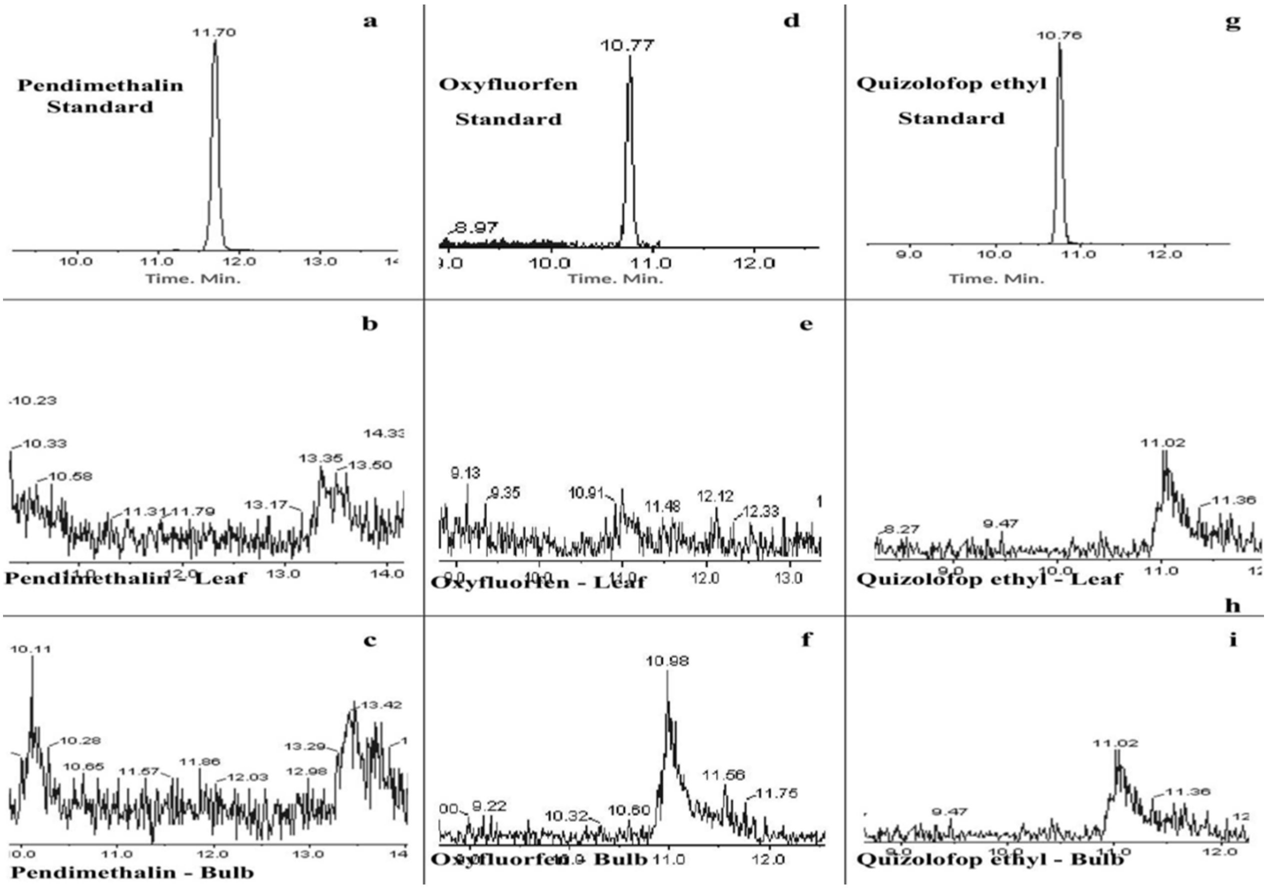


Figure 5. Comparison of pendimethalin (a, b and c), oxyfluorfen (d, e and f) and quizalofop-ethyl (g, h and i) herbicides residue in onion leaf and bulb with standard chromatogram

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RESEARCH ARTICLE

Integrated weed management in onion

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ABSTRACT

Field experiment was conducted at the Instructional Farm of Bidhan Chandra Krishi Vishwavidyalaya, Mohanpur, Nadia, West Bengal, India during *Rabi* season of 2013-14 and 2014-15 to study the effect of integrated weed management practices on weeds and yield of onion (*Allium cepa* L.). At early stage of crop growth *i.e.* at 10 DAT, maximum weed control efficiency (82.57%) was recorded in the treatment of propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha (tank mix) as pre-emergence followed by aqueous extract of cucumber (*Cucumis sativus* L.) 10% 2.5 liter/ha at 1 DAT (72.83%). Weed control efficiency (WCE) was sustained at later stage with 60.98% and 51.96% in these treatments, respectively. While in the later crop growth phase *i.e.* 25 DAT onwards, two hand weeding at 20 and 40 DAT recorded significantly the lowest weed density, biomass and higher weed control efficiency (83.27, 77.02, 64.23% at 25, 50 and 75 DAT, respectively). Notable increase in growth and yield attributes *viz*., plant height, chlorophyll content, LAI, DMA, CGR, bulb diameter, bulb length, scales/bulb, bulb yield, biological yield and harvest index were recorded in two hand weeding followed by PE application of propaquizafop + oxyfluorfen *fb* mechanical weeding (MW) and cucumber aqueous extract 10% *fb* MW. The net return and B:C ratio was significantly higher with propaquizafop+ oxyfluorfen *fb* MW and cucumber aqueous extract 10% *fb* MW due to lesser cost of herbicides usage compared to hand weeding.

Key words: Allelopathy, Onion, Oxyfluorfen, Propaquizafop, Weed management

INTRODUCTION

Onion (*Allium cepa* L.) is the most important biennial vegetable bulb crop grown throughout the world. In India, it occupies an area of about 1.625 million ha with production of 26.64 million tons and productivity of 16.39 t/ha (Anonymous 2021). West Bengal is an onion growing state with production of 0.863 million tons and average productivity of 19.74 t/ha from an area of 0.044 mha (Anonymous 2021). The area under onion cultivation has been tremendously boosted due to release and availability of high-yielding varieties in the state. Onion crop has poor competitive ability with weeds due to inherent characteristics such as short stature, non-branching habit, shallow root system and extremely slow growth in initial stage, causing significant reduction in yield. Yield loss due to weed infestation is reported to the tune of 50-80% (Kumari *et al*. 2019). Even the losses caused by weeds exceed the losses from any other category of agricultural pests in West Bengal (Adhikary 2018). For attaining the maximum yield, timely and effective weed control during the critical period of weed competition becomes necessary (Adhikary *et al*. 2016). Controlling weeds during early phase of crop growth is essential to obtain high yields and marketable produce. As conventional method of weed control, hand weeding is laborious, time consuming and expensive. Sole application of herbicides does not give an effective weed control. Options are limited for chemical weed management in onion while assuring quality of crop produce and ensuring higher benefit – cost ratio. Hence, it was felt necessary to assess different weed management practices applied alone and in combination for improving growth and yield of onion in alluvial zone of West Bengal.

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MATERIALS AND METHODS

Field experiments were conducted in the humid subtropics at the Instructional Farm of Bidhan Chandra Krishi Vishwavidyalaya (BCKV), Mohanpur, Nadia, West Bengal during *Rabi* season of 2013-14 and 2014-15. The experimental site was situated at 22.93°N latitude and 88.53°E longitude with an altitude of 9.75 meters above mean sea level. The local cultivar of onion '*Sukhsagar*' was used in the study. The experiment was laid out in a randomized complete block design with five treatments and four replications. The treatments were weedy check, two hand weeding (HW) at 20 and 40 days after transplanting (DAT), two mechanical weeding (MW) at 20 and 40 DAT, propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha (tank mix) as pre-emergence (PE) at 1 DAT *fb* MW at 40 DAT, and aqueous extract of cucumber (*Cucumis sativus* L.) with 10% 2.5 liters/ha at 1 DAT *fb* MW at 40 DAT. Aqueous extract was prepared as per the procedure described by Adhikary (2012). The inflorescence, leaves, stems and twigs of cucumber plant species were collected from the Instructional Farm (BCKV). The collected samples were dried in shade at room temperature for a week and later dried at 40°C in oven for 48 hours and ground to prepare the dry powder. Aqueous extract was prepared by using 100 g of dry powder dissolved in 1,000 ml of distilled water for 24 hours to obtain a concentration of 10%. Then it was filtered and the filtrate was boiled at a temperature of 60°C for two hours to concentrate the volume. The final extract was left to stand at 40°C for 30 minutes and then again filtered. The aqueous extract was used for spraying in the specific plots on the next day after mixing with non-ionic surfactant (Tween 80). The chemical herbicides as well as cucumber (*Cucumis sativus* L.) aqueous extract were sprayed with the spray volume of 500 liters/ha using knapsack sprayer fitted with flood jet deflector (WFN040 nozzle). All the other recommended agronomic and need-based plant protection measures were followed. Data on weed density and biomass were recorded at 10, 25, 50 and 75 DAT. Weed control efficiency (WCE) of different treatments was computed on the basis of weed biomass. Plant height, chlorophyll content and LAI were recorded at 75 and 100 DAT where as dry matter accumulation (DMA) and CGR were recorded at 25, 50, 75 and 100 DAT. Yield attributes were recorded at harvest. Data were subjected to statistical analyses following analysis of variance (ANOVA) technique, and mean differences were adjusted by the multiple comparison tests (Gomez and Gomez 1984).

RESULTS AND DISCUSSION

Effect on weeds

Dominant weed species found in the experimental plot were *Dactyloctenium aegyptium*, *Digitaria sanguinalis*, *Echinochloa colona*, *Eleusine indica*, *Cyperus rotundus*, *Blumea lacera*, *Chenopodium album*, *Cleome viscosa*, *Commelina diffusa*, *Melilotus alba*, *Nasturtium officinale*, *Physalis minima*, *Portulaca oleracea*, *Trianthema portulacastrum* and *Digera arvensis*. Similar findings on weed flora were also observed by Adhikary *et al*. (2014) and Kumari *et al*. (2019).

The pooled data on weed density at different crop growth stages (**Table 1**) revealed an increasing trend with the progress of crop growth in each treatment. Application of propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha at 1 DAT recorded significantly the lowest total weed density (3.13/m^2) at 10 DAT, which was followed by cucumber aqueous extract 10% (4.41/m^2). Among different treatments, minimum weed density (3.10, 4.17 and 6.55 /m^2 at 25, 50 and 75 DAT was recorded in two hand weeding at 20 and 40 DAT, respectively), whereas the weedy check plots recorded the highest total weed density. The chemical herbicide treated plots recorded significantly the lowest weed biomass (5.08 g/m^2) at 10 DAT and was followed by the use of cucumber plant extract 10% concentration 2.5 liters / ha PE when each of these treatments was combined with mechanical weeding. Since cucumber plants are mostly discarded as large waste after crop harvesting, allelopathy of cucumber plants was investigated for possible weed management options.

Table1. Effect of treatments on weed density, weed biomass and weed control efficiency at different growth stages in onion (pooled over two years)

Treatment	Total weed density (no./m^2)				Weed biomass (g/m^2)				Weed control efficiency (%)			
	10 DAT	25 DAT	50 DAT	75 DAT	10 DAT	25 DAT	50 DAT	75 DAT	10 DAT	25 DAT	50 DAT	75 DAT
Weedy check	6.69(43.7)	7.65(58.0)	8.07(64.1)	10.15(102.2)	29.15	59.41	67.44	104.40	0.00	0.00	0.00	0.00
Two HW	6.41(40.1)	3.10(8.9)	4.17(16.9)	6.55(42.5)	25.15	9.94	15.50	37.45	13.72	83.27	77.02	64.13
Two MW	6.54(41.7)	4.51(19.4)	4.94(24.0)	7.91(61.7)	25.56	15.20	22.13	53.21	12.32	74.42	67.19	49.03
Propaquizafop + oxyfluorfen *fb* MW	3.13(8.9)	3.96(14.7)	4.75(21.9)	6.99(48.2)	5.08	13.05	21.01	40.74	82.57	78.03	68.85	60.98
Cucumber aqueous extract 10% *fb* MW	4.41(18.7)	4.97(23.7)	5.00(25.0)	7.51(56.0)	7.92	20.80	22.38	50.15	72.83	64.99	66.81	51.96
LSD (p=0.05)	0.62	0.59	0.74	0.72	4.11	3.16	3.78	3.59	-	-	-	-

***Original values in parentheses were subjected to square root transformation**

Two potent growth inhibitory substances are present in cucumber (*Cucumis sativus* L.) plants. These substances were determined as HMO (9-hydroxy-4,7-megastigmadien-9-one) and THMO (6,9,10-trihydroxy-4,7-megastigmadien-3-one). HMO and THMO have the ability to inhibit the seed germination and growth of different grass species. Similar allelopathy effect of cucumber extract was observed by Noguchi *et al.* (2015). Two hand weeding (20 and 40 DAT) recorded minimum weed biomass of 9.94, 15.50 and 37.45 g/m^2 at 25, 50, 75 DAT, respectively. Weeds along with propagating materials like bulbs and bulb lets (sedges), tap roots (broad-leaved weeds), stolons (grasses), *etc.* could be removed or uprooted by Khurpi - aided hand weeding or mechanical weeder. Among different weed control treatments, application of propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha *fb* MW at 40 DAT recorded the highest weed control efficiency (WCE) of 82.57% at 10 DAT and was followed by PE application of cucumber aqueous extract 10% *fb* MW at 40 DAT (72.83%). This might be due to control of weeds during early growth stage by pre-emergence application of propaquizafop+ oxyfluorfen (tank mix) and cucumber aqueous extract which prevented emergence of monocot and grassy weeds by inhibiting root and shoot growth, while mechanical weeding (MW) at 40 DAT was responsible for controlling of broad-leaved weeds which caused complete destruction of these weeds at 3-4 leaf stage. Two hand weeding registered maximum weed control efficiency of 83.27, 77.02 and 64.13% at 25, 50 and 75 DAT, respectively. Although two rounds of hand weeding or mechanical weeding could keep the weeds under control from the beginning till harvest, these were cost-prohibitive. Superiority of manual weeding regarding effective weed management and higher productivity was also reported by Adhikary *et al.* (2016) and Shil and Adhikary (2014).

Effect on crop growth

The plant height was significantly influenced by different weed management practices at 75 and 100 DAT (**Table 2**). The highest plant height (46.07 cm) was found under two hand weeding treatment at 100 DAT, which remained at par with the application of propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha *fb* MW at 40 DAT. Weedy check plots registered the lowest plant height of 30.75 and 37.13 cm at 75 and 100 DAT, respectively. Two hand weeding and propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha + MW) recorded the higher chlorophyll content (49.61 and 47.81, respectively) at 75 DAT. Hand weeding is a method that removes competing weeds from onion plants, allowing them to access more sunlight, water, and nutrients, promoting growth. This leads to increased plant height and efficient photosynthesis. Additionally, hand weeding ensures better soil nutrient uptake, supporting overall plant growth. Weeds can induce stress on onion plants by competing for resources and releasing allelopathic chemicals, but hand weeding reduces this stress, allowing plants to focus on growth and chlorophyll production. Both the treatments maintained similar trend in influencing chlorophyll content at 100 DAT. At 100 DAT, the leaf area index (LAI) was maximum in two hand weeding (4.66), followed by the treatment of propaquizafop + oxyfluorfen + MW (3.85). The maximum dry matter accumulation (DMA) at 25 DAT (**Table 2**) was recorded in the treatment received two hand weeding (16.08 g/m^2), which remained at par with the IWM treatment (propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha + MW). These treatments also recorded higher DMA at 75 and 100 DAT, whereas it was always the lowest in weedy check plots (12.78, 27.29, 83.24 and 190.00 g/m^2 at 25, 50, 75 and 100 DAT, respectively). There was a significant effect of weed control treatments on crop growth rate (CGR) over a period of time (**Table 2**). The CGR ranged

Table 2. Effect of treatments on plant height, chlorophyll content, leaf area index, dry matter accumulation and crop growth rate of onion (pooled over two years)

Treatment	Plant height (cm)		Chlorophyll content (SPAD value)		Leaf area index (LAI)		Dry matter accumulation (DMA) (g/ m^2)				Crop growth rate (CGR) (g/m^2/day)		
	75 DAT	100 DAT	75 DAT	100 DAT	75 DAT	100 DAT	25 DAT	50 DAT	75 DAT	100 DAT	25-50 DAT	50-75 DAT	75-100 DAT
Weedy check	30.75	37.13	37.31	35.25	2.09	3.21	12.78	27.29	83.06	190.0	0.58	2.23	4.28
Two HW	36.00	46.07	49.16	46.33	3.36	4.66	16.08	39.42	101.61	290.9	0.93	2.49	7.57
Two MW	33.13	42.84	43.15	41.14	2.80	3.45	14.57	32.17	93.94	279.8	0.70	2.47	7.43
Propaquizafop + oxyfluorfen *Fb* MW	34.58	45.55	47.81	44.94	3.21	3.85	15.14	38.24	100.19	284.7	0.92	2.48	7.38
Cucumber aqueous extract 10% *fb* MW	33.75	43.53	45.14	42.69	2.95	3.53	14.69	36.58	96.53	272.8	0.88	2.40	7.05
LSD (p=0.05)	2.15	1.37	2.76	2.89	0.33	0.76	1.50	2.08	3.96	28.6	0.04	NS	1.17

from 0.58 to 0.93 g/m²/day during 25-50 DAT. The pooled data revealed that the maximum CGR in two HW (0.93 g/m²/day), which was at par with the IWM (propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha + MW) treatment (0.92 g/m²/day). Higher dry matter accumulation per plant was observed in these treatments due to effective control of weeds after imposing the treatments at the early stages of crop growth. As a result, the crop had put forth luxuriant growth and produced more number of leaves and reproductive parts which in turn produced more dry matter accumulation per plant. But it was the minimum in weedy check treatment. Gaharwar *et al.* (2017) reported similar findings.

Effect on yield

Weeds seriously affected bulb development and drastically reduced yield. Two hand weeding (20 and 40 DAT) recorded the highest bulb diameter (51.62 mm), length of bulb (60.49 mm) and number of scales/bulb (7.53) which was at par with propaquizafop + oxyfluorfen followed by PE application of cucumber aqueous extract 10% *fb* MW at 40 DAT (**Table 3**). While, the minimum bulb diameter (37.38 mm), bulb length (46.75 mm), number of scales per bulb (6.03) was recorded in the weedy check treatment. Variability in bulb development was due to different weed control methods which influenced the nutrient availability to the crop plants through various mechanisms. The interaction between weed management practices and nutrient dynamics in the soil is complex and can impact nutrient availability both directly and indirectly. Weeds compete with crop plants for essential nutrients, water, and sunlight. When weeds are present, absorb and utilize nutrients that would otherwise be available to the crop. This can lead to nutrient deficiencies in crop plants, affecting their growth and yield. Some weeds release allele-chemicals into the soil, which can have allelopathic effects on nearby crops. These chemicals may inhibit the germination, growth, or nutrient uptake of crop plants, reducing their ability to access and utilize nutrients from the soil. Two hand weeding (20 and 40 DAT) registered significantly the highest bulb yield (18.17 t/ha), which was at par with propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha PE *fb* MW treatment (17.26 t/ha). On the other hand, application of cucumber aqueous extract 10% (PE) *fb* MW at 40 DAT was found to be statistically at par with two mechanical weeding (20 and 40 DAT) treated plot. The biological yield (25.90 t/ha) was recorded in the treatment HW at 20 and 40 DAT, and it was at par with the propaquizafop + oxyfluorfen (25.12 t/ha). Whereas, significantly the lowest bulb yield (5.50 t/ha) and biological yield (10.78 t/ha) was recorded in the weedy check treatment. The main reason was due to the presence of more number of broad leaved, grassy and sedges weeds associated with the crop which exhibited severe competition throughout the crop growth. And no significant effect was observed in harvest index of onion. These results in respect of yield attributes were in close conformity with the earlier findings of Kalhapure and Shete (2012) and Thakare *et al.* (2018).

Economics

Maximum net monetary return was obtained from the treatment receiving propaquizafop + oxyfluorfen (tank mix) PE at 1DAT *fb* MW at 40 DAT (₹ 98630/ha), followed by two hand weeding (₹ 94235/ha). But in terms of benefit cost ratio, the application of cucumber aqueous extracts 10% (PE) *fb* MW at 40 DAT registered better result (B:C ratio 3.20) than two hand weeding and positioned after chemical herbicide *fb* MW treated plots (B:C ratio 3.50). Whereas the weedy check treatment registered the lowest net return (₹ 9875/ha) and B:C ratio (1.29). Though hand weeding treated plots registered the highest yield, it was cost-prohibitive and ineffective due to high labor cost, timely unavailability of skilled labor and high time requirement. With the timely

Table 3. Effect of treatments on various yield attributes, yield and economics of onion (pooled over two years)

Treatment	Bulb diameter (mm)	Bulb length (mm)	Scales/ bulb	Bulb yield (t/ha)	Biological yield (t/ha)	Harvest index (%)	Cost of cultivation (`/ha)	Gross return (`/ha)	Net return (`/ha)	B:C ratio
Weedy check	37.38	46.75	6.03	5.50	10.78	51.02	34125	44000	9875	1.29
Two HW	51.62	60.49	7.53	18.17	25.90	70.15	51125	145360	94235	2.84
Two MW	48.65	56.31	6.22	12.52	20.14	62.16	40625	100160	59535	2.47
Propaquizafop + oxyfluorfen *fb* MW	50.41	59.19	7.24	17.26	25.12	68.71	39450	138080	98630	3.50
Cucumber aqueous extract 10% *fb* MW	49.00	57.48	6.46	14.23	21.96	64.80	35625	113840	78215	3.20
LSD (p=0.05)	1.05	1.38	0.76	1.77	2.09	NS	-	-	-	-

unavailability of safer chemicals in rural areas, the aqueous extracts of cucumber leaf in combination with mechanical weeding (MW) might be an alternative and feasible option. Adhikary *et al*. (2014 and 2016) reported similar findings.

The study concluded that the integrated weed management practices involving either application of propaquizafop 0.05 kg/ha + oxyfluorfen 0.25 kg/ha (tank mix) at 1 DAT *fb* mechanical weeding at 40 DAT, or aqueous extract of cucumber (*Cucumis sativus* L.) plant 10% 2.5 liters/ha at 1 DAT *fb* mechanical weeding at 40 DAT might be the possible options for cost-effective weed management in onion under irrigated condition in West Bengal.

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RESEARCH ARTICLE

Efficiency and economics of broomrape (*Orobanche* spp.) control by different management practices in tobacco

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ABSTRACT

A field experiment was carried out at Research Farm of Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar during 2014-15 and 2015-16 to evaluate the effect of different weed management practices on yield and economics of tobacco. Five weed management treatments were tried out in a randomized block design with four replications. The results revealed that application of neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP recorded the lowest broomrape population of 11.71 and 12.05/plant and maximum tobacco yield of 2.45 and 2.39 t/ha in both the years, respectively. Highest B : C (2.20) was obtained with neem cake 200 kg/ha at sowing followed by (*fb*) soil drenching of metalaxyl MZ 0.2% at 20 DAP followed by soil drenching of metalaxyl MZ 0.2% at 20 DAP. Hence, it was concluded that for better tobacco yield and broomrape (*Orobanche* spp.) control, neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP was found to be the best practice.

Keywords: Broomrape, Economics, *Orobanche* spp., Metalaxyl MZ, Neem cake, Soil drenching, Tobacco

INTRODUCTION

The primary non-food crop grown in more than 100 countries is tobacco (*Nicotiana tabacum* L.) with a combined land area of 4.2 million hectares (Patel *et al*. 2018). Tobacco is a member of the solanaceae family and of the tubiflorae order, is thought to have been brought to India from its native Central America by the Portuguese in 1603 (Rani *et al*. 2023). China, the United States, India, Brazil, Turkey, Russia, Italy, and Zimbabwe are the top tobacco-producing nations in the world. About 36 million people in India are employed in the production, processing, marketing and export of tobacco, either directly or indirectly. As a result, a substantial portion of the population depends on this crop, especially rural women, tribal people, and other weaker groups in society (Krishnamurthy 2011, Punia 2014). Among different types of tobacco grown in the country, chewing tobacco plays a key role in the national economy in generating employment and income.

In Bihar, tobacco is an important crop but harvesting of it is significantly hampered by the growth of weeds. There is intense crop-weed competition for light, moisture, space, and nutrients as a result of the simultaneous emergence and rapid development of weeds. Broomrape (*Orobanche* spp.) is a total root parasitic annual herb that is propagated by seed. It ranks among the worst weeds in the tobacco crop. Seed germination in soil is induced by exudates from the host root. The host roots close by are then infected by the parasite seedlings, which develop haustoria on them. In just eight weeks, each plant can produce more than a million seeds and can cause yield reduction up to 60% (Patel *et al*. 2017 and Punia 2015). Currently, due to scarcity of human labour, manual weeding is becoming very difficult. Herbicides are one of the most important broomrape management tools in tobacco. Several studies have reported that low doses of total weed killer like glyphosate can stimulate plant growth due to hormesis effect (Ferrari *et al*. 2021). Moreover, glyphosate-based management system has many advantages, including low cost, excellent crop safety, broad spectrum of weed control, and application flexibility (Yadav *et al*. 2020). Presently, due to adverse soil and weather conditions, intercultural operations are not done on time and tobacco growers are dependent on the herbicide mixture for broad-spectrum weed flora; but it has limited choice of herbicides. Continuous use of the herbicides with same mode of action has already led to the problem of herbicide resistance in weeds of tobacco (Krishna *et al*. 2018). Hence, evaluation of integrated weed management approach based on different herbicides is very much required for effective control of weed flora especially broomrape in tobacco. Therefore, considering the importance of different management

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practices on tobacco, the present experiment was conducted to find out the effective management practices for broomrape control and increase yield under north Bihar conditions.

MATERIALS AND METHODS

A field study was conducted during two successive years (2014-15 and 2015-16) at Research Farm, Dr. RPCAU, Pusa. The experiment was laid out in a randomised block design with four replications. The experiment is comprised of five weed management treatments *i.e.*, neem cake 200 kg/ha at sowing followed by (*fb*) soil drenching of metalaxyl MZ 0.2% at 20 days after planting (DAP); imazethapyr 30 g/ha at 40 DAP; glyphosate 100 g/ha at 20 DAP; soil drenching of metalaxyl MZ 0.2% at 20 DAP; weedy check. The soil type was sandy loam having 0.47% organic carbon, alkaline in reaction (pH 8.54), 203.79 kg/ha available nitrogen, 25.09 kg/ha available phosphorus and 153.25 kg/ha available potassium. Tobacco variety *PT76* was transplanted in 90 × 90 cm spacing. Recommended dose of fertilizer 250 kg N, 70 kg P and 70 kg K/ha were applied. All the necessary cultural practices excluding weed management were carried out uniformly to bring the crop at maturity. Weeds were counted at 60, 90 DAP and at harvest using a quadrat of 0.25 square meter (0.5 x 0.5 m), and data obtained were expressed as number of *Orobanche*/plant. For economics analysis the prevalent market price of the chewing tobacco was considered to calculate gross and net returns and finally benefit–cost ratio was calculated. Statistical analysis was done by adopting appropriate method of Analysis of Variance (Gomez and Gomez 1984) and mean comparisons were performed based on the least significant difference (LSD) at 0.05 probability.

RESULTS AND DISCUSSION

Effect on weeds

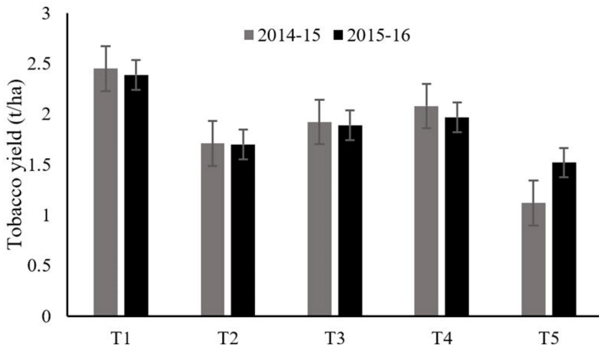
All the weed management treatments reduced the broomrape population as compared to unweeded weedy check in both the years (**Table 1**). Weedy check recorded significantly higher number of weeds than all the other treatments. At 60 DAP, neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP recorded the lowest number of *Orobanche* (4.5 and 5.1/plant) in both the years, respectively respectively. The similar trend was followed at 90 DAP and at harvest. The number of *Orobanche*/plant was recorded 57.2% and 55.1% lower over both the years, respectively with treatment Neem cake 200 kg/ha at sowing followed by (*fb*) soil drenching of metalaxyl MZ 0.2% at 20 days after planting (DAP) than weedy check. This might be due to inhibitory effect of nitrogen to broomrape through application of neem cake at sowing, which effectively hindered the population of *Orobanche* spp. and soil drenching at 20 DAP controlled it later onwards.

Effect on yield

The tobacco yield was significantly influenced by different weed control treatments (**Figure 1**). Application of neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP recorded significantly higher tobacco yield (2.45 and 2.39 t/ha, respectively) which was significantly superior over remaining other treatments during both the years. Moreover, application of neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP improved the yield to the tune of 17.8% and 21.3% over the application of soil drenching of metalaxyl MZ 0.2% at 20 DAP in the both years respectively. In contrast, growth and yield of many solanaceae family crops were enhanced by low doses of glyphosate (Velini *et al*. 2008). Application of imazethapyr 30 g/ha at 40 DAP caused severe phytotoxicity on tobacco leaves. Thus, the growth of plant was severely stunted and size of leaves was decreased leading to loss in yield of the crop by 30.2% and 28.7% in both the years, respectively as compared. Whereas, Sousa *et al.* (2017) found that application metalaxyl altered carbon metabolism, which resulted in a reduction of growth and lower biomass accumulation due to impairment of carbohydrate production (total soluble sugar, starch, rubisco) and increased photorespiration in solanaceous plants. The minimum values of

Table 1. Broomrape population of tobacco as influenced by different levels of weed management practices

Treatment	Broomrape population (no. of *Orobanche*/plant)					
	60 DAP		90 DAP		At harvest	
	2014-15	2015-16	2014-15	2015-16	2014-15	2015-16
Neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP	4.50	5.10	7.52	5.80	11.71	12.05
Imazethapyr 30 g/ha at 40 DAP	11.51	10.88	14.20	13.95	16.52	16.75
Glyphosate 100 g/ha at 20 DAP	9.92	9.10	12.81	11.93	15.20	15.18
Soil drenching of metalaxyl MZ 0.2% at 20 DAP	7.20	6.95	9.62	8.12	14.92	14.70
Weedy check	21.84	22.35	26.40	25.75	27.30	26.85
LSD (p=0.05)	0.75	0.65	1.85	1.83	2.19	2.12



T_1: Neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP, T_2: Imazethapyr 30 g/ha at 40 DAP, T_3: Glyphosate 100 g/ha at 20 DAP, T_4: Soil drenching of metalaxyl MZ 0.2% at 20 DAP, T_5: Weedy check

Figure 1. Yield of tobacco as influenced by different levels of weed management practices

Table 2. Economics of tobacco as influenced by different levels of weed management practices (pooled data)

Treatment	Gross return (₹/ha)	Net return (₹/ha)	B:C ratio
Neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP	478400	342600	2.20
Imazethapyr 30 g/ha at 40 DAP	341000	190200	1.26
Glyphosate 100 g/ha at 20 DAP	377400	227100	1.51
Soil drenching of metalaxyl MZ 0.2% at 20 DAP	395000	244200	1.62
Weedy check	305000	155000	1.03
LSD (p=0.05)	12365	12365	0.19

broomrape/plant throughout the crop growth period in neem cake 200 kg/ha at sowing followed by (*fb*) soil drenching of metalaxyl MZ 0.2% at 20 days after planting (DAP) could be the reason for higher yield of tobacco. Moreover, higher production of tobacco with neemcake application and soil drenching along with herbicidal treatments was due to low broomrape infestation as well as short broomrape competition period. These results are in agreement with the findings of Punia *et al*. (2021) and Singh *et al*. (2020).

Economics

Farmers' first consideration when deciding whether to adopt a new technology is the economics of produce. The results revealed that after two years of experimentation, maximum net returns of ₹ 342600/ha along with B:C value of 2.20 was recorded under application of neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 02% at 20 DAP which was significantly superior over rest of the treatments (**Table 2**). On the contrary, treatment imazethapyr 30 g/ha at 40 DAP; glyphosate 100 g/ha at 20 DAP excluding weedy check recorded minimum gross returns of ₹ 34100/ha, net returns of ₹ 190200/ha with B:C of 1.26. Higher profit was due to chemical control in tobacco have been supported by Mariam and Suwanketnikom (2004).

The present study has clearly demonstrated that tobacco responded well for integrated weed management practices. From the two years study, it was concluded that for effective control of broomrape and securing maximum yield of tobacco as well as profitablity, neem cake 200 kg/ha at sowing *fb* soil drenching of metalaxyl MZ 0.2% at 20 DAP should be applied in Bihar.

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RESEARCH ARTICLE

Deep learning-based weed detection in sesame crops using modified YOLOv5 model

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ABSTRACT

In agriculture, the weed plant identification is a challenging task as it allows farmers to accurately recognize and remove the same plants from their field. In India, conventional methods for detecting and removing weeds require considerable manual labor and skill, resulting in a time-consuming and costly process. With recent advancements in machine learning and computer vision, automated weed detection systems have become more prevalent. We worked an innovative method for crop-weed classification and weed detection that utilizes a Convolutional Neural Network (CNN) to differentiate images of plant into either weed or non-weed categories. The techniques we introduced were developed using an extensive dataset containing 1300 images of sesame (*Sesamum indicum L.*) crops cultivated in farmlands of China. The proposed approach evaluated on a dataset available on the Roboflow platform. We used ResNet50 architecture for image classification and Faster-RCNN and YOLO (You Only Look Once) for object detection. The YOLOv5 model's performance was measured by utilizing Precision (P), Recall (R), and the mean Average Precision (mAP) as performance evaluation metrics. The proposed modified YOLOv5 model achieved the best overall performance within the 'Weeds' validation subset resulting in a P (80.7), R (81.1), and mAP (86.4). This approach is suitable for bermudagrass, crabgrass and pigweed species of weeds in sesame field. The proposed approach has several practical applications in agriculture, including weed management, crop yield optimization, and environmental sustainability. Furthermore, it has potential use when integrated with other precision farming equipment, making it a cost-effective solution for farmers. We concluded the efficacy of employing deep learning methods for the detection of weed plants and suggest that it has the potential to revolutionize modern agriculture.

Keywords: Convolutional Neural Network, Deep learning, Sesame, Weed detection, YOLO model

INTRODUCTION

One of the most important factors of overall crop productivity is weed. Weed competes with crop for assets like water, space, nutrients and light. This competition of weeds with crop plants decreases yields and degrades production quality. Weeds can also host diseases and pests, which can further harm the crops (Singh and Gupta 2022). Furthermore, weeds lower the quality of crops by contaminating them with weed seeds or by making them tough to harvest. The cost of controlling weeds can also be important, as it often needs the herbicides usage or manual work to eliminate them. The present research indicates that the presence of weeds can lead to a reduction in overall productivity ranging from 10% to 90%, depending on the extent of the infestation and the crop variety (Nurudeen *et al.* 2024). To mitigate their influence on crop yields and maintain the sustainability of agricultural systems, it is crucial to effectively manage weeds.

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Weed management plays a crucial role in all crops. Managing weeds is an important task of forestry practices and agriculture (Elhoseny *et al.* 2023), as an uncontrolled growth of weeds can considerably reduce crop production and overall quality (Alotaiby *et al.* 2022). Traditionally weeds are being managed by several methods such as hand weeding and overall chemical spraying but these methods have proven as time-consuming, costly, labor-intensive, and environmentally dangerous (Shanmugam *et al.* 2021). Hence, it is necessary to develop a precision weed management approach that accurately detects weeds and controls them. The overall objective of the weed plant detection method is to identify and localize the presence of weeds accurately in an image or video stream. Because of the high variation in color, texture, appearance and shape of weed species, along with their complexity, this is a particularly difficult task.

With the growth of machine learning algorithms and computer vision over the recent years, it is now possible to develop automated systems for detecting and identifying weeds in agricultural fields. By providing timely and precise information about the location and distribution of weeds, these systems can assist farmers in accurately detecting the weed species and subsequently controlling them. This approach leads to minimizing the use of herbicides, and lowering production costs, increasing crop yields and ensuring the sustainability of agricultural systems. Numerous traditional machine-learning approaches, relying on image processing methods using classifiers such as K-Nearest Neighbor (KNN), Random Forest (RF), Support Vector Machine (SVM) and Decision Tree have been applied. These approaches use various feature extraction techniques, including shape, texture and color analysis, for the detection and categorization of weeds. Furthermore, with the help of deep learning algorithms, these systems can learn from large datasets and gradually improve their performance (Pallottino *et al.* 2022).

In this work, we explored deep-learning techniques for detection and differentiation classification of crop-weeds species. Specifically, we use a CNN to discover weeds in high-resolution imageries.

MATERIALS AND METHODS

The suggested approach involves several steps represented in pictorial form as shown in **Figure 1**. We conducted our experiments on a publicly accessible dataset that is available on the Roboflow platform. The study utilized a dataset of weed and sesame crop images cultivated during the spring season from row-based farmlands located in Nanning, Guangxi, China. The images were acquired during kharif season and under cloudy weather conditions. The variety of sesame used in the study was '*Yuzhi 11*', which has a growth duration of approximately 90-100 days (Jiqing *et al.* 2022). The dataset comprises 1300 images, each having a resolution of 4000 by 3000 pixels. Images were captured at various growth stages of the sesame crop, including germination, vegetative, flowering, and pod-filling stages. The crop was sown using the line sowing method, with a crop geometry of 30 cm row-to-row and 10 cm plant-to-plant distance. The average plant population observed in the field was approximately 330,000 plants per hectare. The weeds observed in sesame crop includes Bermudagrass (*Cynodon dactylon*), Crabgrass (*Digitaria* spp.), Pigweeds (*Amaranthus* spp.) *etc*. We converted all images to 640 x 640 x 3 pixel size. To reduce noise and enhance the image contrastness, we pre-processed the input image.

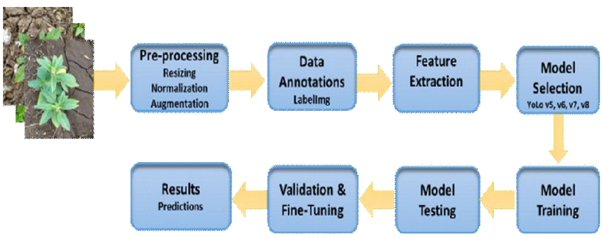

Figure 1. Process flow of weed detection and classification system

The dataset images were manually annotated to discriminate between sesame crops and weeds using the LabelImg tool. All image were meticulously reviewed, and regions containing sesame crops and weeds were labeled to create ground truth data with precise locations and boundaries. Based on the shape, color and texture features, the ground truth data distinguishes between crop and weed. This approach aligns with supervised learning, where the model is trained on input-output pairs to learn the mapping from inputs to the desired outputs. Deep learning benefitted from automatic feature extraction via layers of Convolutional Neural Networks (CNNs).

The YOLOv5 object detection model was selected and trained on an extensive dataset to enhance the model's accuracy. The proposed work evaluates performance in terms of accuracy, precision, and recall, demonstrating their effectiveness in detecting weeds and differentiating them from sesame crop. To further improve the performance of the proposed models, hyperparameter fine-tuning was conducted. The dataset was divided into testing (10%), validation (20%), and training (70%) subsets. We used 900 images for training, 137 for testing and 263 images for validation purposes.

Image classification and object detection models

The proposed work utilized ResNet50 model for image classification and Faster-RCNN, YOLOv5 model for object detection. Proposed model utilized Transfer Learning (TL) methods on pre-trained models ImageNet, VGG16 and ResNet50 leveraging both the Keras and PyTorch frameworks.

A notable example of a two-stage object detection framework is Faster R-CNN. Initially, it generates region proposals through a Region Proposal Network (RPN), followed by refining these proposals for the ultimate purpose of object detection and classification. YOLO stands as a renowned single-stage object detection algorithm that processes the entire image in one forward pass through a neural network. Both Faster-RCNN and YOLOv5 primarily uses the PyTorch framework. Faster R-CNN has been implemented in other deep learning frameworks as well, such as TensorFlow.

The YOLO architecture has consistently been a widely accepted model for object recognition among deep learning professionals. In June 2020, Ultralytics introduced the state-of-the-art object detection model YOLOv5. It represents an improvement over the YOLOv4 framework, which is renowned for its outstanding accuracy and ability to operate in real-time.

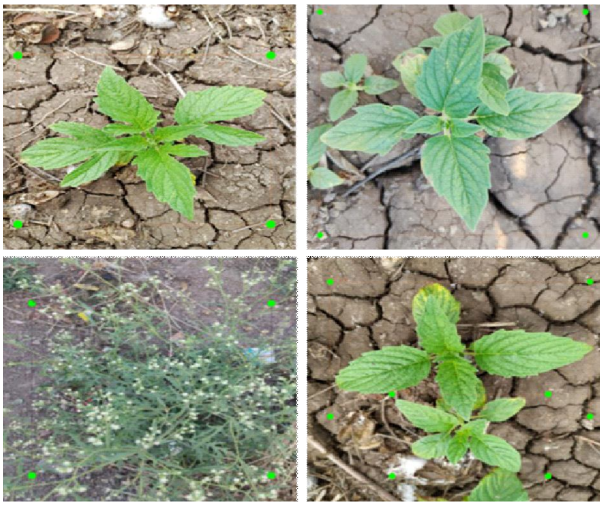

Figure 2. Sample images of sesame crop and weed in the dataset

YOLOv5 features a single-layer object detection network with a CSPDarknet53 feature extractor as the backbone. The model structure incorporates several innovative elements like Spatial Pyramid Pooling (SPP), PAN, and BiFPN, all contributing to enhancing the effectiveness and accurateness of the trained model. The YOLOv5 model has attained leading-edge performance on various benchmark object detection datasets, including Pascal Visual Object Classes (VOC) and Microsoft Common Objects in Context (COCO) (Sportelli *et al.* 2023).

As shown in **Figure 3,** the YOLOv5 architecture relies on a fusion of a cross-stage partial network (CSPNet) and the Darknet, which serves as its foundational framework (C. Y. Wang *et al.* 2016). To fulfill the requirements of the YOLO algorithm, images were annotated using LabelImg tool. LabelImg stores annotations in a variety of formats such as XML, JSON, CSV, or text format (López-Correa *et al.* 2022). In YOLO, bounding box information was stored in text file format following a

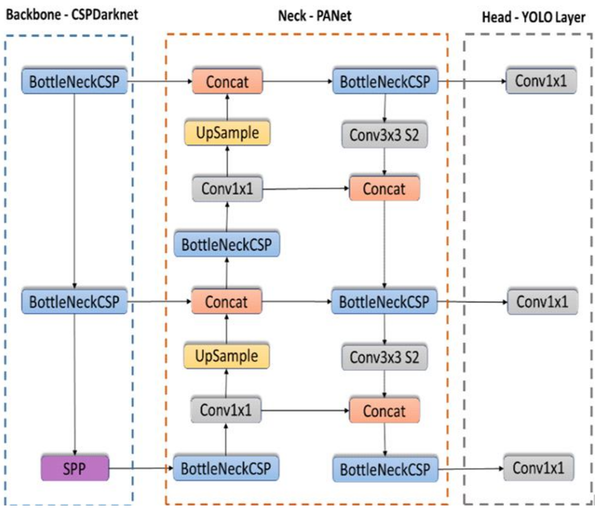

Figure 3. Architecture of YOLOv5

particular syntax. The rectangular (bounding) box were recorded on a separate line and included five numerical values. The initial number indicated the label of class, while the second and third numbers denoted the x and y coordinates of the top-left corner of the bounding box. The 4^{th} and 5^{th} numbers denoted the bounding box's width and height (Aanis Ahmad *et al.* 2021).

The annotation process were applied to all plants within the images, and all the relevant information of annotations of bounding box were stored on a single line of text.

We implemented our proposed methods in Python using TensorFlow and OpenCV libraries. We used a workstation with an Intel Core i3 CPU, 8GB of RAM, and a Google Colab to train and evaluate our models.

We have standardized the following hyper-parameters across all experimental configurations for YOLOv5.

- Training epochs: 100 and 150
- Solver type/Optimizer: SGD (Stochastic Gradient Descent)
- Input image size: 640
- Momentum: 0.937
- Batch size: 4
- Learning rate (LR) policy: Exponential decal
- Weight decay: 0.0004
- Base learning rate: 0.0001
- AutoAnchors: 3.51 anchors/target

To assess the efficiency of the suggested approach, we employed the evaluation metrics: accuracy in the form of mAP (mean Average Precision), recall and precision.

Evaluation metrics

In this proposed work, we used precision, recall and mAP as the evaluation criteria for training the detection model (Jialin *et al.* 2019).

Precision is defined as the ratio of correctly identified weeds of a specific species among the expected weeds. Recall represented the percentage of correctly predicted targets within a weed class within the sample. The following is the formula (Tushar *et al.* 2023):

$$P = \frac{True\ Positives}{True\ Positives + False\ Positives} \quad (1)$$

$$R = \frac{True\ Positives}{True\ Positives + False\ Negatives} \quad (2)$$

In this context, True Positive (TP) denotes the samples count correctly categorized as positive samples, False Positive (FP) signifies the count of erroneously classified positive samples, and FN represented for incorrectly classified negative samples count.

The mAP represents the average of the individual average precisions calculated for all categories within the dataset. This is computed by dividing the summation of average precisions for all categories by the total number of categories:

$$mAP = \frac{\sum AP}{n} \quad (3)$$

RESULTS AND DISCUSSION

The training performance of ResNet50 and Faster-RCNN is given below in **Table 1**. The proposed work achieved accuracy of 81.6% with Faster-RCNN and 79.4% with ReesNet50. The training results of the YOLOv5s model is given below. The **Table 2** provides a comparison between two configurations of the YOLOv5s model in terms of training parameters and performance metrics. The second configuration, which were trained for more epochs, generally outperforms the first configuration in terms all evaluation metrics. From the results, it seems that YOLOv5 outperformed in terms of accuracy.

Table 1. Training results of ResNet-50 and Faster-RCNN

Parameter	ResNet50	Faster-RCNN
No. of training Steps	25,000	25,000
Training time	7 Hrs. (1 sec/step)	7 Hrs. (1 sec/step)
Loss	0.0067	0.0843
Learning Rate	0.0165	0.0185
Accuracy	79.4%	81.6%

Table 2. Training results of YOLOv5s

Parameters	YOLOv5s	
Epochs	100	150
Training time	0.737 hours	1.036 Hours
Precision	76.70	80.70
Recall	78.00	81.11
Accuracy (mAP@0.5)	82.90	86.40
mAP@0.5-0.95	49.70	44.80

Figure 4 given below presented inferencing / detection results (predictions) of YOLOv5 with a confidence level (IoU) of 0.5 on validation dataset visualize the results.

These examination outcomes were displayed using an IoU threshold with 0.5. (In this illustration, the class label, which can be either "weed" or "crop," is situated to the left corner of the bounding box, while the precision score for that class is positioned to the right.). The curves of YOLOv5 are shown below in figure 5. Here, the precision-recall curve of YOLOv5 revealed that the weed class achieved a slightly superior average precision (AP) score of

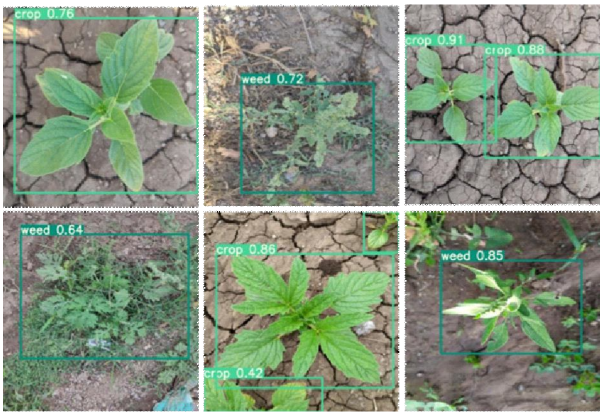

Figure 4. Detection results using YOLOv5 with a bounding box

0.877 compared to the crop class. The solid blue line fig mAP at an 0.5 IoU, calculated on test dataset. The individual average precision (AP) scores for each class and the overall algorithm's mAP were reflective of the area beneath their respective curves on the graph.

In **Figure 5 (a)** A curve that represents the relationship between precision and confidence. From this curve it is cleared that, precision is maximum with a confidence level of 0.877, suggesting a significant proportion of true positive results across all classes. (b) A curve that illustrates the connection between recall and confidence. The recall-confidence curve analysis provides insights into prediction performance, exhibiting a progressive drop in recall values as confidence levels increase. (c) A curve that shows the interplay between precision and recall. Here class 1(weed) achieves a slightly superior average precision of 0.877 than class 0. (d) A curve displaying the connection between F1 score and confidence. The average F1 score reached to 0.81 with a confidence interval of 0.374.

During the fine-tuning of hyper parameters, the metrics and losses are still improving and this is depicted in **Figure 6**. It's evident that the box loss, obj loss and cls loss parameters in both the datasets (training and validation) of the trained model consistently decreased. Simlutaneously, the AP with mAP@0.5 consistently improved. YOLOv5 achieved an mAP@0.5 score near to 0.9, signifying superior training outcomes when using the sesame dataset. The results were recorded in the results.csv file after each epoch and are subsequently visualized as results.png upon completing the process of training. Additionally, we can create plots manually using any results.csv file. After training our model, we achieved less loss value in both the validation and training as given in the following statistics in **Table 3**.

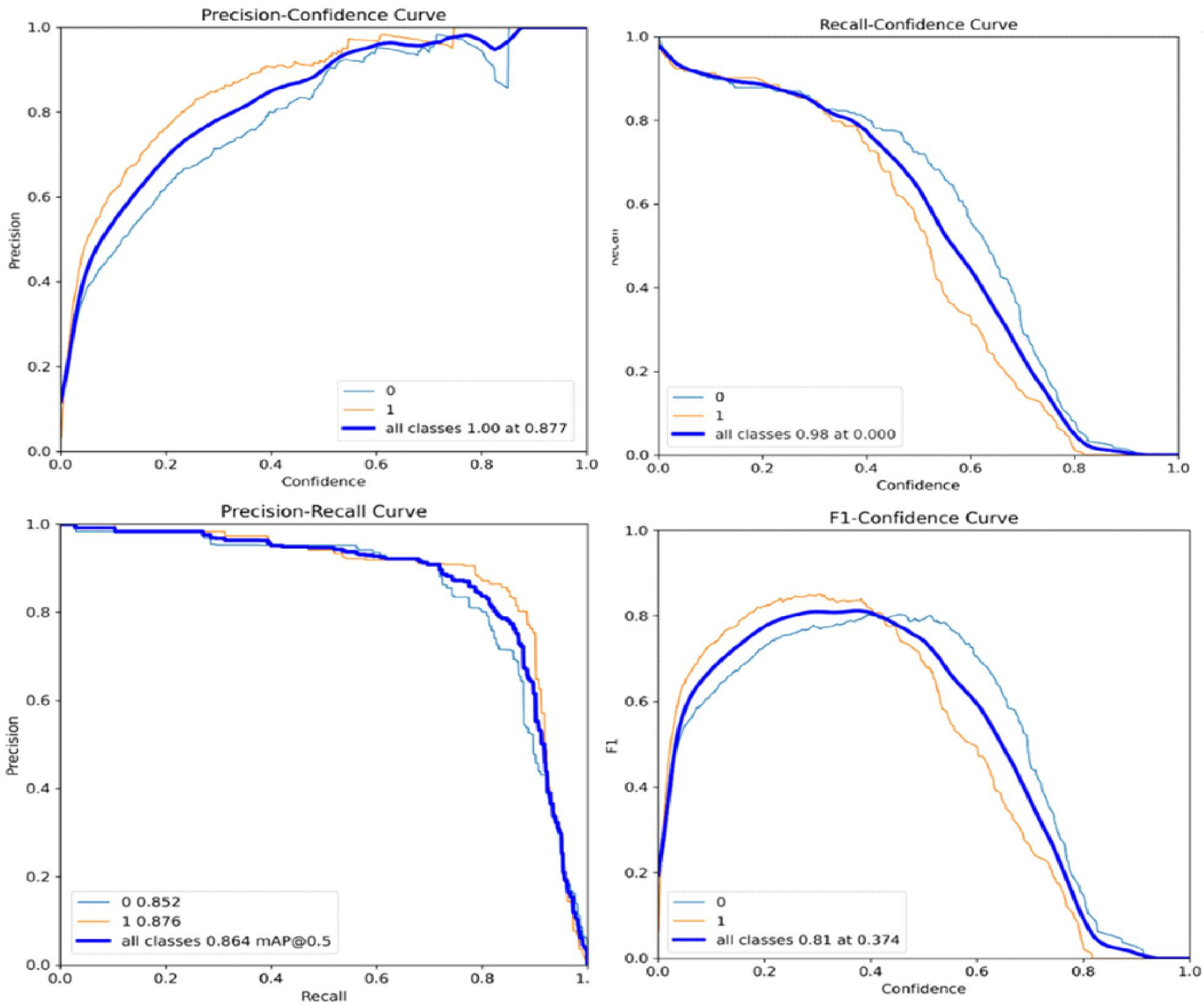

Figure 5. Graphical representation of performance parameters for training via YOLOv5

Table 3. Training and validation loss

Phase	box_loss	obj_loss	cls_loss
Training	0.0288	0.0218	0.0035
Validation	0.0215	0.0086	0.0043

Our suggested approach attained 86.40% accuracy, 80.70% precision, and 81.11% recall in detection of weed species in the dataset. YOLO method outperformed both other methods ResNet and Faster RCNN regarding evaluation metrics precision, recall, accuracy and inferencing speed, demonstrating the superiority of our weed detection approach.

Similar approach was implemented by (Chen *et al*. 2022) who reported that enhancing YOLOv4 model with an attention mechanism and adaptive spatial feature fusion achieved high performance in terms of various metrics.

Dhruw *et al* 2023 in their study proposed three popular object detection algorithms for detecting weeds in soybean plantations such as You Only Look Once (YOLO) v3, v4, and v5. They trained YOLOv4 and v5 algorithms on publicly available soybean dataset to recognize and discriminate the presence of weeds on the farmland. Their simulation results have shown that YOLOv5 delivered the best weed detection accuracy with a mean average precision of 96%.

The outcomes highlighted the efficacy of our approach in precise discrimination between crop-weed and detection of various weed species across diverse agricultural scenarios. The findings shows that of our proposed approach is effective for accurate detection of weed in a given field. This method is effective for controlling bermudagrass, crabgrass, and pigweed weeds in sesame fields. We evaluated our method using a dataset of 1300 images cultivated in *Kharif* season of sesame fields of China with weed infestation levels ranging from 0% to 80%. Infestation was measured as the percentage of field area covered by weeds, determined through visual assessment of each image.

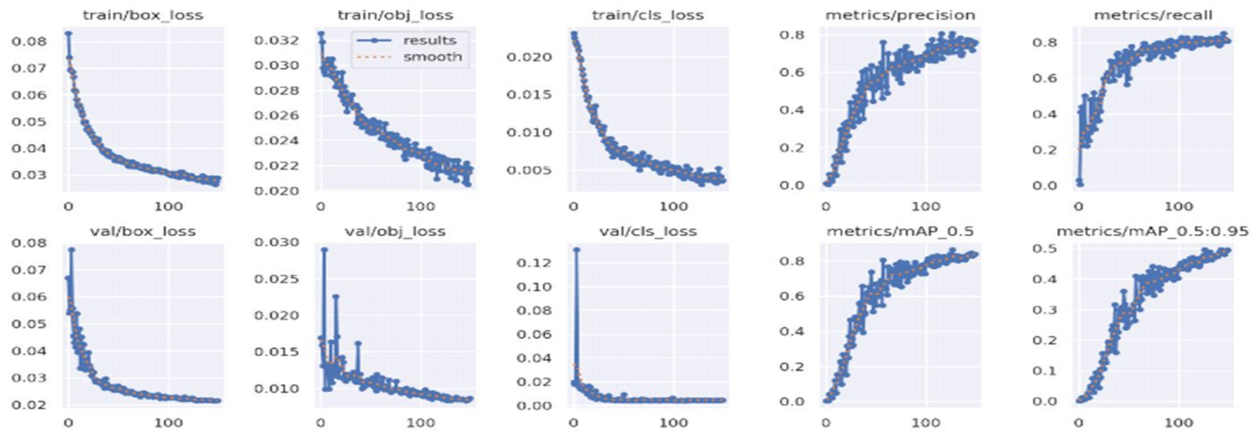

Figure 6. Graphs of YOLOv5 during fine-tuning

This demonstrates the potential for our approach to be used as a tool for farmers to manage their fields more effectively by reducing the need for manual work in weed control. Furthermore, it has potential use when integrated with other precision farming equipment, making it a cost-effective solution for farmers. With precise selective herbicide spraying, we can control the detected weeds. Overall, proposed weed-plant detection system presented a promising solution for the agricultural industry, with the potential to improve crop yields and reduce environmental impact.

Our future work will focus on classification of the weeds into different species. Future efforts will aim to integrate our system into agricultural equipment for real-time weed detection in the field. Additionally, combining our approach with other precision farming techniques has the potential to optimize crop yields and further minimize environmental impact.

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RESEARCH ARTICLE

Mould board weeder for dryland field crops

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ABSTRACT

Weeding is an important agricultural practice that involves the removal of unwanted plants or weeds from cultivated land. A manually operated mould board weeder (MB) was developed at the National Institute of Plant Health Management (NIPHM), Hyderabad for small-scale farming. The major components of the developed weeder are frame, mould board, handle, U-clips and bolts, share point and wheels. The MB weeder is operated by push force applied to the handle to move the weeder forward. While operating, the share point penetrates into the soil and share blade uproots the weeds. The performance of the MB weeder was evaluated at three different speeds *i.e.*, 0.2 m/s (0.72 kmph), 0.31 m/s (1.11 kmph) and 0.42 m/s (1.51 kmph) in sorghum crop. The experimental field soil type was sandy loam, with an average soil moisture content of 12.8% (dry basis). The MB weeder of average draft was found to be 11.8 kg, field capacity 0.048 ha/h, overall weeding efficiency 86%, overall plant damage 2%, and the performance index 521.99. It is suitable for sorghum, chili, maize, cotton, and all vegetable crops but it could also be used for other crops with a row spacing of 300 mm or above, which can be adjusted in the machine.

Keywords: Manually operated, Mould board, Weeder, Weeding efficiency, sorghum.

INTRODUCTION

Weeding is an important agricultural practice that involves the removal of unwanted plants or weeds from cultivated land. Weeds compete with crops for resources such as water, nutrients, and sunlight, and can significantly reduce crop yield and quality (Fernandez-Quintanilla *et al.* 2008). Weed control is therefore crucial for the success of any agricultural production system, and various methods are used to achieve it.

Manual weeding is a traditional method that involves the use of hand tools such as hoes or sickles to remove weeds. This method is time-consuming and labour-intensive, but it is still commonly used, especially in small-scale farming systems (Anwar *et al.* 2021). Mechanical weeding, on the other hand, involves the use of machines to remove weeds. These machines can be powered manually, electrically, or by tractors (Kramer *et al.* 2015). Mechanical weeding is faster and more efficient than manual weeding but requires a higher initial investment.

Weed control is important not only for crop yield and quality but also for the sustainability of agricultural production. Improper weed management can lead to soil degradation and erosion and increased use of synthetic herbicides that can have negative environmental impacts (Oerke *et al.* 2012, Potdar *et al.* 2023). Proper weeding practices can help to control weeds, improve crop yield and quality, and ensure the sustainability of agricultural production. Therefore, an effort has been made to develop a manually operated mould board weeder for dryland crops and to evaluate the performance in field conditions.

MATERIALS AND METHODS

Development of mould board weeder

The manually operated mould board weeder was developed at the National Institute of Plant Health Management (NIPHM), Hyderabad for small-scale farming. The major components of the developed weeder are frame, mould board, handle, U-clips and bolts, share point and wheels. The frame was made of mild steel flat with a length of 600 mm and a width of 200 mm. U-clamps and bolts are provided on the square rod to adjust the different depths of the mould board during the operation (**Figure 1c**). The square rod (20 mm thickness) was fitted to the body of the frame at a distance of 310 mm from the wheels. The mould board (**Figure 1a**) was made of MS (Mild steel) sheet of 18 gauge and 12mm thickness. The MS sheet was cut into a mould board shape and it was tuned and twisted to an angle of 25-30º and the length of curvature was 268 mm. The share points of

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(a) Mould board **(b) Handle** **(c) U-clamp and bolts** **(d) Wheels**

Figure 1. Major components of mould board weeder (a) Mould board (b) Handle (c) U-clamp and bolts (d) Wheels

the two mould boards are facing opposite to each other. The distance between the two mould boards was 150 mm. The share was made of MS sheet and attached with an angle of 25-30º to the mould board. The Share point (**Figure 1a**) was made of MS square rod with a length of 250 mm and 16 mm thickness and attached to mould board to provide a 10 º tapered angle. The share point penetrates into the soil up to 25 mm deep. The share blades were sharpened at the lower end for easy penetration into the soil during the weeding operation. The handle (**Figure 1b**) was made of MS square hollow pipe (25 × 25 × 3 mm). The length of the handle 1000 mm, horizontal handle length 500 mm and the diameter of round bar was 20 mm. U-clamps (**Figure 1c)** were made of a 6 mm thickness MS sheet. These clamps were used to connect the mould board and frame with the help of ½ inch (12.5 mm) length and 40 mm thickness of bolts. The holes were made in a frame every 50 mm heights to adjust the different depths of the mould board during the operation. The Wheels (**Figure 1d)** are made of MS flat (20 × 6 mm) and the diameter was 300 mm. These wheels were attached to the frame on both sides. Both wheels are firmly fixed on a round bar with the help of a washer. The spokes were provided for attaching the hub in the center of the wheel. Spokes are made of 8mm square rod and 130mm in length. The final assembled view and overall specifications of the mould board weeder are shown in **Figure 2** and **Table 1**.

Operating procedure of MB weeder

The weeding operation has to start from the corner of the selected field having more than 300 mm row-to-row spacing crops. The MB weeder is placed in between the two rows of the crop. The operating procedure of the MB weeder is holding the handle with two hands and push force was applied to move the weeder in a forward direction. For easy operation, the handle should grip with stretched hands. While operating the weeder the share point was penetrated into the soil about 2-3 inches and then the share blade gets penetrated for uprooting the weeds. As the weeder moves in the forward direction uprooting of the weeds and inversion of the soil and burried along with the curvature of the mould board. The uprooted weeds are inverted into the soil.

Figure 2. Assembled view of developed mould board weeder

Table 1. Overall Specifications of the developed mould board weeder

Parts	Type of material	Length	Breadth	Thickness	Quantity
Frame	MS flat	590	40	6	1
Handle	MS round bar	500		25∅	1
Mould board	MS sheet (18gauge)		Angle 25-30º	1.2	2
U-clips	MS	30	-	6	2
Nut Bolts	MS		Nominal size (M1.6)	1.3	2
Share point	MS square rod (taper10º)	250	16	16	2
Wheels	MS flat	30∅	20	6	2
Square rod	MS	250	20	20	2

Performance evaluation of developed MB weeder

The performance of the MB weeder was evaluated in the field of sorghum crop at the National Institute of Plant Health Management (NIPHM), Hyderabad. According to Ramadan *et al.* (2022), Manjunatha *et al.* (2014), soil parameters were taken such as soil type, soil moisture content, machine parameters; operating speed, draft, actual field capacity, theoretical field capacity, crop parameters: type of crop, row-to-row distance of crop, weed root zone depth, and weed density. The performance parameters: weeding efficiency, plant damage, field efficiency and performance index (Yadav and Pund. 2007).

The experimental field was 40 m^2 (10 × 4 m) and soil type sandy loam, with an average soil moisture content of 12.8% (dry basis). The developed MB weeder was operated at three different speeds *i.e.*, 0.2 m/s (0.72 kmph), 0.31 m/s (1.11 kmph) and 0.42 m/s (1.51 kmph).

Weeding efficiency

The weeding efficiency was calculated using a quadrant (50 × 50 cm) with an area of 0.25 m^2. A quadrant was thrown in the experimental field with three different locations and counted the number of weeds available before weeding and after weeding. The weeding efficiency was calculated by using following equation

$$WE = \frac{W_1 - W_2}{W_1} \ldots (1)$$

Where,

WE = Weeding efficiency (%)

W_1 = No.of weeds in a quadrant of an area 0.25m^2 before weeding

W_2 = No. of weeds in a quadrant of an area 0.25m^2 after weeding

Plant damage

The plant damage was calculated before and after the developed MB weeder weeding. The number of damaged plants was observed and counted in a 10 m row length before and after weeding with three operating speeds. The percentage of plant damage was calculated during field operation using the following equation:

$$\text{Plant damage (\%)} = \left(1 - \frac{q}{p}\right) \times 100 \ldots (2)$$

Where,

q = No. of plants in a 10 m row length after weeding

p = No. of plants in a 10 m row length before weeding

Power requirement

The input power required to operate the MB weeder during the weeding operation was calculated by using the following equation and considering the draft and maximum operating speed.

$$\text{Power (hp)} = \frac{D \times S}{75} \ldots (3)$$

Where,

D = Draft, kg

S = operating speed, m/sec

Draft

The draft was measured by using spring-type dynamometer fixed in the horizontal handle bar during the weeding operation. Before fixing, Springs are calibrated with the help of knowing weights and observing how much compression of spring takes place for each knowing weight. Based on that draft was calculated by using the following equation.

$$D = p \cos\theta \ldots (4)$$

Where,

D – Draft of the weeder (horizontal soil resistance, N)

p – Force exerted along the handle,

θ– Handle angle (degrees)

Performance index

The performance index of the MB weeder was calculated by using the following equation (5).

$$P.I. = \frac{A \times E \times (100 - R)}{P} \ldots (5)$$

Where,

PI = Performance Index

A = Field Capacity of weeder, ha/hr

E = Weeding efficiency (%),

R = Plant damage (%),

P = Power input, HP

RESULTS AND DISCUSSION

The performance evaluation of the developed machine was carried out under field conditions. The experimental field was taken length 10 m and width 4 m with an area of 40 m^2. Before operating the MB weeder, the soil parameters were observed such as soil type; sandy loam and average soil moisture content was found 12.8% (dry basis). The crop parameters were observed such as type of crop; sorghum, average row-to-row distance 320 mm, average weed root zone depth 28.4 mm and average weed density 68.33.

The developed MB weeder was operated at three different speeds *i.e.*, 0.2 m/s (0.72 kmph), 0.31 m/s (1.11 kmph) and 0.42 m/s (1.51 kmph) in the field was evaluated each dependent variable.

Weeding efficiency

The operating speed of a developed mouldboard weeder can significantly affect its weeding efficiency. The maximum weeding efficiency was found 88% at the operating speed of 0.42 m/s because if the speed is high, it may not penetrate deeply enough to effectively uproot the weeds. The minimum weeding efficiency was 83.3% at the operating speed of 0.2 m/s because if the operating speed is too low, it might dig too deeply, potentially damaging crops and unnecessary soil disruption. If it goes more than 25 mm deep, the amount of soil lifting increases, the required force also increases and it will affect the weeding efficiency. The range of weeding efficiency was found 83.3% to 88% and overall efficiency was 86% (**Figure 3a**).

Plant damage

The maximum plant damage was found at 2.9% at the operating speeds of MB weeder 0.31 and 0.42 m/s because operating the weeder at high speeds increases the likelihood of inadvertently hitting or damaging sensitive parts of the plants, such as stems, leaves, or roots, leading to reduced yields or even crop loss. The skill and experience of the operator play a vital role in mitigating plant damage. The overall plant damage was 2% (**Figure 3b**).

Power requirement

The draft is an important parameter for manually operated implements because it should be within the physical limits of the operator. The average draft of MB weeder required for weeding was found to be 11.8 kg. However, the maximum pushing force for Indian agricultural work ranges from 25 to 30 kg (Mehta *et al.* 2022). The average power requirement for the MB weeder was estimated to be 0.775 hp, which was higher because of the wider width of the cut. The performance index for the developed weeder was 521.99. It was observed that the mould board weeder was suitable for use in sorghum, chili, maize, cotton, and all vegetable crops but it could also be used for other crops with above 300 mm row spacing, which can be adjusted in the machine. The depth of operation of mould board can be changed as per the requirement. The field capacity of the mould board weeder was found to be 0.048 ha/h, which was similar to the existing weeder (Yadav and Pund, 2007).

Conclusions

The weeding efficiency of the developed MB weeder was satisfactory and it is easy to operate. It works up to 50 mm depth with a field capacity of 0.048ha/hr and overall weeding efficiency was obtained up to 86%. The weight of the mould board weeder was 13.5 kg. The overall performance of the weeder was satisfactory. The depth of the weeder can be changed as per the requirement of the depth of the weed. The recommendation for a 2 hp motor to increase the efficiency of weeding.

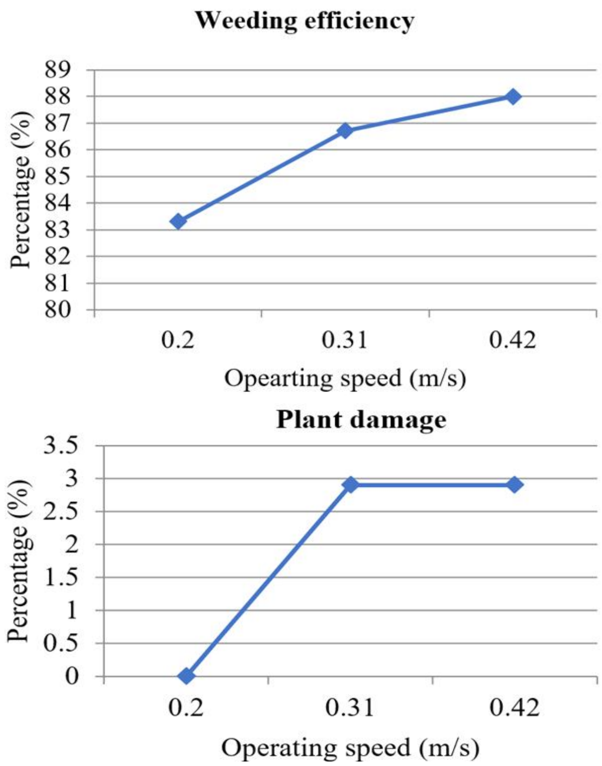

Figure 3. Effect of operating speed developed MB weeder (a) Weeding efficiency (b) Plant damage

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RESEARCH NOTE

Effect of varied levels of *Salvinia molesta* vermicompost on soil fertility and crop productivity of rice under coastal conditions of Udupi, Karnataka

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ABSTRACT

It was found that using *Salvinia molesta* vermicompost at a rate of 13.2 t/ha or *Salvinia* vermicompost with an additional 45:13:62 kg N:P:K/ha resulted in significantly improved growth parameters such as plant height (89.94 cm), number of tillers/m2 (520.24), and total dry matter production (77.52 g/plant) at harvest. Additionally, yield parameters like productive tillers/m2 (499.95), panicle length (21.86 cm), grain yield (5.23 t/ha), straw yield (6.66 t/ha), harvest index (0.44), and low chaff percentage were also positively impacted. The next best treatment was the application of 9.9 t/ha of *Salvinia* vermicompost along with 45:13:62 kg N:P:K/ha. Furthermore, significantly higher levels of available N (389.65 kg/ha) and K (225.42 kg/ha) in the soil were observed with the *Salvinia* vermicompost application. However, the application of 3.3 t/ha of *Salvinia* vermicompost with 45:13:62 kg N:P:K/ha resulted in the highest benefit-cost ratio of 2.50.

Keywords: Crop productivity, Rice, *Salvinia molesta* vermicompost, Soil fertility

Rice is a crucial cereal and serves as the primary food source for over half of the world's population. Globally, rice provides 21% of per capita energy and 5% of per capita protein for humans (Maclean *et al.* 2002). India holds a prominent position in rice production among food crops cultivated worldwide, with an area of 45.07 million hectares dedicated to its cultivation, yielding a production of 122.27 million tonnes and a productivity of 2713 kg/ha (Anonymous 2021). In Karnataka, rice is grown in an area of 9.93 lakh hectares, with a production of 29.07 lakh tonnes and a productivity of 2927 kg/ha (Anonymous 2018). In the Udupi district of Coastal Karnataka, rice is cultivated in an area of 37729 hectares, with a productivity of 3729 kg/ha.

In certain areas of the Udupi district in Coastal Karnataka, *Salvinia molesta* has become an extremely invasive and dominant aquatic weed. It is commonly found in lakes, ponds, and rice fields. This plant has the ability to multiply and grow at a rapid rate, increasing its biomass twofold in just two days. As a result, it forms thick, floating mats that block light, reduce oxygen levels, and compete for nutrients, sunlight, and other environmental factors. *Salvinia molesta* can obstruct waterways and disrupt agricultural irrigation. Due to its highly invasive and colonization properties, *Salvinia* has been listed as one of the world's 100 worst invasive alien species. Physical removal is still commonly used to manage *Salvinia*. The biomass that is removed can be turned into organic manure through processes like composting, vermicomposting, or anaerobic digestion. Among these, vermicomposting is the preferred method due to its faster biomass degradation and the higher quality of the end product.

Considering the points mentioned above, one appropriate method at the farmer's level to address the issue of the aquatic weed *Salvinia molesta* in Udupi district is vermicomposting and its application based on the nutrient level. As a result, a field investigation was conducted in the Coastal Zone of Karnataka to assess the direct effects of different levels of *Salvinia* vermicompost on rice as a nutrient source.

The experiment conducting during the *Kharif* (rainy season) of 2021 at the Zonal Agricultural and Horticultural Research Station in Brahmavara, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences, Shivamogga. The location is at 12° 542 N latitude and 74° 542 E longitude, with an altitude of 10 meters above mean sea level. This area falls within Karnataka's Agro-Climatic Zone-X (Coastal Zone) as per the NARP (National Agricultural

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Research Project) classification. The study area experienced an average annual rainfall of 3998 mm, with maximum temperatures ranging from 29.27°C to 31.23°C during the experimental period. The soil at the experimental site was sandy loam in texture, with 1.20% organic carbon and a pH of 5.10. The available N, P, and K content in the soil were 336.00, 59.10, and 106.80 kg/ha, respectively. The treatments included the application of the recommended dose of fertilizers (10 t FYM + 60:30:75 kg N:P:K/ha), and in the remaining treatments, *Salvinia molesta* vermicompost was applied at rates of 3.3, 6.6, 9.9, and 13.2 t/ha, along with 45:13:62 kg N:P:K/ha (with 75% of RDF applied as Nitrogen). Nitrogen content in FYM was 0.45% and 1.49% in *Salvinia* vermicompost. 50% of the Nitrogen was applied at the time of transplanting, 25% was top dressed at 30 days after transplanting (DAT), and the remaining 25% at 55 DAT. The variety used was '*BMR-MS-1-2-1*' (*Sahyadri Brahma*), known for its heavy tillering and a growth duration of 130 to 135 days. The experiment was set up in a randomized block design with five treatments, each replicated four times. The crop was transplanted at a spacing of 20 × 15 cm with a net plot size of 3.8 × 3.6 m.

Whole plants of the aquatic weed *Salvinia* (*S. molesta*) were directly vermicompost. *Salvinia* weed is pre-treated with animal manure in a 70:30 ratio (*Salvinia molesta*: cow dung) and left to pre-decompose for 20-25 days. After that, earthworms were introduced for further decomposition. The *Salvinia* vermicompost was ready in 60 to 65 days.

Growth parameters such as plant height (cm), number of tillers per square meter, and total dry matter production (g/plant) were measured at 30, 60, and 90 days after transplanting (DAT) and at crop harvest. Five plants were randomly selected through destructive sampling within the gross plot area at each of these stages to record dry matter production. The samples were oven-dried at 65°C to 70°C until they reached a constant weight. Total dry matter production was recorded and expressed in grams per plant. Yield parameters, including the number of productive tillers per square meter, filled grains per panicle, chaffy grains per panicle, grain and straw yield (kg/ha), and harvest index (HI), were recorded at harvest. Grain and straw yield were measured from a 1 m^2 area, with rice grain yield expressed at 14% moisture content.

Soil samples from all treatments were collected after crop harvest from a depth of 0 to 15 cm. These samples were analyzed for available nitrogen, phosphorus, and potassium. Available nitrogen (kg/ha) was determined using the alkaline potassium permanganate method. Available phosphorus and potassium (kg/ha) were measured using Bray's method and the Flame photometric method with a neutral normal NH4OAC extractant, respectively.

The data underwent statistical analysis through Fisher's Analysis of Variance (ANOVA) method. The significance level for the 'F' test was set at 5%. Critical difference (CD) values, indicating significant differences, were provided in the tables at a 5% level of significance wherever the 'F' test yielded significance.

Crop growth components

The use of different amounts of *Salvinia molesta* vermicompost has produced significant results, greatly impacting growth parameters. Upon harvesting, observed that, applying 13.2 t/ha of *Salvinia* vermicompost along with 45:13:62 kg N:P:K/ha led to the tallest plant height (89.94 cm) and the highest number of tillers/m2 (520.24). This exceptional outcome was similarly achieved with 9.9 t/ha of *Salvinia* vermicompost + 45:13:62 kg N:P:K/ha, resulting in a plant height of 87.26 cm and 506.24 tillers/m2. Notably, these superior results surpassed the plots treated with the recommended dose of fertilizer (RDF) (10 t/ha FYM + 60:30:75 kg N:P:K/ha) in terms of plant height, tillers/m^2, and total dry matter production/plant (**Table 1**).

The higher growth components observed can be attributed to the presence of humic acids in *Salvinia molesta* vermicompost. Humic acids are known to play a vital role in stimulating plant growth by promoting increased cell division, enhancing the uptake of nutrients, and enriching the soil microbial population (Xu *et al.* 2016). The application of *Salvinia molesta* vermicompost likely led to an increased availability of nutrients throughout the crop growth period, consequently contributing to higher growth, improved dry matter partitioning, and greater dry matter accumulation (Kumar and Gajalakshmi 2015).

Yield attributes

The result showed that applying 13.2 tons per hectare of *Salvinia* vermicompost + 45:13:62 kg of N:P:K per hectare resulted in significant improvements in various rice growth and yield parameters. These included an increase in the number of productive tillers per square meter (499.95), longer panicles (21.86 cm), a higher number of filled grains per panicle (90.00), and a lower number of chaffy grains per panicle (11.00). This led to a significantly higher grain yield of 5231.00 kilograms per hectare, which was comparable to the application of 9.9 tons per hectare of *Salvinia* vermicompost alongside 45:13:62 kilograms of N:P:K per hectare (**Table 2**). As the levels of *Salvinia molesta* vermicompost increased, there was a corresponding rise in nutrient release in the soil due to microbial action, leading to improved nutrient availability, uptake, and ultimately higher growth and yield components. The harvest index ranged from 0.41 to 0.44, consistent with the findings of previous research by Singh *et al.* (2008) and Garg *et al.* (2006).

Available nutrients in soil

The addition of nutrients through *Salvinia molesta* vermicompost significantly affected the available nutrient levels in the soil (**Table 3**). The treatment of 13.2 t/ha of *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha resulted in higher available N and K content in the soil, at 389.65 kg/ha and 225.42 kg/ha, respectively, which was significantly better than the other treatments. This was closely followed by the treatment of 9.9 t/ha of *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha. The increase in available nutrients may be attributed to the release of nutrients bound in organic matter and

Table 1. Effect of varied levels of *Salvinia molesta* vermicompost on growth parameters of rice

Treatment	Plant height (cm)				Total no. of tillers/m^2				Total dry matter production (g/plant)			
	30 DAT	60 DAT	90 DAT	At Harvest	30 DAT	60 DAT	90 DAT	At Harvest	30 DAT	60 DAT	90 DAT	At Harvest
RDF (10 t/ha FYM + 60: 30: 75 kg N: P: K/ha)	35.80	71.55	79.83	83.42	246	372	415	371	4.12	17.25	47.49	65.74
3.3 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	36.25	72.20	82.88	84.18	277	400	498	454	5.10	20.34	52.23	70.48
6.6 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	37.10	72.70	83.19	86.02	300	434	506	469	5.26	21.03	54.51	72.60
9.9 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	37.15	76.58	85.75	87.26	322	462	547	506	5.53	22.11	56.69	75.94
13.2 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	37.25	79.95	87.08	89.94	338	486	567	520	5.98	23.49	59.17	77.52
LSD (p=0.05)	NS	3.39	3.80	3.90	13	20	23	21	13.55	0.52	0.94	2.45

RDF- Recommended dose of fertilizers; FYM- Farm yard manure; DAT- Days after transplanting; cm-centimeter; t/ha-tonnes per hectare; g/plant- grams per plant

Table 2. Yield attributes of rice as influenced by varied levels of *Salvinia molesta* vermicompost

Treatment	No. of productive tillers/m^2	Panicle length (cm)	Grain yield (t/ha)	Straw yield (t/ha)
RDF (10 t/ha FYM + 60: 30: 75 kg N: P: K/ha)	385.11	18.15	4.27	6.15
3.3 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	413.82	19.20	4.51	6.23
6.6 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	448.14	20.18	4.83	6.36
9.9 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	475.53	21.51	5.02	6.65
13.2 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	499.95	21.86	5.23	6.66
LSD (p=0.05)	20.21	1.60	0.22	0.29

RDF- Recommended dose of fertilizers; FYM- Farm yard manure; cm- centimeter

Table 3. Available nutrient status [N, P, K (kg/ha)] in soil as influenced by the varied levels of *Salvinia molesta* vermicompost in rice after the harvest

Treatment	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
RDF (10 t/ha FYM + 60: 30: 75 kg N: P: K/ha)	289.42	29.05	179.51
3.3 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	317.98	34.89	190.06
6.6 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	341.41	38.60	204.82
9.9 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	375.29	40.91	216.24
13.2 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	389.65	42.50	225.42
LSD (p=0.05)	15.69	1.69	9.23

RDF- Recommended dose of fertilizers; FYM- Farm yard manure; N- Nitrogen; P- Phosphate; K- Potassium

Table 4. Economics of rice as influenced by varied levels of *Salvinia molesta* vermicompost

Treatment	Cost of cultivation ₹/ha	Gross returns ₹/ha	Net returns ₹/ha	B: C ratio
RDF (10 t/ha FYM + 60: 30: 75 kg N: P: K/ha)	74087	116232	42145	1.57
3.3 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	38377	95812	57435	2.50
6.6 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	54877	104300	49423	1.90
9.9 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	71377	108607	37230	1.52
13.2 t/ha *Salvinia* vermicompost + 45: 13: 62 kg N: P: K/ha	87877	111750	23873	1.27

RDF- Recommended dose of fertilizers; FYM- Farm yard manure; COC- Cost of cultivation

exchange reactions in the soil. These findings were similar to those of Kiyasudeen *et al.* 2015.

Economics

The success of any technology hinges on its economic viability. In the realm of rice cultivation, economic performance varied based on the levels of *Salvinia molesta* vermicompost, outlined in **Table 4**. Additionally, the total cost of rice cultivation exhibited variations in line with the differing rates of application of *Salvinia molesta* vermicompost. Notably, the application of 3.3 t/ha of *Salvinia* vermicompost in conjunction with 45:13:62 kg N:P:K/ha resulted in higher net returns (₹ 57435/ha) and a commendable benefit-cost ratio of 2.50. As a result of the lower cost of cultivation and the higher economic yield, this approach significantly augmented net returns and the benefit-cost ratio. Conversely, the relatively lower net returns observed in the case of RDF (₹ 42145/ha) can be attributed to the comparatively lower economic yield of rice.

Conclusion

After conducting the study, It has been confirmed that applying 3.3 tons per hectare of *Salvinia molesta* vermicompost in combination with 45:13:62 kilograms of N:P:K per hectare is more financially viable in contrast to RDF (10 tons of farm yard manure + 60:30:75 kilograms of N:P:K per hectare) in the Coastal zone of Udupi, Karnataka, India. This suggests that the invasive aquatic weed *Salvinia molesta* could be effectively repurposed as a valuable source of nutrients.

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RESEARCH NOTE

Influence of integrated weed management practices on weeds, physiology, quality and yield of direct sown ragi (*Eleusine coracana* L. Gaertn)

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ABSTRACT

Field experiment was conducted at Coconut Research Station, Balaramapuram during January 2022 to April 2022 to assess the effect of weed management on weeds, physiology, quality and yield of direct sown ragi. The experiment was conducted in randomized block design with twelve treatments. The percentage reduction in weed density at 60 DAS due to weed management ranged from 45.4% to 81.8%. The lowest weed dry weight at 60 DAS was observed in PE pyrazosulfuron-ethyl 20 g/ha on the day sowing *fb* WHW at 25 DAS. The treatments, wheel hoe weeding (WHW) at 15 and 30 DAS, pre-emergence (PE) pyrazosulfuron-ethyl 20 g/ha on the day of sowing *fb* WHW or post directed application of penoxsulam + cyhalofop-butyl 135g/ha at 25 DAS recorded higher values for crop growth rate, relative growth rate, leaf area index and chlorophyll content. The treatment, PE pyrazosulfuron-ethyl 20g/ha on the day of sowing *fb* WHW at 25 DAS recorded higher protein content while PE pyrazosulfuron-ethyl 20 g/ha on the day of sowing *fb* post directed application of penoxsulam + cyhalofop-butyl 135 g/ha at 25 DAS recorded the highest starch content and these two treatments also recorded higher grain yield compared to other treatments.

Key words: Bensulfuron-methyl + pretilachlor, Bispyribac-sodium, Pyrazosulfuron-ethyl, Penoxsulam + cyhalofop-butyl, Oxyfluorfen, Wheel hoe weeding

Finger millet (*Eleusine coracana* L. Gaertn.), commonly known as ragi, is one of India's important staple food crops. In India, it covers an area of 0.97 million ha with an average yield of 1.62 t/ha, during 2019-20 (Tonapi 2020). Inclusion of finger millets in the diet provides health benefits through their anti-diabetic, anti-tumorigenic, anti-diarrheal, anti-inflammatory, antioxidant, and antimicrobial properties.

In India the production and productivity of finger millet is low and weed infestation is found to be the major constraints in finger millet cultivation. Since the crop is having slower initial growth, weeds dominate over the crop easily and remove the soil nutrients, moisture, and other growth factors at a faster rate and affect crop growth and development. Patil *et al*. (2013) also reported heavy weed infestation during initial growth period of finger millet which ultimately led to higher crop weed competition and drastic reduction in yield. Presence of weeds not only causes yield loss but also affect the quality of the produce and intensify the disease and pest incidence by serving as an alternate host. Kujur *et al.* (2019) reported that weed management practices had significant impact on physiological parameters of finger millet, which was evident from the higher values of crop growth rate (CGR), relative growth rate (RGR) and LAI, recorded in the weed control treatments. Post emergence application of bispyribac-sodium 20 g/ha recorded significantly higher leaf area per hill compared to weedy check in finger millet (Banu *et al*. 2016*)*. With this back ground, the present investigation was carried out to study the effect of weed management practices on weed parameters, physiological parameters, yield and quality of direct seeded finger millet.

Field study was conducted at Coconut Research Station, Balaramapuram, Thiruvananthapuram, Kerala, Kerala, located at 8° 22' 52'' North latitude and 77° 1' 47'' East longitude and at an altitude of 9 m above MSL during January 2022 to April 2022 with an objective to assess the effect of weed management practices on physiological parameters, weed parameters, yield and quality of direct seeded finger millet. The variety *PPR 2700* (*Vakula*) was used as

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the test crop. The crop was grown as an intercrop in 60-year-old coconut palms that were spaced 7.6 m apart and had 70% light transmission rate. The textural class of soil in the experimental site was sandy loam with acidic character (soil pH 5.19), and was very low in organic carbon (0.25%), low in N (275.96 kg/ha), medium in P (17.23 kg/ha), and high in K (324.8 kg/ha). Total rainfall during the experimental period was found to be 129.8 mm. The experiment was carried out in randomized completely block design with 12 treatments (**Table 1**) in three replications. The method of sowing adopted was direct seeding with the help of a seed cum fertilizer drill. The seed rate adopted was 5 kg/ha and seeds were sown at a spacing of 25 x 15 cm. Farm yard manure 5 t/ha was uniformly applied to the plots. The crop was fertilized with NPK 45: 22.5: 22.5 kg/ha. At the time of seeding, full doses of P and K and half of the N were applied, and top-dressing was done with the remaining N at 21 DAS. The spray fluid adopted for the experiment was 500 L/ha. Pre-emergence herbicides were applied with the help of hand-operated knapsack sprayer with a flat fan nozzle on the day of sowing, and post emergence herbicides were applied with the aid of a crop protective herbicide applicator on 25 DAS. Weed density at 20 DAS, 40 DAS and 60 DAS were determined by randomly placing quadrat of 0.25 m^2 area in each plot and weeds present within the quadrant were counted and expressed in no./m^2. Weed dry weight was determined by recording the dry weight of uprooted weeds and expressed as g/m^2. The leaf area index was calculated by the formula proposed by Watson (1952). The leaf chlorophyll content was determined by the method suggested by Yoshida *et al.* (1976). The crop growth rate was calculated at three-time intervals, 20-40 DAS, 40-60 DAS, and 60 DAS to harvest using the formula suggested by Watson (1958). The relative growth rate was calculated at time intervals, 20-40 DAS, 40-60 DAS, and from 60 DAS to harvest using the formula proposed by Evans (1972). The grain harvested from the net plot area was sun dried and the grain weight was expressed in kg/ha. The nitrogen content of the finger millet grain was multiplied by a factor 6.25 to compute the crude protein content (Simpson *et al.* 1965) and expressed as percentage on dry weight basis. The starch content of the finger millet grain was estimated by titrimetric method (Aminoff *et al.* 1970) and the values were expressed in percentage. Analysis of variance technique for RBD was used for the statistical analysis of the experimental data and the significance was tested using F test. Wherever the F values were found significant, the critical difference was calculated at five per cent probability level.

Effect of weed management on total weed density and weed dry weight

The major weed flora in the experimental field were *Panicum maximum* Jacq., *Setaria barbata* (Lam.) Kunth, and *Digitaria sanguinalis* (L.) Scop., *Mimosa pudica* L., *Phyllanthus niruri* L., *Boerhavia diffusa* L. and *Synedrella nodiflora* (L.) Gaertn.

Weedy check recorded the highest weed density at 20 DAS (100 no./m^2), 40 DAS (65.33 no. /m^2), and 60 DAS (44 no. /m^2) (**Table 1**). The treatment PE oxyfluorfen 50 g/ha on 0 DAS *fb* WHW at 25 DAS recorded significantly lower weed density (12 no. /m^2) at 20 DAS. At 40 DAS, the lowest weed density was noted in PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* WHW at 25 DAS (12 no./m^2). However, at 60 DAS, PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS recorded the lowest weed density which was statistically identical with PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl

Table 1. Effect of weed management on total weed density

Treatment	Total density of weeds (no./m^2)		
	20 DAS	40 DAS	60 DAS
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* WHW at 25 DAS	4.79 (22.0)	3.54 (12.0)	3.60 (12.0)
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	4.12 (16.0)	4.43 (18.7)	2.95 (8.0)
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125g/ha at 25 DAS	5.25 (26.7)	3.95 (14.7)	5.00 (24.0)
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS	6.71 (44.0)	5.00 (24.0)	3.78 (13.3)
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	8.19 (66.0)	4.43 (18.7)	3.40 (10.7)
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS	6.40 (40.0)	4.96 (24.0)	3.00 (8.0)
PE oxyfluorfen 50 g/ha 0 DAS *fb* WHW at 25 DAS	3.61 (12.0)	4.43 (18.7)	4.12 (16.0)
PE oxyfluorfen 50 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	4.36 (18.0)	4.04 (15.3)	3.61 (12.0)
PE oxyfluorfen 50 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS	5.75 (32.0)	3.76 (13.3)	3.75 (13.3)
WHW 15 and 30 DAS	5.38 (28.0)	3.78 (13.3)	3.78 (13.3)
HW 15 and 30 DAS	6.55 (42.0)	4.57 (20.0)	4.58 (20.0)
Weedy check	10.05 (100.0)	8.14 (65.3)	6.71 (44.0)
LSD (p=0.05)	0.474	0.756	0.556

DAS- Days after sowing; *fb*- followed by; HW- hand weeding; WHW- wheel hoe weeding

125 g/ha at 25 DAS and PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS.

Weedy check resulted in significantly higher weed dry weight at 20 DAS, 40 DAS and 60 DAS (14.4 g/m^2, 90.13 g/m^2, and 393.73 g/m^2, respectively) (**Figure 1**). At 20 DAS, PE oxyfluorfen 50 g/ha on 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS resulted in the lowest weed dry weight (1.04 g/m^2). At 40 DAS, significantly lower weed dry weight was observed in HW at 15 and 30 DAS which was *fb* PE pyrazosulfuron-ethyl 20 g/ha on 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS and at 60 DAS, the lowest weed dry weight was observed in PE pyrazosulfuron-ethyl 20 g/ha on 0 DAS *fb* WHW at 25 DAS. Pandey *et al*. (2018) also came to similar conclusion that uncontrolled weed growth in weedy check resulted in higher weed density and weed dry weight.

Effect of weed management on total chlorophyll content

Total chlorophyll content was significantly influenced by weed management at 20 DAS and 60 DAS (**Table 2**). At 20 DAS, the highest chlorophyll content was recorded in WHW at 15 and 30 DAS (2.654 mg/g) and it was statistically on par with HW at 15 and 30 DAS. However, at 60 DAS the treatment PE pyrazosulfuron-ethyl 20 g/ha *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS recorded the highest chlorophyll content (4.027 mg/g) and it was statistically on par with all treatments except weedy check. At 60 DAS, weed management treatments recorded significantly higher chlorophyll content than that of weedy check. This was mainly attributed to higher nutrient uptake due to significant reduction in the nutrient removal of weeds.

Effect of weed management on leaf area index

At 20 DAS the treatment WHW at 15 DAS and 30 DAS recorded higher LAI (**Table 2**). However, at 40 DAS, the treatment PE pyrazosulfuron-ethyl 20 g/ha *fb* WHW at 25 DAS resulted in the highest LAI. The treatments, PE pyrazosulfuron-ethyl 20 g/ha *fb* WHW or penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS, and PE pyrazosulfuron-ethyl 20 g/ha *fb* bispyribac-sodium 20 g/ha at 25 DAS recorded higher LAI at 60 DAS. The reason was due to the production of a greater number of tillers per m^2 and higher leaf area resulting from longer and wider leaves. Muhammadi *et al.* (2016) reported higher values of LAI at 90 DAS in hand-weeded plots (4.07), wheel hoe weeded plots (3.96), and herbicide-treated plots (3.68), compared to weedy check (3.28) in dry direct seeded rice.

Effect of weed management on crop growth rate and relative growth rate

Crop growth rate and relative growth rate was also significantly influenced by weed management at time intervals 20 DAS - 40 DAS and at 40 DAS - 60 DAS (**Table 3**). At 20 DAS - 40 DAS, PE pyrazosulfuron-ethyl 20 g/ha *fb* penoxsulam + cyhalofop-butyl 125 g/ha resulted in the highest CGR and RGR. At 40 DAS-60 DAS, WHW at 15 DAS and 30 DAS recorded the highest CGR. At 20 DAS - 40 DAS, the RGR was higher in PE pyrazosulfuron-ethyl 20 g/ha *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS and 40 DAS - 60 DAS, PE pyrazosulfuron-ethyl 20 g/ha *fb* WHW at 25 DAS recorded higher RGR. Higher CGR and RGR in these treatments might be due to significant reduction in weed density and weed biomass, which enabled the crop to utilize the resources more efficiently. Increased N uptake

Table 2. Effect of weed management on total chlorophyll content and leaf area index (LAI) of direct sown finger millet

Treatment	Total chlorophyll content (mg/g)			LAI	
	20 DAS	40 DAS	60 DAS	20 DAS	40 DAS
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* WHW at 25 DAS	1.860	3.626	3.901	0.216	2.466
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	1.863	3.910	3.745	0.276	2.621
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS	1.778	3.886	3.920	0.243	2.646
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS	1.978	3.922	3.986	0.755	3.251
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	1.935	3.870	3.939	0.648	2.755
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS	1.863	3.917	4.027	0.728	2.808
PE oxyfluorfen 50 g/ha 0 DAS *fb* WHW at 25 DAS	1.832	3.893	3.947	0.617	2.713
PE oxyfluorfen 50 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	1.783	3.795	3.895	0.541	2.378
PE oxyfluorfen 50 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS	1.792	3.865	3.897	0.613	2.678
WHW 15 and 30 DAS	2.654	3.923	3.950	0.858	2.656
HW 15 and 30 DAS	2.593	3.906	3.900	0.810	2.543
Weedy check	2.469	3.562	3.032	0.782	2.056
LSD (p=0.05)	0.0870	NS	0.4710	0.0880	0.5070

DAS- Days after sowing; *fb*- followed by; HW- hand weeding; WHW- wheel hoe weeding enhanced the vegetative growth and hence larger assimilatory area for intercepting solar radiation and this in turn resulted in higher CGR and RGR. Significant reduction in crop weed competition for the resources resulted in better expression of growth and yield attributes which also contributed to higher CGR and RGR in weed management treatments compared to weedy check. Shanmugapriya *et al*. (2022) reported remarkable improvement in CGR and RGR due to weed management in finger millet.

Effect of weed management on yield

Among the weed management treatments, the highest grain yield (2072 kg/ha) was recorded in treatment PE pyrazosulfuron-ethyl 20 g/ha *fb* WHW at 25 DAS which was statistically on par with PE pyrazosulfuron-ethyl 20 g/ha *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS (**Figure 2**). The yield enhancement observed in these treatments was due to significant reduction in weed density and dry weight, higher leaf area index, chlorophyll content, crop growth and relative growth rate. Satish *et al*. (2018) revealed that PE application of bensulfuron-methyl + pretilachlor *fb* one intercultivation resulted in higher yield compared to PE application of bensulfuron-methyl + pretilachlor alone. Weedy check recorded the lowest grain yield.

Effect on NPK uptake by grain

Nutrient uptake by grain was significantly influenced by weed management (**Table 3**). Compared to weedy check, an increase in NPK uptake by grain was observed in the weed management treatments. Better control of weeds provided a competition-free environment for crop growth. It was found that nutrient uptake was directly related to the nutrient content and dry matter

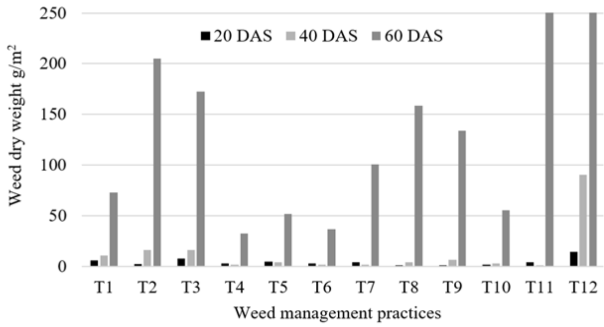

Figure 1. Effect of weed management practices on weed dry weight in finger millet

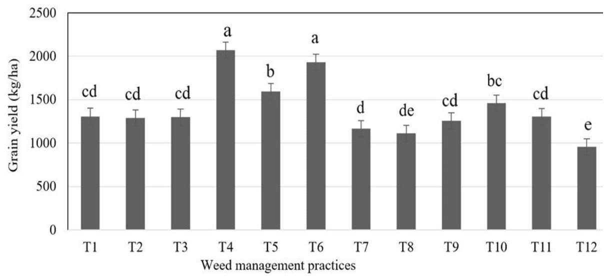

Figure 2. Effect of weed management on grain yield in finger millet

Note: T_1: PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* WHW at 25 DAS; T_2: PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS; T_3: PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125g/ha at 25 DAS; T_4: PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS; T_5: PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS; T_6: PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS; T_7: PE oxyfluorfen 50 g/ha 0 DAS *fb* WHW at 25 DAS; T_8: PE oxyfluorfen 50 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS; T_9: PE oxyfluorfen 50 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS; T_{10}: WHW 15 and 30 DAS; T_{11}: HW 15 and 30 DAS; T_{12}: Weedy check

Table 3. Effect of weed management on crop growth rate (CGR) and relative growth rate (RGR) of direct sown finger millet

Treatment	CGR (g/m^2/day)			RGR (g/g/day)		
	20-40 DAS	40-60 DAS	60 DAS-Harvest	20-40 DAS	40-60 DAS	60 DAS-Harvest
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* WHW at 25 DAS	6.82	6.34	11.93	0.080	0.089	0.090
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	6.15	5.96	12.74	0.076	0.088	0.093
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS	6.64	8.35	11.35	0.080	0.100	0.088
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS	7.44	9.01	12.54	0.086	0.105	0.092
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	7.12	7.94	12.07	0.084	0.099	0.090
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS	9.23	6.92	11.39	0.097	0.093	0.088
PE oxyfluorfen 50 g/ha 0 DAS *fb* WHW at 25 DAS	7.72	6.66	9.92	0.088	0.085	0.083
PE oxyfluorfen 50 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	7.09	5.63	9.48	0.083	0.082	0.082
PE oxyfluorfen 50 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS	6.70	5.55	11.27	0.081	0.073	0.088
WHW 15 and 30 DAS	8.53	9.04	11.25	0.093	0.102	0.088
HW 15 and 30 DAS	7.26	8.19	10.41	0.085	0.100	0.085
Weedy check	5.19	5.43	9.13	0.068	0.076	0.081
LSD (p=0.05)	1.156	1.197	NS	0.0090	0.0120	NS

DAS- Days after sowing; *fb*- followed by; HW- hand weeding; WHW- wheel hoe weeding; NS- not significant

Table 4. Effect of weed management on nutrient uptake by finger millet grain

Treatment	Nutrient uptake by grain (kg/ha)		
	N uptake by grain	P uptake by grain	K uptake by grain
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* WHW at 25 DAS	10.91	11.95	22.86
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	10.86	11.98	22.84
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125g/ha at 25 DAS	11.00	12.14	23.14
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS	10.96	13.00	23.96
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	11.84	12.41	24.25
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS	10.86	13.32	24.18
PE oxyfluorfen 50 g/ha 0 DAS *fb* WHW at 25 DAS	11.49	10.76	22.25
PE oxyfluorfen 50 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	11.88	12.20	24.08
PE oxyfluorfen 50 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS	13.50	11.21	24.71
WHW 15 and 30 DAS	13.44	11.78	25.22
HW 15 and 30 DAS	10.73	12.80	23.53
Weedy check	11.05	10.49	21.55
LSD (p=0.05)	0.386	0.347	0.532

DAS- Days after sowing; *fb*- followed by; HW- hand weeding; WHW- wheel hoe weeding

Table 5. Effect of weed management on crude protein and starch content of finger millet grain

Treatment	Crude protein content (%)	Starch content (%)
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* WHW at 25 DAS	8.05	55.70
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	7.00	54.89
PE pretilachlor + bensulfuron-methyl 495 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125g/ha at 25 DAS	8.05	56.25
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS	9.69	61.82
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	8.75	60.93
PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS	7.88	64.85
PE oxyfluorfen 50 g/ha 0 DAS *fb* WHW at 25 DAS	6.96	58.86
PE oxyfluorfen 50 g/ha 0 DAS *fb* bispyribac-sodium 20 g/ha at 25 DAS	8.75	62.51
PE oxyfluorfen 50 g/ha 0 DAS *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS	6.30	59.99
WHW 15 and 30 DAS	9.43	61.21
HW 15 and 30 DAS	7.70	57.42
Weedy check	4.55	50.77
LSD (p=0.05)	1.003	6.188

DAS- Days after sowing; *fb*- followed by; HW- hand weeding; WHW- wheel hoe weeding

production. Higher N, P, K uptake by the grain in weed management treatments were due to higher dry matter accumulation by the crop and also due to higher N, P, and K content. The treatment PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS recorded the highest total N uptake by grain. Whereas, the highest total P uptake by crop was recorded in PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS which was statistically on par with PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS. Similar to P uptake, the highest K uptake was also recorded in PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS. Sunil *et al.* (2011) also came to similar conclusion that higher nutrient uptake by crop was mainly due to reduction in weed population and weed dry weight which helped the crop to grow vigorously and absorb more nutrients from the soil.

Effect on quality

The treatment PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* WHW at 25 DAS resulted in the highest protein content (9.69 (**Table 4**). Whereas, the highest starch content was observed in PE pyrazosulfuron-ethyl 20 g/ha 0 DAS *fb* penoxsulam+ cyhalofop-butyl 125 g/ha at 25 DAS (64.85%). Higher N content of the grain resulted in higher protein content of grain. Since N is regarded as the building block of amino acids, an enhancement in N uptake in turn increased the protein content of grain. Jagtap *et al.* (2018) also reported lower protein content in rice grain under unweeded conditions compared to other treatments. Higher starch content was observed in weed management treatments compared to weedy check. Shaban *et al.* (2016) also reported higher carbohydrate content in maize in weed control plots compared to the weedy check. Among the treatments the lowest crude protein (4.55%) and starch content

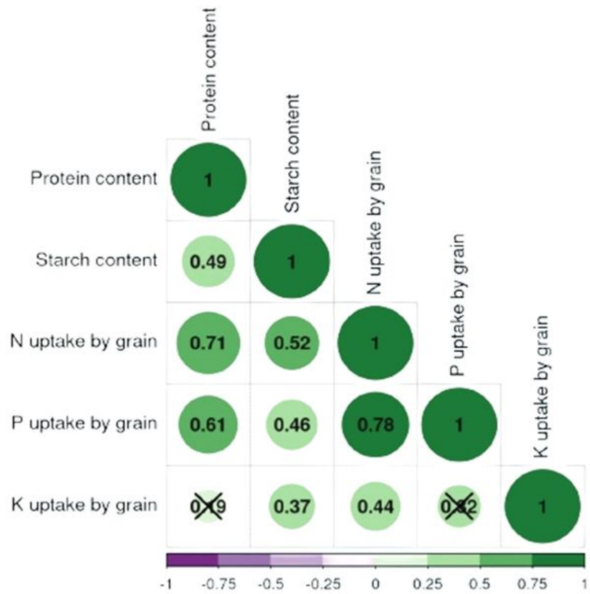

Figure 3. Correlation between NPK uptake by grain and protein and starch content of finger millet grain

(50.77%) was recorded in weedy check. From the correlation data, it was evident that the protein content was positively correlated with N and P uptake by grain and at the same time, starch content was positively correlated with N, P, and K uptake by grain (**Figure 3**).

Weed management had significant effect on weed, physiology, nutrient uptake by grain, quality and grain yield of direct seeded finger millet. Among the treatments, PE pyrazosulfuron-ethyl 20 g/ha on the day sowing *fb* penoxsulam+ cyhalofop-butyl 125 g/ha or WHW at 25 DAS recorded higher values of CGR, RGR, LAI chlorophyll content and lower values for weed density and dry weight. These treatments also recorded higher protein and starch content. The highest yield was recorded in PE pyrazosulfuron-ethyl 20 g/ha on the day of sowing *fb* WHW at 25 DAS and it was on par with PE pyrazosulfuron-ethyl 20 g/ha *fb* penoxsulam + cyhalofop-butyl 125 g/ha at 25 DAS. Hence it can be concluded that, PE pyrazosulfuron-ethyl 20 g/ha *fb* WHW at 25 DAS or post directed application of penoxsulam + cyhalofop-butyl at 25 DAS could be recommended as the best integrated weed management practices for higher yield and quality in direct sown finger millet.

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RESEARCH NOTE

Efficacy of pre- and post-emergence herbicides on weed flora and nutrient uptake by weeds and blackgram

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ABSTRACT

The field experiment was carried out at Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India, during the *Kharif* season of 2018 to study the efficacy of pre- and post-emergence herbicides on suppressing weed flora and nutrients uptake by weed and blackgram (*Phaseolus mungo*) crop. The experiment was laid out with eleven treatments in a randomised complete block design with three replications. Nine weed species (one sedges, two grassy and six broad-leaved) belonging to eight families were found dominant in blackgram. Among the major sedges observed in the experimental plot, *Cyperus rotundus* (Cyperaceae) was the most dominant and aggressive weed. Some grass weeds were *Echinochola colona* (Poaceae) and *Cynodon dactylon* (Cyperaceae) whereas broad-leaved included *Phyllanthus niruri ((Phyllanthaceae), Solanum nigrum ((Solanaceae), Trianthema portulacastrum (Aizoaceae), Cucumis melo* (Cucurbitaceae), *Cleome gynandra (Capparaceae) and Mimosa pudica (Fabaceae).* A significant reduction in weed flora was observed in weed free plot, further among the herbicidal treatments' pre-emergence application of pendimethalin 30 EC 75 kg/ha followed by imazethapyr 0.060 kg/ha as post-emergence reduced the weed flora at 15, 30, 45 and 60 Days after sowing respectively. The lowest nutrient depletion by weed, highest seed yield (925 kg/ha), net return (₹ 48549/ha), B: C ratio (2.65) and nutrient uptake by blackgram were recorded with pre-emergence pendimethalin 30 EC 0.75 kg/ha followed by imazethapyr 0.060 kg/ha as post-emergence.

Key words: Blackgram, B: C ratio, Nutrient uptake, Pod yield, Weed flora

Blackgram (*Phaseolus mungo* L.) is the major *Kharif* pulse crops and the third most widely produced pulse crop in India after chickpea and pigeon pea. It is rich source of protein (24%), fat (1-5%), carbohydrates (60%), amino acids, minerals and vitamin. Blackgram fix nitrogen up to 20-80 kg/ha Hayat *et al*. (2008). This crop faces Critical period of crop-weed competition at 20-40 DAS (Singh *et al*. 2016). Crop weed competition leads to 50-70% reduction in seed yield of blackgram. The magnitude of loss as a result of crop weed competition depends upon type of weed species, associated with crop and duration of labour in time and field accessibility during *Kharif* season becomes the constrain in timely control of weeds. Hence selective pre- and post-emergence herbicide can one of the best alternatives for economical and timely weed control in blackgram. Therefore, keeping the facts in mind, the present study was undertaken to evaluate the performance of herbicide weed management in providing effective control on blackgram.

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The experiments were conducted in the Bihar Agricultural University (B.A.U.) Sabour, Bhagalpur, Bihar (25°23'N latitude and 87°07'E longitude with an altitude of 37.19 m above mean sea level), during the 2018 *Kharif* season. The experimental site was located in the Southern region of Bihar. The soil of the experimental site was well-drained sandy-loam in texture, comprising 47.4% sand, 32.6% silt and 19.6% %.Before the start of the experiment the initial reading of the soil pH was neutral (pH 7.4), low available nitrogen (206.20 kg/ha), medium available phosphorous (19.23 kg/ha) and potassium (168.42 kg/ha),low in organic carbon (0.46%), with electrical conductivity of 0.032 dS/m. Cumulative rainfall recorded was 248.7mm during experiment period from 13-19August to 19-25 November,2018 which was 916.3mm less than the normal rainfall (1165 mm) for this location. The experiment comprises of 11 treatment combinations (**Table 1**) were assigned in a randomized block design with three replications.

A knapsack sprayer equipped with a flat fan nozzle was used to apply pendimethalin (pre-emergence) 30 EC 0.75 kg/ha and Oxyfluorfen (pre-emergence) 23.5 EC 0.125 kg/ha were sprayed at within 24 hours of sowing, Fenoxaprop p-ethyl (post-emergence) 10 EC at 0.010 kg/ha, imazethapyr (post-emergence) 10 SL 0.060 kg/ha, and quizalofop-p-ethyl (post-emergence) 5 EC 0.05 kg/ha at 23–25 days after sowing, using 500 litres of water per hectare. In case of Interculture operation, weeds were removed manually with a Trowel at 20 and 40 Days after sowing. In the case of weed control plots, weeds were allowed and in weed-free plots, weeds were removed with a Trowel tool during the growing season of the crop.

Seed of blackgram, variety "*IPU 2-43*" were sown in lines at the rate of 22-25 kg/ha and a depth of 2-3 cm maintaining spacing between plant to plant and row to row 30 x10 cm. The area of gross plot was 4.2 x 3.6 m^2, while net plot was 4 x 3 m^2. The crop was fertilized with 20-60-40 kg N-P-K/ha through Urea, Single super phosphate and Muriate of potash respectively. The crop was sown on 18^{th} August and harvested at 20^{th} November 2018.

Data on weeds were counted separately with in a random quadrat (50 x 50 cm) in each plot at 15, 30,45 and 60 DAS and expressed as number of no./m^2. Weeds were cut near ground level in a quadrat in each plot and dried at 65°C for 48 hours to constant weight. At 15, 30, 45, and 60 days after sowing, the number of weeds was identified species wise from two spots selected randomly in each plot through a quadrat of 50 x 50 cm and expressed as number per meter square area. The average of the two counts was calculated and expressed in terms of weed count per m^2.Species wise (grass, sedge and subjected to square root transformation before statistical analysis to normalize their distribution. Seed yield was recorded from the net plot area and converted to kg/ha.Net returns as well as benefit: cost (B:C) ratio were also worked out. Data obtained on the number of weeds, nutrient uptake by crop, and nutrient removal by weeds were tabulated and statistical analysis was performed using a randomized block design (RBD) with three replicates. Two–way ANOVA was performed to assess the variability of treatments and its spatial variability with depth Gomez and (Gomez 1984). The standard error of mean (SEm±) and the value of LSD (p=0.05) were indicated in the tables to compare the difference between the mean value.

Weed flora

Cypres rotundus (sedges) was the most prevalent weed at the experimental site, while *Cynodon dactylon* and *Echinochloa colona* were the most common grasses. Many types of broad-leaf weeds were also recorded during the crop growth period and prominent broad-leaf weeds were *Phyllanthus niruri, Trianthema portulacastrum, Mimosa pudica* (sweet melon), *Cucumis melo, Cleome gynandra* and *Solanum nigrum*. Similar weed flora has also been reported by Pankaj and Dewangan (2017) in their experiment. All the herbicide combination were found effective in supressing the different weed flora as compare to the weedy check at different stages of the crop. The most weeds were found in the weedy check, followed by the intercultural operation at 20 and 40 days after sowing at 15 days after sowing. (**Table 1**.). Out of these, weeds sedges have been found in the greatest number followed by weeds. In different herbicide treatments, higher weed flora was observed with the application of (pre-emergence) oxyfluorfen 23.5 EC 0.125 kg/ha followed by (pre-emergence) pendimethalin 30 EC 0.75 kg/ha. At 30, 45 and 60 DAS among chemical treatments (**Table 2, 3** and **4** respectively) total lowest numbers of different weed flora were recorded with Pendimethalin (pre-emergence) 30 EC 0.75 kg/ha followed by imazethapyr (post-emergence) 0.060 kg/ha which was statistically at par with treatment oxyfluorfen 0.125 followed by imazethapyr 0.060 kg/ha.

Nutrient uptake by crop and weed

Significant decrease in total N, P and K uptake by weed were recorded due to all weed management practices over weedy check (**Table 5**).

All weed control treatments significantly increased N, P, and K uptake by seed and straw compared to the weedy check. Weed free treatment resulted in significantly highest total uptake of N (71.76 kg/ha), P (13.22 kg/ha), and K (53.37 kg/ha) by the crop compared to weedy check (30.83, 5.94 and 25.53 kg/ha), respectively. The possible reason for better nutrient uptake by crop could be attributed to more favourable environment for growth and development of crop plants apparently due to lesser weed competition which led to increased growth of crop and thereby increase in nutrient uptake by accumulation of higher amount of nutrients in blackgram seeds.

Nutrient uptake by weed

The removal of N, P and K by weeds was reduced significantly by various herbicidal interventions and it was found negligible under weed-free treatment, whereas significantly highest N, P and K uptake by weeds was recorded in the weedy check treatment (**Table 5**). This could possibly be attributed to luxuriant growth of unchecked weeds in weedy check treatment. These results corroborate the findings of Kaur *et al.* (2010). Among the herbicidal

Table 1. Effect of major weed flora (no./m^2) at 15 DAS as influenced by weed control treatment in blackgram

Treatment	Sedge	Grasses		Broad-leaved						Total
	Cyperus rotundus	*Cynodon dactylon*	*Echinochloa colona*	*Trianthema portulacastrum*	*Phyllanthus niruri*	*Solanum nigrum*	*Mimosa pudica*	*Cucumis melo*	*Cleome gynandra*	
Pendimethalin 0.75 kg/ha	4.30 (18.0)	2.17 (4.2)	1.36 (1.3)	1.22 (1.0)	2.86 (7.7)	1.34 (1.3)	1.58 (2)	1.87 (3)	1.22 (1)	6.33 (39.4)
Oxyfluorfen 0.125 kg/ha	4.26 (17.7)	2.59 (6.2)	1.67 (2.3)	1.87 (3.0)	2.61 (6.3)	1.79 (2.7)	1.58 (2)	2.02 (3.6)	1.22 (1)	6.73 (44.77)
Pendimethalin 0.75 *fb* imazethapyr 0.060 kg/ha	4.18 (17.0)	2.34 (5.0)	1.41 (1.5)	1.41 (1.5)	2.17 (4.2)	1.41 (1.5)	1.34 (1.3)	1.22 (1)	0.89 (0.3)	5.81 (33.3)
Pendimethalin 0.75 *fb* fenoxaprop 0.10 kg/ha	4.26 (17.7)	2.13 (4.0)	1.92 (3.2)	1.48 (1.7)	2.05 (3.7)	0.89 (0.3)	1.48 (1.7)	2.26 (4.6)	0.71 (0)	6.11 (36.9)
Pendimethalin 0.75 *fb* quizalofop 0.05 kg/ha	4.30 (18.0)	2.35 (5.0)	1.67 (2.3)	1.34 (1.3)	2.68 (6.7)	1.10 (0.7)	1.22 (1)	1.95 (3.3)	1.10 (0.7)	6.29 (39.04)
Oxyfluorfen 0.125 *fb* imazethapyr 0.060 kg/ha	4.26 (17.7)	2.40 (5.2)	1.30 (1.2)	1.34 (1.3)	2.28 (4.7)	1.55 (1.9)	0.89 (0.3)	1.70 (2.4)	0.89 (0.3)	5.96 (35.02)
Oxyfluorfen 0.125 *fb* fenoxaprop 0.10 kg/ha	4.14 (16.7)	2.39 (5.2)	1.67 (2.3)	1.48 (1.7)	2.68 (6.7)	1.22 (1)	1.34 (1.3)	2.19 (4.3)	0.71 (0)	6.30 (39.17)
Oxyfluorfen 0.125 *fb* quizalofop 0.05 kg/ha	4.10 (16.3)	2.72 (6.9)	1.70 (2.4)	0.71 (0)	1.58 (2)	1.58 (2)	1.87 (3)	1.87 (3)	0.71 (0)	6.01 (35.61)
Hand weeding 20 and 40 DAS	4.64 (21.0)	3.32 (10.5)	3.24 (10)	1.22 (1)	1.48 (1.7)	1.45 (1.6)	1.10 (0.7)	2.19 (4.3)	1.05 (0.6)	7.20 (51.4)
Weedy check	4.74 (22.0)	3.55 (12.1)	3.06 (8.9)	1.34 (1.3)	1.10 (0.7)	1.84 (2.9)	1.52 (1.8)	2.34 (5)	1.22 (1)	7.49 (55.7)
Weed free	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)
SE m ±	0.08	0.04	0.03	0.02	0.04	0.02	0.02	0.03	0.01	0.12
LSD (p=0.05)	0.23	0.13	0.10	0.06	0.11	0.06	0.06	0.09	0.03	0.35

Table 2. Effect of major weed flora (no./m^2) at 30 DAS as influenced by weed control treatment in blackgram

Treatment	Sedge	Grasses		Broad-leaved						Total
	Cyperus rotundus	*Cynodon dactylon*	*Echinochloa colona*	*Trianthema portulacastrum*	*Phyllanthus niruri*	*Solanum nigrum*	*Mimosa pudica*	*Cucumis melo*	*Cleome gynandra*	
Pendimethalin 0.75 kg/ha	5.92 (34.6)	3.27 (10.2)	2.02 (3.6)	0.84 (0.2)	2.59 (6.2)	1.41 (1.5)	0.89 (0.2)	0.71 (0)	1.70 (2.4)	7.70 (58.90)
Oxyfluorfen 0.125 kg/ha	6.14 (37.23)	3.87 (14.5)	2.17 (4.2)	0.71 (0)	2.85 (7.6)	1.30 (1.2)	0.71 (0)	1.76 (2.6)	1.48 (1.7)	8.34 (69.03)
Pendimethalin 0.75 *fb* imazethapyr 0.060 kg/ha	3.96 (15.23)	2.95 (8.23)	1.38 (1.4)	1.22 (1)	1.58 (2)	0.71 (0)	0.89 (0.3)	0.71 (0)	1.05 (0.6)	5.41 (28.76)
Pendimethalin 0.75 *fb* fenoxaprop 0.10 kg/ha	4.85 (23)	2.85 (7.6)	1.76 (2.6)	0.95 (0.4)	1.92 (3.2)	0.71 (0)	1.22 (1)	1.22 (1)	0.84 (0.2)	6.28 (39.00)
Pendimethalin 0.75 *fb* quizalofop 0.05 kg/ha	5.84 (33.58)	2.97 (8.3)	2.26 (4.6)	0.89 (0.3)	2.12 (4)	0.89 (0.3)	0.71 (0)	1.05 (0.6)	1.22 (1)	7.29 (52.68)
Oxyfluorfen 0.125 *fb* imazethapyr 0.060 kg/ha	4.01 (15.63)	2.99 (8.43)	1.64 (2.2)	0.84 (0.2)	1.87 (3)	0.71 (0)	1.30 (1.2)	0.71 (0)	0.71 (0)	5.58 (30.66)
Oxyfluorfen 0.125 *fb* fenoxaprop 0.10 kg/ha	4.25 (17.6)	2.95 (8.2)	1.58 (2)	0.95 (0.4)	2.12 (4)	0.84 (0.2)	1.22 (1)	1.05 (0.6)	0.71 (0)	5.87 (34.00)
Oxyfluorfen 0.125 *fb* quizalofop 0.05 kg/ha	4.70 (21.6)	3.02 (8.6)	2.55 (6)	0.71 (0)	2.34 (5)	0.71 (0)	1.14 (0.8)	0.71 (0)	1.22 (1)	6.59 (43.00)
Hand weeding 20 and 40 DAS	3.70 (13.23)	3.03 (8.7)	2.85 (7.6)	0.71 (0)	2.34 (5)	0.71 (0)	0.71 (0)	1.05 (0.6)	1.22 (1)	6.05 (36.13)
Weedy check	7.36 (53.65)	4.37 (18.57)	3.18 (9.6)	1.30 (1.2)	3.33 (10.6)	1.55 (1.9)	1.10 (0.7)	1.26 (1.1)	2.17 (4.2)	10.10 (101.52)
Weed free	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)
SE m ±	0.09	0.06	0.04	0.01	0.04	0.01	0.01	0.01	0.02	0.13
LSD (p=0.05)	0.27	0.17	0.11	0.03	0.12	0.03	0.03	0.04	0.05	0.38

treatments at different intervals, significantly lowest values of N, P and K uptake by weeds were recorded with the application of pendimethalin (pre-emergence) 30 EC 0.75 kg/ha followed by imazethapyr (post-emergence) 0.060 kg/ha followed by oxyfluorfen (pre-emergence) 0.125 kg/ha followed by imazethapyr (post-emergence) 10 SL 0.060 kg/ha 23-25 days after sowing showed relatively better efficacy against weeds whose infestation was predominantly lower in these relatively superior herbicidal treatments. Similar findings were made by Komal *et al.* (2015) and Kavad *et al.* (2016). Reduced-nutrient uptake by weeds under the influence of different weed control measure had also reported by Kavad *et al.* (2016) and Mahajan *et al.* (2022).

Table 3. Effect of major weed flora (no./m^2) at 45 DAS as influenced by weed control treatment in blackgram

Treatment	Sedge	Grasses		Broad-leaved						Total
	Cyperus rotundus	*Cynodon dactylon*	*Echinochloa colona*	*Trianthema portulacastrum*	*Phyllanthus niruri*	*Solanum nigrum*	*Mimosa pudica*	*Cucumis melo*	*Cleome gynandra*	
Pendimethalin 0.75 kg/ha	5.85 (33.75)	3.09 (9.05)	1.80 (2.75)	1.36 (1.35)	0.91 (0.32)	1.46 (1.63)	0.90 (0.31)	1.59 (2.02)	2.25 (4.55)	7.50 (55.73)
Oxyfluorfen 0.125 kg/ha	6.05 (36.08)	3.77 (13.75)	1.88 (3.05)	1.82 (2.81)	0.71 (0)	1.96 (3.34)	0.71 (0)	1.80 (2.73)	2.08 (3.84)	8.13 (65.59)
Pendimethalin 0.75 *fb* imazethapyr 0.060 kg/ha	3.82 (14.08)	2.75 (7.08)	0.74 (0.05)	1.24 (1.04)	0.76 (0.08)	0.71 (0)	1.35 (1.33)	0.71 (0)	1.10 (0.71)	4.98 (24.36)
Pendimethalin 0.75 *fb* fenoxaprop 0.10 kg/ha	4.82 (22.75)	2.69 (6.75)	1.50 (1.75)	1.36 (1.35)	1.46 (1.62)	0.71 (0)	1.23 (1.02)	1.23 (1.02)	0.89 (0.3)	6.09 (36.57)
Pendimethalin 0.75 *fb* quizalofop 0.05 kg/ha	5.74 (32.42)	2.71 (6.85)	2.06 (3.75)	1.24 (1.04)	1.76 (2.59)	1.39 (1.42)	0.71 (0)	1.49 (1.72)	0.71 (0)	7.09 (49.79)
Oxyfluorfen 0.125 *fb* imazethapyr 0.060 kg/ha	3.86 (14.42)	2.79 (7.28)	1.24 (1.05)	1.26 (1.08)	1.38 (1.4)	0.71 (0)	1.35 (1.33)	0.71 (0)	0.71 (0)	5.20 (26.56)
Oxyfluorfen 0.125 *fb* fenoxaprop 0.10 kg/ha	4.09 (16.25)	2.75 (7.05)	1.50 (1.75)	1.61 (2.08)	1.26 (1.08)	1.35 (1.31)	1.01 (0.53)	1.10 (0.71)	0.71 (0)	5.59 (30.76)
Oxyfluorfen 0.125 *fb* quizalofop 0.05 kg/ha	4.61 (20.75)	2.87 (7.75)	2.50 (5.75)	1.36 (1.35)	1.63 (2.16)	0.71 (0)	1.53 (1.84)	1.49 (1.73)	0.71 (0)	6.47 (41.33)
Hand weeding 20 and 40 DAS	3.05 (8.8)	2.29 (4.75)	1.80 (2.75)	1.10 (0.7)	1.38 (1.4)	0.71 (0)	0.71 (0)	1.10 (0.7)	0.71 (1)	4.43 (19.1)
Weedy check	7.27 (52.42)	4.23 (17.42)	3.04 (8.75)	1.82 (2.81)	2.01 (3.56)	1.85 (2.93)	2.09 (3.88)	1.93 (3.24)	1.96 (3.33)	9.94 (98.34)
Weed free	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)
SE m ±	0.09	0.05	0.03	0.02	0.02	0.06	0.02	0.02	0.02	0.12
LSD (p=0.05)	0.27	0.16	0.09	0.06	0.06	0.16	0.05	0.05	0.06	0.36

Table 4. Effect of major weed flora (no./m^2) at 60 DAS as influenced by weed control treatment in blackgram

Treatment	Sedge	Grasses		Broad-leaved						Total
	Cyperus rotundus	*Cynodon dactylon*	*Echinochloa colona*	*Trianthema portulacastrum*	*Phyllanthus niruri*	*Solanum nigrum*	*Mimosa pudica*	*Cucumis melo*	*Cleome gynandra*	
Pendimethalin 0.75 kg/ha	5.65 (31.45)	2.70 (6.78)	0.95 (0.40)	0.92 (0.34)	1.68 (2.31)	2.26 (4.62)	1.95 (3.21)	1.23 (1.01)	1.40 (1.45)	7.21 (51.57)
Oxyfluorfen 0.125 kg/ha	5.85 (33.73)	3.45 (11.40)	1.10 (0.70)	1.14 (0.80)	1.75 (2.55)	2.20 (4.33)	1.22 (1.00)	1.49 (1.72)	1.11 (0.74)	7.58 (56.97)
Pendimethalin 0.75 *fb* imazethapyr 0.060 kg/ha	3.50 (11.73)	2.29 (4.73)	0.71 (0.00)	1.23 (1.02)	1.60 (2.07)	0.71 (0)	1.32 (1.23)	0.71 (0)	0.71 (0)	4.61 (20.78)
Pendimethalin 0.75 *fb* fenoxaprop 0.10 kg/ha	4.58 (20.45)	2.22 (4.45)	1.47 (1.65)	0.91 (0.32)	1.76 (2.61)	1.22 (1.00)	0.71 (0)	1.23 (1.01)	0.84 (0.20)	5.67 (31.69)
Pendimethalin 0.75 *fb* quizalofop 0.05 kg/ha	5.53 (30.15)	2.25 (4.56)	1.38 (1.40)	1.23 (1.02)	1.75 (2.58)	1.68 (2.32)	0.71 (0)	1.06 (0.62)	0.71 (0)	6.57 (42.65)
Oxyfluorfen 0.125 *fb* imazethapyr 0.060 kg/ha	3.56 (12.15)	2.35 (5.01)	1.22 (1.00)	1.25 (1.07)	1.70 (2.39)	0.71 (0)	1.32 (1.23)	0.71 (0)	0.71 (0)	4.83 (22.85)
Oxyfluorfen 0.125 *fb* fenoxaprop 0.10 kg/ha	3.74 (13.52)	2.28 (4.70)	1.47 (1.65)	1.60 (2.06)	1.25 (1.07)	1.34 (1.29)	0.96 (0.43)	1.05 (0.71)	0.71 (0)	5.08 (25.33)
Oxyfluorfen 0.125 *fb* quizalofop 0.05 kg/ha	4.35 (18.45)	2.43 (5.40)	1.97 (3.40)	0.92 (0.34)	1.91 (3.15)	1.58 (2.00)	1.11 (0.74)	1.06 (0.63)	0.71 (0)	5.88 (34.11)
Hand weeding 20 and 40 DAS	2.85 (7.65)	2.04 (3.65)	1.47 (1.65)	1.10 (0.70)	1.82 (2.80)	1.70 (2.40)	0.71 (0)	1.05 (0.60)	1.07 (0.65)	4.54 (20.10)
Weedy check	6.75 (45.10)	4.06 (16.00)	2.83 (7.50)	1.14 (0.80)	3.15 (9.43)	2.33 (4.92)	1.87 (3.00)	1.62 (2.14)	1.32 (1.23)	9.52 (90.12)
Weed free	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0.00)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)	0.71 (0)
SE m ±	0.08	0.05	0.02	0.01	0.03	0.02	0.02	0.01	0.01	0.11
LSD (p=0.05)	0.25	0.13	0.07	0.04	0.09	0.07	0.05	0.04	0.03	0.34

Effect on crop yield

Weed free (1024 kg/ha) recorded the highest seed yield followed by interculture operation 20 and 40 DAS (950 kg/ha) and among the chemical treatment pendimethalin (pre-emergence) 30 EC 0.75 kg/ha followed by imazethapyr (post-emergence) 0.060 kg/ha (925 kg/ha). Weed free plot was significantly superior to all other treatments in respect of yield whereas minimum yield was obtained under weed control treatment (399 kg/ha).

Economics

The economic feasibility and utility of a treatment could be properly determined in terms of benefit: cost ratio and net returns (**Table 5**). The maximum net returns were obtained from the weed free plots, followed by treatment. among the herbicide treatment maximum net return (₹ 48549/ha) with benefit cost ratio (BCR) of 2.65 was obtained under treatment pendimethalin (pre-emergence) 30 EC 0.75 kg/ha followed by imazethapyr (post-

Table 5. Effect of different weed management practices on nutrient uptake by crop, weed, grain yield, net returns and B: C ratio in blackgram

Treatment	Nutrient uptake by crop (kg/ha)			Nutrient uptake by weeds (kg/ha)			Seed yield (kg/ha)	Net returns (x10^3 ₹/ha)	B:C ratio
	N	P	K	N	P	K			
Pendimethalin 0.75 kg/ha	44.55	6.54	35.22	15.98	6.85	15.78	560	25.69	1.51
Oxyfluorfen 0.125 kg/ha	42.72	8.34	34.04	17.62	6.97	17.30	558	24.16	1.34
Pendimethalin 0.75 *fb* imazethapyr 0.060 kg/ha	65.58	13.11	50.01	6.60	2.40	6.26	925	48.55	2.65
Pendimethalin 0.75 *fb* fenoxaprop 0.10 kg/ha	62.95	12.71	47.32	6.66	3.43	6.31	885	44.80	2.32
Pendimethalin 0.75 *fb* quizalofop 0.05 kg/ha	62.14	11.91	46.66	8.86	2.83	8.48	860	43.55	2.27
Oxyfluorfen 0.125 *fb* imazethapyr 0.060 kg/ha	64.80	12.64	48.33	7.08	3.63	8.95	892	45.69	2.37
Oxyfluorfen 0.125 *fb* fenoxaprop 0.10 kg/ha	62.45	12.94	47.03	9.52	3.75	6.72	865	42.71	2.10
Oxyfluorfen 0.125 *fb* quizalofop 0.05 kg/ha	60.53	12.82	47.70	10.36	4.08	9.89	814	40.06	1.99
Hand weeding 20 and 40 DAS	67.39	13.62	51.29	5.74	2.40	5.44	950	44.52	1.86
Weedy check	30.83	5.94	25.53	21.61	8.96	21.17	399	14.51	0.89
Weed free	71.76	13.22	53.37	0.00	0.00	0.00	1024	46.79	1.77
LSD (p=0.05)	6.71	1.32	5.12	2.58	1.37	2.88	92.81	6.77	0.34

emergence) 0.060 kg/ha which was at par with oxyfluorfen (pre-emergence) 0.125 kg/ha followed by imazethapyr (post-emergence) 0.060 kg/ha with net retruns of (₹ 45686/ha) and BCR 2.37 as compared to interculture operation 20 and 40 DAS (BCR of 1.86) (**Table 5**). weedy check recorded the lowest net returns (₹ 14509/ha)with minimum BCR (0.89), This could be because of the low yield obtained in this treatment due to severe weed competition. These results were in harmony with the finding of Sakthi *et al.* (2018).

It can be concluded that among the different herbicides, pre-emergence followed by post-emergence application of pendimethalin (pre-emergence) 30 EC 0.75 kg/ha *fb* imazethapyr (post-emergence) 0.060 kg/ha improve the grain yield of blackgram by effectively controlling the weeds, lowest values of N, P and K uptake by weeds and provides highest net return (₹ 48549/ha) and B: C ratio (2.65).

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RESEARCH NOTE

Mathematical modelling for pea-weed competition

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ABSTRACT

A field experiment was conducted to investigate the pea-weed competition which revealed a significant reduction in pea yield with increasing duration of crop weed competition. The weed density in the season-long weedy plot was found to increase up to 60 days after sowing (DAS) and decreased thereafter. However, the weed dry matter accumulation increased progressively with duration of the weedy period. *Galinsoga parviflora* was the most dominant weed species as indicated by higher values of summed dominance ratio (SDR) in all the treatments. Relative yield loss (RYL) in peas was predicted using logistic and Gompertz equations in weed and weed free set of treatments, to determine 21 to 48 DAS as the beginning and end of the critical period of pea-weed competition, respectively, which is equivalent to 260 to 510°C day growing degree days (GDD). The economic threshold (ET) for multi-weed species for pea crop was estimated to range between 2.15 to 20.91 plants/m^2.

Keywords: Critical period of weed competition, Summed dominance ratio, Economic threshold level, Growing degree days, Relative yield loss, Weed diversity

Pea (*Pisum sativum* L.) is an important *Rabi* (winter) season pulse crop. Based on consumption, peas are of two types: dry peas and green peas. Dry peas (10-15% moisture) are used as split (dal) and green peas (72-80% moisture) are used as vegetables. Pea can provide nutritional security as they are an exemplary source of proteins and dietary fiber. Pea also leaves considerable residual soil nitrogen for the following crop, making it an important rotational crop. However, pea seed yield is subjected to wide variation, which can be attributed to various biotic and abiotic factors. Weeds are an important biotic factor, which hinders the growth of crops causing enormous yield loses. Weeds compete with crops mainly for nutrients, sunlight, soil moisture and CO2, which adversely affects the crops especially when these are limited in supply. Weeds also harbour various insects and pests, thus reducing both the quality and quantity of crop produce. Studying crop weed competition is important as uncontrolled weed growth has been reported to cause yield reductions of up to 45% in pea (Kaur *et al.*, 2020). In pea, the slow initial growth and wider spacing provide a congenial environment for weed growth. Though weeds compete with crops throughout the growing season, the extent of damage to the crop does not remain same during all the stages. Timing of weed emergence and duration of weed competition have significant effect on crop yield (Singh *et al.* 2016). Moreover, the removal of weeds throughout the growing season is neither feasible nor economical. Therefore, to reduce the yield losses as well as to avoid extravagant expanses on weed management, it is important to identify the exact critical period of weed and pea competition. The critical period of weed-crop competition (CPWC) is defined as the short span or ‘‘window’’ in the life cycle of a crop during which weed causes maximum yield reductions. Thus, the knowledge of CPWC as a part of integrated weed management strategy, would be useful in efficient weed management by targeting weed control measures at the right time. However, total eradication of weeds in a field might result in inefficient use of resources. Therefore, the economic threshold (ET) concept can be adopted which advocates maintaining the weed density at economic optimum levels. ET is the density of weeds at which the cost of control measures equals the benefits obtained (Hazra *et al.* 2011). Considering the above facts, it is evident that modelling of crop-weed interaction is of utmost necessity for developing a successful weed management strategy and its lacking in the sub-tropical hill (NEH-5) Agro-Climatic Zone of Meghalaya especially for pea crop. An experiment was conducted to determine the critical period of pea weed competition and ET for multi species weeds.

The field study was conducted in the winter (*Rabi)* season of 2020-21) at the experimental farm of College of the Post Graduate Studies in Agricultural Sciences, Central Agricultural University, Umiam, Meghalaya, India. The experimental site is situated at 25°68.157’ N latitude and 91°91.203’ E longitude and

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at an altitude of 950 m above the mean sea level. The soil of the experimental site was sandy clay loam in texture, acidic in reaction (pH 4.86), very high organic carbon (1.7%), low in available N (213.25 kg/ha) and P (18.24 kg/ha) and medium in K (202.72 kg/ha). The experiment was conducted in a randomised block design, with 14 treatments replicated thrice. The 14 treatments were divided into two sets *viz*., weedy set, where weeds were allowed to grow for 0 (W_0 : T1), 10 (W_{10} : T2), 20 (W_{20} : T3), 30 (W_{30} : T4), 40 (W_{40} : T5), 50 (W_{50} : T6) and 60 (W_{60} : T7) DAS; and weed free set, in which plots were kept weed free for 0 (WF_0 : T8), 10 (WF_{10} : T9), 20 (WF_{20} : T10), 30 (WF_{30} : T11), 40 (WF_{40} : T12), 50 (WF_{50}: – T13) and 60 (WF_{60} : T14) DAS. Pea (Variety '*Arkel*') was selected as the test crop and sown at a spacing of 30 x 10 cm. Standard agronomic practices other than weed management practices were followed during the crop growth period. Weeds were managed only by hand weeding according to treatment and no herbicides were used. The weed density, abundance and frequency in individual plots and the total dry weight of weeds were recorded from three randomly selected quadrates (0.25 m^2) in each plot at 10 days interval. No weeds were introduced to the experimental plots and weed density represents the naturally occurring weeds in the region. Weed samples were oven dried at 60 °C to constant weight. Pod yield, stover yield and seed index were recorded at harvest. A total of three pickings (harvests) were done and added to give the final harvest.

Summed Dominance Ratio (SDR) =

(Relative density + Relative abundance + Relative frequency)/3

The analysis and interpretation of data were done using the Fisher's protected least significant difference (LSD) test and means were separated at pd"0.05.

The Gompertz equation (Anwar *et al.,* 2012) was used to describe the effect of the increasing duration of weed free period on yield:

$$y = y0 + a * \exp\left[-\exp\left\{-\frac{(x - x0)}{b}\right\}\right]$$

A logistic equation (Smitchger *et al.* 2012) was used to describe the effect of the increasing duration of weed interference on yield:

$$y = y0 + \left[\frac{a}{\left\{1 + abs\left(\frac{x}{x0}\right)^{b}\right\}}\right]$$

Where, y is the relative yield (% of season-long weed-free yield), y0 is the lower limit of y, a is the upper limit for y, x0 is the number of days/GDD to give 50% yield, x is number of days/GDD after sowing and b is the slope. Estimation of the parameters and curve fitting was done using Sigma Plot 12.0.

Economic Threshold (ET)

$$ET\ (Economic\ Threshold) = \frac{Cost\ involved\ in\ weeding}{Y0 * P * L}$$

Where, Y0 weed free pea yield (t/ha), P is the value per unit of crop (Rs/ha), L is proportional loss per unit weed density (Hazra *et al*. 2011).

Cost involved in weeding was calculated considering 10 man-days are needed for each weeding and price per man-day was Rs 300. Value per unit of pea was Rs 48/kg.

Weed density, dry matter and SDR

Weed density significantly varied with various weedy and weed free treatments (**Figure 1**). The highest weed density was observed in the weedy plot throughout the growing season (WF_0) at 60 DAS (480/m^2). However, in the same plot at harvest, lower weed density was recorded (467/m^2). This suggests that weed density increased up to a certain point and then a decreasing trend was noticed. The shading effect of taller weeds and crops on newly germinated weeds might be a reason for the decrease. However, the dry matter of weeds increased progressively with increasing duration of the crop-weed competition (**Figure 2**). At the harvest stage, the highest dry matter accumulation was recorded from the weedy plot throughout the growing season (WF_0). **Table 1** shows the weed flora observed in the experimental field along with their summed dominance ratio (SDR). *Galinsoga parviflora* recorded the highest value of SDR disparate of various duration of crop weed competition, signifying its overall dominance. Treatment of weedy set W_{10} and W_{20} showed higher values of SDR for *Galinsoga parviflora*, indicating its ability to germinate and establish earlier than other weeds, which might be the reason for its dominance in the weed composition.

Yield and yield attributes

Season-long weed free plot (WF_0) resulted in maximum seed index, pod yield and stover yield (**Table 2**). As the period of crop weed interference increased, yield decreased and lowest values were observed in season-long weedy plot, which differed significantly from weed free control (WF_0). Lesser duration of crop-weed interference resulted in reduced weed density and weed dry matter accumulation, which in turn reduce the weed competitiveness and allelopathic effect. Conversely, when weeds were allowed to grow for longer duration, it caused taller weeds, thereby reducing light availability for photosynthesis, attributing to decrease in yield attributes of pea. The yield of field pea was decreased by 44.3% when weeds were allowed to compete for the entire season. Pea yield losses of up to 50% due to weed competition were also reported by Singh *et al.* (2016).

Table 1. SDR and Weed composition of pea during the experimental season

Summed dominance ratio	*W_{10}	W_{20}	W_{30}	W_{40}	W_{50}	W_{60}	**WF_{0}	WF_{10}	WF_{20}	WF_{30}	WF_{40}	WF_{50}	WF_{60}
Galinsoga parviflora	100.00	67.46	44.84	39.04	47.53	49.53	42.71	39.63	45.89	36.46	33.78	36.26	32.78
Polygonum aviculare	-	-	8.42	14.28	10.14	7.12	5.36	5.21	5.00	8.52	6.09	6.07	6.60
Vicia sativa	-	-	-	7.17	3.83	-	4.15	-	-	-	-	-	-
Bidens bipinnata	-	10.09	12.00	11.70	8.51	3.83	4.99	5.14	3.54	5.90	7.08	5.74	8.29
Oxalis acetocella	-	12.36	9.38	-	4.86	15.76	10.62	9.17	6.64	9.97	10.38	9.01	7.45
Echinochloa crusgalli	-	10.09	15.99	9.13	5.50	6.86	4.26	4.59	5.47	5.90	6.09	3.91	5.29
Cynodon dactylon	-	-	9.38	9.64	7.50	6.86	5.48	6.65	6.35	5.61	6.42	7.17	5.81
Ambrosia artemnisifolia	-	-	-	2.68	2.79	-	4.15	5.89	5.47	5.63	7.08	3.91	4.24
Emalia sonchifolia	-	-	-	2.68	-	-	4.01	3.65	3.54	2.86	3.72	4.37	4.24
Ageratum conyzoides	-	-	-	3.69	5.50	3.14	3.54	3.65	4.59	2.86	4.54	6.07	6.33
Crassocephalus crepidioides	-	-	-	-	3.83	4.80	4.26	6.40	4.63	5.90	4.28	6.44	7.03
Cardamine flexuosa	-	-	-	-	-	2.11	1.97	5.39	4.59	5.32	5.10	5.33	5.34
Bidens Pilosa	-	-	-	-	-	-	4.50	4.64	4.30	5.08	5.43	5.70	6.60
Total	100	100	100	100	100	100	100	100	100	100	100	100	100

*W-weedy (where weed to allow to grow for different days); **WF-Weed free (where plots were kept weed free for different days)

Table 2. Seed index, pod yield, stover yield of pea and ET as influenced periodically by different stages of weedy and weed free treatments

Treatment	Seed index (g)	Pod yield (t/ha)	Stover yield (t/ha)	ET
*W_{0}	54.85a	8.17a	7.24ab	0
W_{10}	54.77a	8.13a	7.14ab	0.2146
W_{20}	52.44abc	7.85ab	7ab	0.5143
W_{30}	51.36bcde	7.22ab	6.68abc	0.3546
W_{40}	49.72cde	6.18cd	6.64abc	0.2731
W_{50}	48.9e	5.97d	6.54abc	0.2880
W_{60}	48.67e	5.31de	6.41abc	0.4113
**WF_{0}	48.45e	4.55e	4.7d	0
WF_{10}	49.25de	4.92e	5.59cd	0.4367
WF_{20}	49.28de	5.38de	5.89bcd	0.3502
WF_{30}	50.71bcde	6.16cd	6.1abc	0.4043
WF_{40}	51.18bcde	6.97bc	7.03ab	0.5709
WF_{50}	52.04abcd	7.92ab	7.32a	2.1484
WF_{60}	53.09ab	8.15a	7.36a	20.910
LSD (p=0.05)	2.69	0.98	1.37	-

*Figures not sharing the same letters in the same column differs significantly at pd”0.05; *W-weedy (where weed to allow to grow for different days); **WF-Weed free (where plots were kept weed free for different days); (Weed free pea pod yield = 8.17 t/ha); ET, economic threshold

Growing Degree Day (GDD)

Accumulated heat units in terms of growing degree day (GDD) were estimated for the entire growing season of the pea crop, with 5 °C as base temperature. The total heat units accumulated in terms of °C day from sowing to final harvest was 1289.9 °C day.

Critical period of weed- crop competition (CPWC)

The CPWC was determined using relative pea yield (% of weed free pea yield) and Days after sowing DAS or GDD. The logistic equation was best fitted to the relative yield of weedy set of treatments and gave the beginning of the critical period. While, the Gompertz equation was a good fit for the relative yield of weed free set of treatments and was used to estimate the end of critical period. The experimental results showed that at 5% relative yield loss (RYL), the critical period for pea weed competition began at 21 DAS and continued up to 48 DAS. At 10% RYL, the critical period was estimated to be from 28 to 44 DAS (**Figure 3**). Mostly the critical period of crop weed competition of various crops has been reported as days after sowing (DAS). Similarly, Singh *et al.* (2016) reported that the CPWC for field pea varied from 20-63 days at 5% RYL, and 30-53 days at 10% RYL. Zimdahl *et al.* (1988) opined that CPWC is not an inherent property of a crop and can vary depending on weed species, site, specific crop and even season. Ka *et al.* (2020) reported the CPWC for sorghum between 15-45 and 15-55 DAS under unfertilized conditions and 10-55 and 15-55 DAS under fertilized conditions. Elamin *et al.* (2019) reported that the critical period of weed-okra competition was between 6 and 8 weeks after sowing.

However, differences in prevailing climatic conditions and varied sowing dates may lead to greater variability in the CPWC among locations and even seasons, thereby making results for experiments conducted on same crop in a specific season and location unreliable in other location. As GDD provides more meaningful insights into the time required for plant growth and development, in recent studies it has been used as a basis to estimate the CPWC, over DAS. In the current study, the critical period of pea weed competition was 260 to 510 °C GDD and 330 to 480 °C day GDD, at 5% and 10% RYL, respectively (**Figure 4**). Smitchger *et al.* (2012) also estimated that weeding should be done between 270 to 999 °C day GDD in lentils so as to prevent yield loss more than 5%.

Economic threshold (ET)

The economic threshold of multi-species weeds in pea varied with pea weed competition, yield and cost of weeding. The ET of W_0, W_{10}, W_{20}, W_{30}, W_{40}, W_{50}, W_{60}, WF_0, WF_{10}, WF_{20}, WF_{30}, and WF_{40}

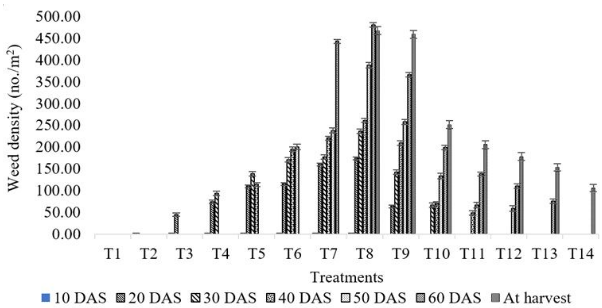

Figure 1. Density of weeds in pea as influenced periodically by different stages of weedy and weed free treatments

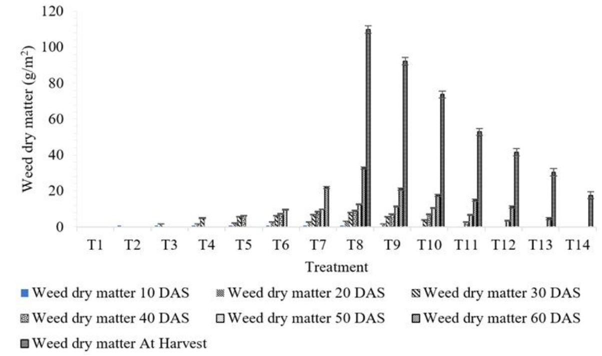

Figure 2. Dry matter accumulation of weeds in pea as influenced periodically by different stages of weedy and weed free treatments

ranged from 0 to 0.57 plants/m^2 (**Table 2**), which were uneconomical. Further, the ET of weed free plot up to 50 DAS (WF$_{50}$) and 60 DAS (WF$_{60}$) was 2.15 and 20.91 plants/m^2, where the cost of weeding/ha as ₹ 10800 and ₹ 12600, yield was 7.92 and 8.15 t/ha, price of the produce was ₹ 3,80,000 and ₹ 3,91,360/ha, proportional loss of yield per unit weed density was 0.17% and 0.19%, respectively. The findings are in accordance with Galon *et al.* (2016), who reported an ET of 2.20-8.72 plants/m^2 for various bean cultivars and Al Mamun (2014) reported when weed population exceeds 2.93 plants/m^2 can embark economic and yield losses.

It can be concluded that for optimum utilization of resources and maximization of yield, weeding practices in pea should begin at 21 DAS and continue up to 48 DAS, which is equivalent to 260-510 °C day GDD, at 5% RYL. At 10% RYL, the CPWC for pea was 28 to 44 DAS or 330 to 480 °C day GDD. The ET for pea crop was estimated to be 2.15 to 20.91 plants/m^2. Maintaining weed population below 2.15 plants/m^2 will be uneconomical, while weed population above 20.91 plants/m^2 will cause economic losses.

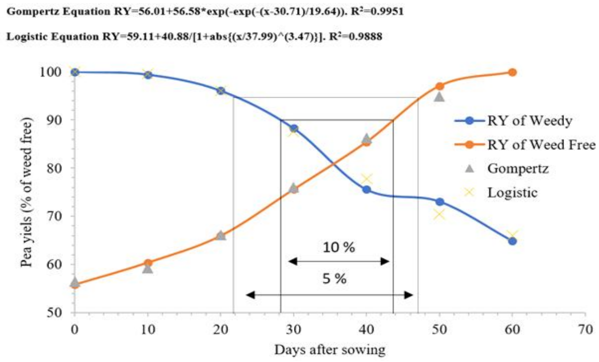

Figure 3. Critical period for pea-weed competition (DAS basis)

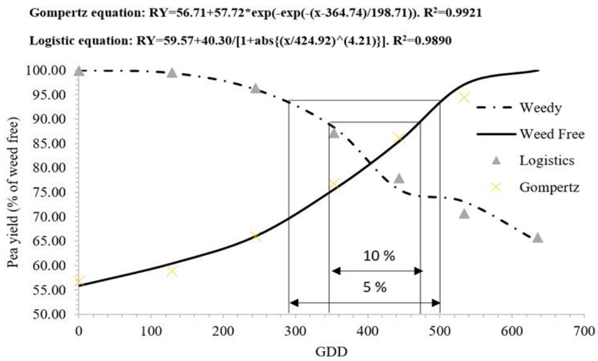

Figure 4. Critical period for pea-weed competition (GDD basis)

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