Elm-Ow-Fon Scientific Research Journal
Vol. 63, No. 2, 2025

Integrated Approaches to Weed Management in Wheat Crops: A Comprehensive Review

Mohammad Shafiq Faieq[1*]
[1]Department of Agronomy, Agriculture Faculty, Kabul University
*Corresponding Author Email: m.shafiqfaieq@Ku.edu.af

Abstract

The aim of this review article is to explore and assess various effective solutions for weed control in wheat fields. By analyzing existing research and practices, this article seeks to provide valuable insights that can assist in developing better strategies to manage weed competition, improve wheat yields, and contribute to food security. The data utilized in this review were sourced from reputable databases such as Google Scholar, Web of Science, Scopus, and PubMed. The findings indicate that weed infestation is a major challenge to wheat production, significantly reducing crop yields. Wheat crops are affected by a variety of weed species, including grass, sedges, and broadleaf plants. While many farmers rely on chemical herbicides due to their cost-effectiveness and efficiency, overuse can lead to herbicide-resistant weeds and environmental harm. Other control methods, however, may incur higher costs. As a result, there is a growing need for more sustainable, environmentally friendly weed management strategies to reduce damage and minimize yield losses. Chemical weed control, although effective, must be complemented with cultural and mechanical methods, which offer rational weed suppression and yield improvement, especially in organic farming systems. Integrated Weed Management (IWM), which combines multiple practices such as appropriate sowing methods, optimal sowing times, correct seed rates, suitable crop varieties, and proper fertilizer and herbicide application, presents a holistic approach to weed control. Additionally, proper farm implements, and crop rotation play a crucial role in managing weed populations. In regions with labor shortages, such as highland agro-ecosystems, herbicidal weed management remains essential to improve wheat productivity. However, a balanced approach integrating chemical, mechanical, and cultural methods is necessary for effective weed management, particularly when labor is scarce. To optimize weed management and sustain wheat yields, further research and location-specific experiments are needed to provide accurate recommendations. Ultimately, the adoption of IWM approaches will contribute to more effective and environmentally responsible weed control strategies.

Keywords: Reduced wheat yield, weed control methods, integrated weed management, Sustainable agriculture

راهبرهای تلفیقی مدیریت علف های هرزه در زراعت گندم: یک مرور همه جانبه

محمد شفیق فایق[۱]

[۱]دیپارتمنت اگرونومی، پوهنځی زراعت، پوهنتون کابل

خلاصه

این مرور جامع، به بررسی روش‌های اصلی مدیریت علف‌های هرزه در کشت گندم می‌پردازد و میزان اثربخشی، محدودیت‌ها و امکان ترکیب این روش‌ها را ارزیابی می‌کند. در این راستا، جستجوی منظمی در پایگاه‌های اطلاعاتی معتبر مانند Google Scholar، Web of Science، Scopus و PubMed انجام شده و مطالعاتی که به موضوع رقابت علف‌های هرزه، روش‌های مدیریت و سیستم‌های کنترول تلفیقی در تولید گندم پرداخته‌اند، انتخاب شده‌اند. در این مقاله، چالش‌های مهمی که انواع مختلف علف‌های هرزه مانند علف‌های باریک‌برگ (grasses)، جگن‌ها (sedges) و پهن‌برگ‌ها (broadleaf) ایجاد می‌کنند، بررسی شده است. این علف‌های هرزه می‌توانند به‌طور قابل توجهی موجب کاهش حاصل گندم در مناطق مختلف زراعتی شوند. چهار روش اصلی برای مدیریت علف‌های هرزه مورد بررسی قرار گرفته‌اند: کیمیاوی، میکانیکی، زراعتی و بیولوژیکی. روش‌های کیمیاوی (علف‌کش‌ها) همچنان رایج‌ترین گزینه هستند، زیرا سرعت عمل بالایی دارند و نسبتاً کم‌هزینه‌اند؛ به‌ویژه در مناطقی که با کمبود نیروی کار مواجه‌اند. با این حال، استفاده بیش از حد از علف‌کش‌ها می‌تواند موجب مقاومت علف‌های هرزه و آسیب‌های محیط زیستی شود. روش‌های میکانیکی و زراعتی مانند قلبه، زمان مناسب کاشت، تناوب زراعتی و تنظیم مقدار تخم ریز، می‌توانند به‌عنوان روش‌هایی پایدار و مکمل برای کنترول کیمیاوی به کار روند. کنترول بیولوژیکی با استفاده از دشمنان طبیعی علف‌های هرزه یا کاشت گیاهانی با خواص بازدارنده(allelopathic crops)، به‌عنوان روشی امیدوارکننده، به‌ویژه در زراعت ارگانیک مطرح است؛ با این حال، هنوز کاربرد آن محدود و کمتر رایج است. این مرور بر اهمیت مدیریت تلفیقی علف‌های هرزه (IWM) تأکید دارد؛ روشی که با ترکیب چندین روش مختلف و با در نظر گرفتن شرایط محلی، می‌تواند در بلندمدت موجب کاهش مؤثر علف‌های هرزه شود و در عین حال، اثرات منفی بر محیط زیست را نیز کاهش دهد. در پایان، مطالعه حاضر به برخی خلأهای علمی اشاره می‌کند و پیشنهاد می‌دهد که تحقیقات منطقه‌ای انجام شود تا برنامه‌های IWM به‌صورت دقیق‌تر تنظیم شده و حاصل گندم به‌طور پایدار افزایش یابد.

کلیمات کلیدی: کاهش حاصل گندم، روش‌های مدیریت علف‌های هرزه، مدیریت تلفیقی علف‌های هرزه، زراعت پایدار

Introduction

Wheat (Triticum aestivum L.) stands as one of the most important cereal crops globally, playing a crucial role in ensuring food security worldwide. As a primary food source, it contributes significantly to the daily nutritional intake of people across the planet. Wheat satisfies approximately 19% of the daily caloric requirements and 21% of the protein needs for the global population. This highlights the vital contribution of wheat to human diets and its essential role in sustaining nutritional balance for billions of people worldwide (Buhler, 2002). Due to its remarkable adaptability, wheat is capable of thriving in a variety of agro-climatic environments, allowing it to be cultivated in diverse regions with differing climate and soil conditions. This resilience makes it a versatile crop, well-suited to a wide range of agricultural settings.

Wheat is cultivated across approximately 215 million hectares (mha) globally, with an annual production reaching around 700 million tonnes (mt) (Galon et al., 2019). Projections indicate that by the year 2050, the global demand for wheat is expected to rise to 900 million tonnes (mt) (FAO, 2006). This growing demand underscores the increasing importance of wheat in meeting the nutritional needs of the world’s population.

Wheat is a crucial staple food crop in Afghanistan, making up approximately 83% of the country’s total cereal consumption. According to the National Statistics and Information Authority of Afghanistan, wheat was grown on a total of 2,534,000 hectares (ha) of land, with 1,566,000 ha dedicated to irrigated wheat and 968,000 ha to rain-fed wheat. The overall wheat production reached 4,890,000 metric tonnes (MT), with 4,089,000 MT coming from irrigated wheat and 801,000 MT from rain-fed wheat. The average productivity for irrigated wheat was approximately 2.6 MT/ha, while rain-fed wheat had an average yield of about 0.83 MT/ha, resulting in an overall national average productivity of 1.93 MT/ha (Badiyala et al., 1991).

Weed infestation is a significant challenge that severely restricts the productivity of crops. To achieve the maximum genetic potential of a crop's yield, proper and effective weed control is a critical component. Weeds not only diminish crop yields but also complicate the harvesting process, making it more labor-intensive and less efficient. Given the need to sustain and increase food grain production to meet the demands of a growing global population and ensure long-term food security, it is vital to implement effective weed management strategies. Without such control, crop production is at risk of substantial losses, affecting both food supply and economic stability.

Among the various biotic stresses that affect crop production, weeds are recognized as one of the most significant and challenging issues. The critical period of crop-weed competition occurs between 11 to 21 days after the crop has emerged (Gerhards et al., 2022). During this time, weeds compete most intensely with the crop for vital resources such as light, water, and nutrients, which can significantly hinder crop growth and development. Effective weed management during this crucial period is essential to minimize competition and ensure the healthy establishment of the crop, ultimately leading to higher yields. The impact of weeds on wheat yields can be substantial, with losses ranging from 30% to 50%, depending on the level of weed infestation (Pandey & Singh, 1997). To achieve optimal wheat yields and ensure food security, effective weed control measures are essential (Kudsk & Mathiassen, 2007). Managing weeds is therefore a critical step in improving agricultural productivity and sustaining wheat production in Afghanistan. The aim of this review article is to explore and assess various effective solutions for weed control in wheat fields. By analyzing existing research and practices, this article seeks to provide valuable insights that can assist in developing better strategies to manage weed competition, improve wheat yields, and contribute to food security.

Methodology

In this review, a comprehensive literature search was conducted using reputable academic databases including Google Scholar, Web of Science, Scopus, and PubMed. The search focused on research articles, review papers, and official reports related to weed management in wheat cultivation systems. The following keywords were used for the search: "Weed competition in wheat," "Weed flora in wheat fields," "Yield losses due to weeds," "Weed management strategies," "Preventive control," "Mechanical weed control," "Cultural practices," "Biological weed control," "Chemical weed control," "Integrated weed management (IWM)," and "Challenges and opportunities in weed management." The inclusion criteria were as follows:

- ❖ Publication years: Studies published between 1990 and 2022
- ❖ Language: Only articles published in English
- ❖ Type of documents: Peer-reviewed journal articles, review papers, books, official reports, and relevant proceedings
- ❖ Exclusion: Duplicates, non-peer-reviewed documents, or studies with insufficient methodological detail

After collection, the articles were categorized based on the weed management approach: chemical, mechanical, cultural, biological, and integrated. A descriptive review method was applied to identify major themes, summarize key findings, and highlight existing knowledge gaps in each category. This methodology ensures a comprehensive and structured assessment of weed management practices in wheat, offering practical insights for research and application.

Restuls and Descussion

Competition posed by weeds

Weed infestation creates a highly competitive environment for wheat, as weeds compete directly with the crop for essential resources such as water, nutrients, light, and space (Jinxia, 1996). Weeds are responsible for approximately one-third of the total crop losses caused by all pests. In severe cases, they can lead to the complete failure of the crop. Furthermore, weeds increase production costs by raising expenses related to chemicals, labor, equipment, and other management practices (Singh et al., 2015). Beyond these direct effects, weeds also have indirect impacts on crop production. These indirect effects primarily involve the provision of a habitat for various insect pests, a reduction in grain quality, and an increase in processing costs (Zimdahl, 2013). Thus, the presence of weeds not only affects crop yield but also influences overall production efficiency and quality.

Gerhards et al., (2022) studied the effects of weed control methods on crop-weed competition between 11 to 21 days after crop emergence. They found that wheat yield loss due to competition with ryegrass could reach up to 59%, highlighting the significant impact of ryegrass on wheat growth. This emphasizes the importance of effective weed management, especially in the early stages of crop development, to prevent substantial yield losses.

Saha et al., (2016) highlighted the importance of removing weeds during the critical competition period for optimal wheat yields. This period, which occurs between 0 to 30 days after sowing, is vital as weeds compete with wheat for essential resources such as nutrients, water, and light. Effective weed control during this time is crucial to ensure that wheat can grow without significant interference from weeds, leading to higher yields.

Weed flora associated with wheat cultivation

The weed flora in wheat fields can vary significantly across different regions and individual fields. This variation depends on a range of factors, including local environmental conditions, irrigation practices, fertilizer application, soil composition, weed management techniques, and the sequence of crops grown in rotation (Anderson & Beck, 2007). Amare, (2014) reported that the weed flora in their study consisted of 83.3% broadleaf species and 16.6% grasses. Among the grasses identified were species such as *Avena fatua* L., *Phalaris paradoxa* L., while the broadleaf weeds included *Caylusea byssinica* Meisn, C. trigyna L., *Chenopodium album* L., *Corregiola capensis* Wild, *Guizotia scabra* (Vis.) Chiov., *Oxalis latifolia* HBK, *Polygonum paleaceum* L., *Raphanus raphanistrum* L., *Spergula arvensis* L., and *Tagetes minuta* L.

- ❖ A study conducted in Gujarat identified several monocot and dicot weeds. Among the monocot weeds were *Brachiaria serrata* and *Echinochloa colonum*, while the dicot weeds included *Amaranthus viridis*, *Digera arvensis*, *Chenopodium album*, and *Euphorbia hirta*. Additionally, the study highlighted Cyperus rotundus as the dominant sedge species in the area (Pisal & Sagarka, 2013).
- ❖ Ahmed et al., 2020, in their study conducted in Bangladesh, reported that the common weed species present at the experimental wheat field included *Amaranthus spinosus* L., *Anagallis arvensis* L., *Celosia argentea* L., *Chenopodium album* L., *Cleome rutidosperma* DC., *Cynodon dactylon* (L.) Pers., *Cyperus rotundus* L., *Digitaria ciliaris* (Retz.) Koel., *Echinochloa colona* (L.) Link, and *Phyllanthus niruri* L.
- ❖ Yadav et al., (2019) in their study conducted at Hisar, observed that the weed flora in the experimental field primarily consisted of *Phalaris minor* Retz. Among the grassy weeds. In addition, the broadleaf weeds included Lathyrus aphaca L., Coronopus didymus L., *Vicia sativa* L., *Medicago denticulata* L., *Melilotus indica* L., and *Anagallis arvensis* L.

- Another study conducted in Pakistan, observed that the weed flora at the experimental site consisted of both narrow- and broad-leaved species. The weeds identified included wild oat (*Avena fatua* L.), canary grass (*Phalaris minor* Retz.), lambsquarters (*Chenopodium album* L.), fathen (*Chenopodium murale* L.), blue pimpernel (*Anagallis arvensis* L.), and swine cress (*Coronopus didymus* L.). Similar resutls find by another study, impairment of wheat yields due to weed competition (Jeet et al., 2010).

Imppairment of wheat yield due to weed competition

- Khan et al., (2003) reported that weeds can result in a significant reduction in wheat grain yield, with losses reaching as high as 48%. This yield loss occurs due to the competition between weeds and the wheat crop for essential resources such as water, nutrients, and sunlight, which ultimately hampers the growth and development of the wheat plants. A study also highlighted that the extent of yield losses due to weeds varies based on factors such as the type and density of the weed species, its time of emergence, and the duration of its interference with the crop (Jabran et al., 2012).
- Oad et al., (2007) reported that weeds can lead to significant economic losses in wheat, with losses varying between 24% and 39.95%. The extent of the damage depends on several factors, including the type and density of the weeds, as well as their competition with the wheat crop for essential resources like light, water, and nutrients.
- A study also found that weeds caused a significant reduction in wheat grain yield, with a loss of 55.7%. This decline was attributed to the competition between weeds and wheat crops for vital resources such as water, light, and nutrients, which ultimately affected the growth and productivity of the wheat plants (Kumar et al., 2011).
- Lee & Thierfelder, (2017) observed that weeds led to a significant reduction in wheat grain yield, with a loss of 59.3%. This decrease in yield was primarily due to the competition between weeds and the wheat crop for essential resources such as light, water, and nutrients in the soil, which ultimately hindered the growth and development of the wheat plants.
- Braun et al., (2010) found that the growth of weeds led to a 40.3% reduction in wheat grain yield. This significant decrease in yield was primarily due to the competition between the weeds and wheat plants for key resources such as water, sunlight, and nutrients, which inhibited the proper growth and development of the wheat crop.
- Malik et al., (2013) observed that allowing weeds to grow throughout the crop season resulted in a significant reduction in wheat grain yield, ranging from 42.9% to 45.1%. Similarly, (Amare, 2014) found that weed growth during the entire crop growth period led to a yield reduction between 57.6% and 73.2%. (Singh et al., 2015) reported that the average yield losses caused by weeds in various wheat-growing zones ranged from 20% to 32%.
- Amare et al., (2016) also highlighted that prolonged weed growth throughout both cropping seasons caused a drastic yield reduction of 72%. Kaur et al., (2017) further confirmed that the season-long presence of weeds resulted in a wheat yield decrease of up to 38.5%. Pawar et al., (2017) reported even higher losses, with weeds causing reductions of 55.7% and 52.2% in wheat grain yield.

Approaches to Weed Management

Among the various approaches to weed management, the selection of crop cultivars with competitive growth traits plays a critical role. The study results emphasized that different crop cultivars have distinct growth characteristics, which play a significant role in shaping the competition between crops and weeds. Some culti-vars grow more quickly and establish their canopy earlier than others. This early canopy formation is particularly important because it allows the crops to shade the weeds, reducing the amount of sunlight available to them. As a result, weeds struggle to grow and compete for re-sources like light, water, and nutrients. In contrast, slower-growing cultivars, which take longer to develop their canopy, face more competition from weeds during the early stages of growth. This can lead to higher weed pressure, ultimately affecting the crop's overall yield. Therefore, selecting cultivars with rapid growth and early canopy formation can be an effective strategy for minimizing weed competition (Leinonen & Närkki, 2004).

According to Zimdahl, (2018), there is a negative relationship between the competitive ability of wheat and its yield potential in a weed-free environment. High-yielding dwarf varieties of wheat tend to have weaker competitive abilities against weeds, leading to greater yield losses when weeds are present. On the other hand, taller wheat varieties, which generally have lower yield potential, are better at competing with weeds and experience less yield loss due to weed competition. This illustrates the trade-off between having a higher yield potential and the ability to effectively compete with weeds.

Another study reported that tall wheat genotypes, such as those reaching 115 cm in height, are more effective in suppressing the impact of Phalaris minor compared to shorter wheat genotypes. The taller varieties, due to their size, are better at shading out weeds, thus reducing weed competition. Additionally, tillage has been found to play a role in controlling weed infestations. It affects soil properties such as bulk density, surface roughness, and penetration resistance, all of which can help limit weed growth by disrupting weed seed germination and root development (Montazeri, 1995).

Tillage practices can have a significant impact on the dispersal patterns of weed seeds (Wang et al., 2022). These practices can disrupt or alter the natural spread of the seeds, leading to changes in their distribution. As a result, the variations in how weed seeds are spread can influence and reshape the dynamics of weed populations over time (Buhler, 1991).

Tillage practices are essential in managing weed populations as they help to bury weed seeds deeper in the soil profile. This process effectively reduces the presence of weed seeds in the upper layers of the soil, which are more susceptible to germination (Shivran et al., 2020). However, the introduction and widespread use of synthetic, carbon-based herbicides significantly altered agricultural practices. As these herbicides became more efficient in controlling weeds, the need for frequent tillage decreased. This shift in weed management practices eventually led to the widespread adoption of zero-tillage farming systems, where the soil is left undisturbed (Malik & Singh, 1995).

In zero tillage systems, the infestation of *Phalaris minor* can be minimized by using pre-emergence herbicides like glyphosate or paraquat. The reduced disturbance to the soil due to zero tillage also leads to fewer weed seed germinations, especially those lying in the deeper soil layers (Chandra et al., 2018). Moreover, zero tillage contributes to a reduction in field preparation costs (Chhokar & Sharma, 2008). While burning rice straw can suppress weed germination, it also negatively impacts the effectiveness of certain herbicides. For instance, the ash from burned rice straw diminishes the efficacy of herbicides like isoproturon and pendimethalin. Therefore, leaving the straw residue on the soil surface is beneficial as it helps conserve soil moisture, suppresses weeds, and enhances the physical and chemical properties of the soil (Singh et al., 2015). Research indicates that the use of 1000 kg ha-1 of residue can reduce weed seedling emergence by 14 percent (Khan & Haq, 2002). Thus, retaining residue alongside zero tillage proves to be an effective strategy for managing weed populations in wheat crops (Samedani & Meighani, 2022).

Mechanical methods are also effective in managing weeds in agricultural fields. This approach involves the removal of weeds using various tools, including manual weeding (Verma et al., 2015). While manual weeding can be efficient, it requires significant labor, is time-intensive, and is considered one of the more traditional methods. Certain weeds, such as wild oats and Phalaris minor, closely resemble the crops in terms of morphology, making mechanical weed control particularly challenging before the flowering stage (Malik & Singh, 1995). Chemical control, on the other hand, is often preferred for its efficiency, cost-effectiveness, and the fact that it requires less time compared to other techniques. Choosing the right herbicides tailored to the specific weed species, along with applying them in the proper amounts and at the right time, can lead to effective weed management (Graziani et al., 2012).

(i) Preventive approaches

Prevention is considered the most cost-effective strategy for managing weeds, but it is often underutilized. To prevent the introduction of weeds into agricultural fields, the most straightforward and inexpensive methods should be adopted. One of the simplest and most effective approaches is to use certified, clean, and weed-free crop seeds. For example, wheat seeds contaminated with even small amounts of seeds from canary grass have been a significant factor in both the local and long-distance spread of this weed (Singh et al., 2005).

To prevent the spread and introduction of weeds, it is essential to take several precautionary measures. One important step is to use clean farm equipment and machinery, ensuring that weeds are removed before they have a chance to set seeds. Additionally, controlling weeds in animal feed, fodder, and bedding areas is crucial, as some weed seeds can remain viable and active even after passing through the digestive system of animals. It is also recommended to use only well-rotted manure that has been aged for at least 4 to 5 months. This is because unrotted or partially rotted manure may contain viable weed seeds, which can be introduced into the fields and spread to new areas. While organic manures such as farmyard manure (FYM) and vermi-compost are important sources of crop nutrition, they can also carry weed seeds, which may contribute to the increase in weed infestations and the introduction of new weeds into the fields (Bharat et al., 2012; Singh, 2007).

(ii) Mechanical weed control

In organic winter wheat, mechanical weed control using spring tine harrowing is commonly applied at early growth stages, up to early tillering (Rasmussen et al., 2010). This method treats the entire field, posing a risk of crop damage since both crops and weeds receive the same treatment. Selectivity, defined by the balance between weed control and crop damage, is crucial in post-emergence weed harrowing (Ramesh & Beena, 2008; Rueda-Ayala et al., 2011). Low selectivity can reduce yields, particularly when weed competition is minimal, the timing is off, or the equipment is poorly adjusted (Rasmussen & Svenningsen, 1995). Recent advancements in site-specific mechanical weed management, such as automated harrowing systems, improve weed control by adjusting intensity based on crop and weed detection, thus minimizing crop damage while enhancing effectiveness (Mennan & Işik, 2004; Pannacci et al., 2017; Rueda-Ayala et al., 2013).

Among inter-row mechanical methods, hoeing is a highly selective technique, unaffected by soil moisture, type, or timing (Rasmussen, 2004). Inter-row cultivators can be more efficient than harrowing for controlling weeds between rows (Mennan & Işik, 2004; Pannacci & Tei, 2014). Traditional hoes use various tools like blades or sweep to cut, uproot, and bury weeds, while rotary hoes use discs and spike wheels for similar effects (Pannacci et al., 2017). Over the years, non-chemical, eco-friendly weed control methods, such as hand weeding and hoeing, have gained attention for their effectiveness against annual and biennial weeds. However, with industrialization, manual labor is becoming scarce and costly, making mechanical control a more viable option (Loddo et al., 2021). Moreover, mechanical methods can also stimulate nitrogen mineralization in soil, which, if timed with crop needs, can improve both yield and quality (Delfosse, 1990).

(iii) Cultural practices

A study conducted in Bihar, where they found that hand weeding at 25 days after sowing (DAS) in wheat crops led to notable improvements in several yield-attributing parameters (Surin et al., 2013). Specifically, hand weeding resulted in a 31.3% increase in the number of productive tillers per square meter, a 5.3% increase in spike length, and an 8.6% higher straw yield compared to the weedy check.

In another study, Amare et al., (2016) demonstrated that a combination of manual hand weeding and the herbicide 2,4-D at a rate of 2.0 kg/ha led to the highest grain yield of 4.3 t/ha in wheat. Similarly, (Safina & Absy, 2017) observed that using both herbicides and hand weeding twice significantly increased wheat yield, reaching 11.8 t/ha, along with considerable improvements in various yield components when compared to the weedy check. Rasool et al., (2017) also found that manual hand weeding contributed to a significant increase in wheat grain yield, with a recorded yield of 4.98 t/ha when compared to the weedy check. Additionally, Sasode et al., (2017) reported that performing two manual hand weedings at 30 and 60 DAS resulted in an increase in wheat grain yield to 4.66 t/ha.

(iv) Biological weed control

Biological weed management involves using living organisms to control weeds, typically by releasing a specific biological control agent such as insects, nematodes, fungi, or bacteria into weed-infested areas, where they attack the weeds. Each control agent is designed to target a specific weed species. Livestock grazing is also considered a form of biological control but is less effective in targeting specific weeds. Biological control of weeds, or biocontrol, has a long history and has shown good success (Julien, 1998). Unlike biocontrol for arthropod pests, biocontrol of weeds places more emphasis on host-testing, with classical biocontrol methods being more common than integrated pest management (IPM).

Weeds are significant economic and environmental pests, with a large portion of global pesticide use directed at them, and weeding, often done by hand, accounting for up to 60% of pre-harvest labor in developing countries (Webb & Conroy, 1995). Invasive weeds cause severe environmental damage, which is only now gaining recognition. The literature on biological weed control is relatively concise, with an up-to-date catalog of all agents used globally available (Julien, 1998), and a fourth edition due for publication soon (Kaur et al., 2021). This catalog is more comprehensive than published records, which are often inadequate. Current biocontrol projects are discussed at the International Symposia on the Biological Control of Weeds, held every few years, and the proceedings from the last three symposia (Delfosse & Scott, 1995; Devilliers et al., 2001; Nandula et al., 2007).

(v) Chemical weed control

Clodinafop-propargyl and tribenuron-methyl are post-emergence herbicides used to selectively control grasses and broad-leaved weeds in wheat fields (Bharat et al., 2012). Clodinafop-propargyl inhibits acetyl coenzyme A carboxylase (ACCase), an enzyme crucial for lipid biosynthesis, while tribenuron-methyl belongs to the sulfonylurea group and works by inhibiting acetolactate synthase (ALS), the key enzyme in the biosynthesis of branched-chain amino acids (FAO, 2018). When mixed, these herbicides can have a synergistic effect, increasing efficacy compared to single herbicide applications. This combination is typically used by farmers to reduce machinery passes, enhance efficacy, prevent weed resistance, and save time and resources (Baghestani et al., 2007; Moran & Hoffmann, 1996). Research has shown that mixing clodinafop-propargyl and tribenuron-methyl effectively controls wild oat (Avena ludoviciana Durieu.) and wild mustard (Sinapis arvensis L.) (Scott et al., 1998).

Like other foliar-applied herbicides, clodinafop-propargyl and tribenuron-methyl require a surfactant to improve control (Buttar et al., 2022). Surfactants lower the surface tension of herbicide droplets (Julien, 1992; Zabkiewicz, 2000), which reduces the contact angle and increases the deposition on leaf surfaces (Sharma & Singh, 2000). This leads to better cuticular penetration and stomatal infiltration, enhancing herbicide translocation and absorption, resulting in more effective weed control (Julien, 1992). In the context of chemical control dominance, farmers are encouraged to reduce herbicide usage and minimize environmental impact (Kumar et al., 2013). Surfactants, particularly non-ionic types, have been shown to improve the foliar activity of several ACCase and ALS inhibitor herbicides, including tralkoxydim, fluazifop-P-ethyl, and clethodim (Dollinger, 2005; National Statistics and Information Authority of Afghanistan (NSIA), 2020; Scott et al., 1998). As well as primisulfuron and foramsulfuron

(Buttar et al., 2022; Sanyal, 2008). The cationic surfactant, Frigate, enhances the foliar activity of herbicides like glyphosate and quinclorac (Zawierucha & Penner, 2001). The efficacy of surfactants depends on their chemical characteristics, such as surface tension and critical micelle concentration (CMC), and their interactions with the herbicide and leaf surface (Sharma & Singh, 2000). However, no surfactant is proven to increase the absorption rate of a specific herbicide without experimental confirmation, and selecting the correct concentration and type of surfactant is challenging for users (Kudsk, 1997).

Integrated weed management strategies

Effective weed management in wheat crops requires the adoption of Integrated Weed Man-agement (IWM) practices. These practices encompass a range of strategies such as proper field preparation, using the stale seed bed technique, effective residue management, and choosing the right planting time and method. Additionally, increasing the seed rate, narrowing row spacing, and selecting competitive cultivars are also essential components of IWM. Fertilizer application methods, crop rotation, and careful timing and method of herbicide application further contribute to managing weeds effectively. Herbicide rotation and mixtures, along with mechanical weeding, play a crucial role in developing a sustainable weed control system for wheat.

It is evident that relying solely on herbicides will not resolve the weed problem in wheat crops. Thus, attention must be given to optimizing sowing techniques that integrate mechanical and cultural methods with herbicide application for a more comprehensive and sustainable solution. Integrated Weed Management (IWM) is considered the most effective approach for offering a long-term and sustainable solution to the weed problem (Storkey et al., 2021). It involves understand-ing environmental factors, available technologies for weed control, and the ecology and biology of weeds, all while minimizing risks to both the environment and human health (Sanyal et al., 2006).

In IWM, various control strategies are employed, including both chemical and non-chemical methods. Studies have shown that the combination of chemical herbicides with certain biological agents resulted in effective weed control and helped reduce weed populations (Subramanian & Martin, 2006). On the other hand, in the absence of chemical methods, integrating a rice/wheat cropping system with intercropping of green gram or ses-bania led to a reduction in the populations of sedges and grasses (Singh et al., 2008). The key challenge for agricultural researchers today is to develop highly effective, eco-friendly, and economically viable IWM systems that can be applied in both current and future cropping practices (Rao & Nagamani, 2007).

Furthermore, the combination of herbi-cides and hand weeding has been shown to provide effective and long-lasting weed control. Using herbicides in conjunction with hand weeding helps control late-emerging weeds. Significant reductions in weed intensity and dry matter at harvest were observed in weed-free plots, fol-lowed by the application of pendimethalin pre-emergence at 1.0 kg/ha plus hand weeding. The highest weed intensity and dry matter were found in the weedy check plots (Patil & Dhonde, 2009). Additionally, the integration of isoproturon at 0.75 kg/ha and 2,4-D at 0.5 kg/ha, combined with one intercultural operation at 30 days after sowing (DAS), was the most effective treatment in reducing weed populations and dry weight at various crop growth stages (Rathi et al., 2008).

Challenges and Opportunities in Weed Management Strategies

Challenges

Weeds pose a significant challenge to crop production worldwide. In many regions, direct seeding of rice is replacing transplantation due to factors like labor shortages, high labor costs, and water scarcity (Chauhan et al., 2012a; Rodell et al., 2009). However, direct-seeded rice systems face higher weed-related yield losses because there is no standing water to suppress weed growth, and rice and weed seedlings are harder to differentiate (Rao & Nagamani, 2010). This shift may lead to an increase in hard-to-control weeds (Chauhan, 2013). The widespread use of herbicides has resulted in herbicide resistance, weed population shifts, and higher control costs (Bunting et al., 2004; Chauhan et al., 2012a). A notable example is the resistance of Phalaris minor to Isoproturon in wheat in India (Melander et al., 2015). Resistance to ALS inhibitors is becoming more common, and multiple resistances to herbicides are emerging which challenges the sustainability of herbicides. Weedy rice, which shares similar traits with cultivated rice, further complicates control (Collins & Helling, 2002). It has variable seed dormancy, early grain shattering, and higher nitrogen-use efficiency than cultivated rice (Chauhan, 2013).

Opportunities

There is a need for more research into the ecology and biology of weeds, particularly in understanding seed bank dynamics across different regions and cropping systems. Gaining a better understanding of weed seed germination is essential for effective control. For instance, utilizing narrow row spacing and higher seeding rates can help reduce weed growth (Chauhan et al., 2012a). In addition to developing competitive crop varieties, there is potential in identifying and evaluating allelopathic crop varieties. Crop rotation strategies, including different planting methods (e.g., direct seeding vs. transplanted rice), tillage practices (e.g., no-till, reduced-till, and conventional tillage), and herbicide use, could contribute to more effective weed management. The effectiveness of herbicides may be enhanced when crops and herbicides are rotated. However, there is limited information on how different rotation practices influence weed population suppression in various cropping systems (Chauhan, 2012b). Research in these areas will contribute to improved weed control. Furthermore, it is important to explore how climate change (such as shifts in temperature, water availability, and CO_2 levels) interacts with weed behavior, as better understanding these responses will help improve weed management in the future.

Conclusion

Weed infestation remains one of the most critical constraints in wheat production, causing significant yield losses across different agro-ecosystems. This review highlights that although chemical herbicides are widely used due to their immediate effectiveness, their overuse has led to resistance development and environmental concerns. The review also shows that non-chemical methods—such as cultural and mechanical practices—play an important role, especially in herbicide-restricted and organic systems. The analysis of existing literature reveals that Integrated Weed Management (IWM) offers the most sustainable and effective approach. IWM incorporates a combination of practices, including optimized sowing, crop rotation, varietal selection, appropriate fertilizer use, and timely herbicide application. However, current research is still heavily focused on chemical control, and there are clear gaps in the development and adoption of biological and mechanical methods, especially in resource-limited or labor-scarce regions.

Furthermore, the lack of region-specific wheat varieties and localized agronomic recommendations remains a key barrier to effective weed control. Future studies should emphasize site-specific trials, biological alternatives, and the integration of precision agriculture tools to refine IWM strategies. Ultimately, the adoption of IWM not only enhances weed control and maintains wheat yield but also contributes to long-term environmental sustainability and global food security. Strengthening farmer education, interdisciplinary collaboration, and policy support are essential to facilitate the transition from chemical-dominant weed control toward integrated, resilient systems.

Directions for Future Research and Suggested Approaches

Future research should focus on developing herbicide-resistant wheat and sustainable, non-chemical weed control methods like mechanical and biological tools. Understanding weed ecology and using precision agriculture can improve weed management. Educating farmers on integrated weed management (IWM) and promoting interdisciplinary collaboration will support region-specific, sustainable wheat production.

Reference

1. Ahmed, S., Alam, M. J., & Chauhan, B. S. (2020). Effect of application timings and tank mixture of herbicides on weed suppression, crop growth and yield of wheat. *Journal of Research in Weed Science, 3*(2), 214–229.
2. Amare, T. (2014). Effect of weed management methods on weeds and wheat (Triticum aestivum L.) yield. African *Journal of Agricultural Research, 9*(24), 1914–1920.
3. Amare, T., Raghavaiah, C. V., & Zeki, T. (2016). Productivity, yield attributes and weed control in wheat (Triticum aestivum L.). *Advances in Crop Science and Technology, 4*(1), 206.
4. Anderson, R. L., & Beck, D. L. (2007). Characterizing weed communities among various rotations in central South Dakota. *Weed Technology, 21*(1), 76–79.
5. Badiyala, D., Verma, S. P., Singh, C. M., & Suresh, G. (1991). Effect of supplemental nitrogen sources and fertilizer nitrogen on weed density and growth in maize + soybean – wheat cropping sequence. *Indian Journal of Weed Science, 23*, 38–42.
6. Baghestani, M. A., Zand, E., Soufizadeh, S., Jamali, M., & Maighany, F. (2007). Evaluation of sulfosulfuron for broadleaved and grass weed control in wheat (Triticum aestivum) in Iran. *Crop Protection, 26*(9), 1385–1389.
7. Bharat, R., Kachroo, D., Sharma, R., Gupta, G. M., & Sharma, A. K. (2012). Effect of different herbicides on weed growth and yield performance of wheat. *Indian Journal of Weed Science, 44*(2), 106–109.
8. Braun, H. J., Atlin, G., & Payne, T. (2010). Multi-location testing as a tool to identify plant response to global climate change. Cli*mate change and crop production,* 115–138.
9. Buhler, D. D. (1991). Influence of tillage systems on weed population dynamics and control in the northern corn belt of the United States. *Advances in Agronomy India,* 1, 51–60.
10. Buhler, D. D. (2002). Challenges and opportunities for integrated weed management. *Weed Science,* 50, 273–280.
11. Bunting, J. A., Sprague, C. L., & Riechers, D. E. (2004). Proper adjuvant selection for foramsulfuron activity. *Crop Protection*, 23, 361–366.
12. Buttar, G. S., Kaur, S., Kumar, R., & Singh, D. (2022). Phalaris minor Retz. Infestation in wheat crop as influenced by different rice straw management usage in Punjab, India. *Indian Journal of Weed Science, 54*(1), 31–35.
13. Chandra, S., Kumar, S., Acharya, S., Kumar, P., & Tyagi, S. (2018). Effect of different weed management practices on growth and yield of wheat and associated weeds. *International Journal of Current Microbiology and Applied Sciences, 7*, 3859–3865.
14. Chauhan, B. S. (2012b). Weed ecology and weed management strategies for dry-seeded rice in Asia. *Weed Technology,* 26, 1–13.
15. Chauhan, B. S. (2013). Strategies to manage weedy rice in Asia. *Crop Protection,* 48, 451–456.
16. Chauhan, B. S., Mahajan, G., Sardana, V., Timsina, J., & Jat, M. L. (2012a). Productivity and sustainability of the rice-wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent: problems, opportunities, and strategies. *Advances in Agronomy,* 117, 315–369.
17. Chauhan, D. S., Sharma, R. K., & Chhokar, R. S. (2003). Comparative performance of tillage options in wheat (Triticum aestivum) productivity and weed management. *Indian Journal of Agricultural Sciences, 73*(7), 402–406.
18. Chhokar, R. S., & Sharma, R. K. (2008). Multiple herbicide resistance in little seed canary grass (Phalaris minor): A threat to wheat production in India. *Weed Biology and Management*, 8, 112–123.
19. Collins, R. T., & Helling, C. S. (2002). Surfactant enhanced control of two Erythroxylum species by glyphosate. *Weed Technology,* 16, 851–859.
20. Delfosse, E. S. (Ed.). (1990). Proceedings of the 7th International Symposium on Biological Control of Weeds. Rome: Ministry of Agriculture and Forestry.
21. Delfosse, E. S., & Scott, R. R. (1995). Proceedings of the 8th International Symposium on Biological Control of Weeds. Melbourne: CSIRO.
22. Devilliers, B. L., Kudsk, P., Smit, J. J., & Mathiassen, S. K. (2001). Tralkoxydim: adjuvant, MCPA and other effects. *Weed Research,* 41, 547–556.
23. Dollinger, M. (2005). Classification of herbicides according to mode of action. In Grower's IPM Guide for Florida Tomato and Pepper Production (pp. 1–8). Leverkusen, Germany: Bayer AG.
24. Food and Agriculture Organization of the United Nations. (2018). FAOSTAT. http://www.fao.org/faostat/en/
25. Food and Agriculture Organization. (2006). *World agriculture: Towards 2030/2050 – Interim report*. Rome: Global Perspective Study Unit.
26. Galon, L., Basso, F. G. M., Chechi, L., Pilla, T. P., Santin, C. O., Michelon, M. A., Bagnara, M. A. M. (2019). Weed interference period and economic threshold level of ryegrass in wheat. *Bragantia,* 78(3), 409–422.

27. Gerhards, R., Sanchez, D. A., Hamouz, P., Peteinatos, G. G., Christensen, S., & Quintanilla, C. F. (2022). Advances in site-specific weed management in agriculture – A review. *Weed Research*, 62,123–133.
28. Graziani, F., Onofri, A., Pannacci, E., Tei, F., & Guiducci, M. (2012). Size and composition of weed seed bank in long-term organic and conventional low-input cropping systems in Europe. *European Journal of Agronomy, 39*, 52–61.
29. Jabran, K., Ali, A., Sattar, A., Ali, Z., Yaseen, M., Hussain, M., Iqbal, J., & Munir, M. K. (2012). Cultural, mechanical and chemical weed control in wheat. *Crop and Environment, 3*(2), 50–53.
30. Jeet, S., Kler, D. S., Kumar, R., & Kumari, A. (2010). Response of seed rates and nitrogen levels in relation to crop residue management on microenvironment of bed-planted soybean (Glycine max) – wheat (Triticum aestivum) system. *Environment and Ecology*, 28, 1571–1576.
31. Jinxia, S. (1996). *Characterization of organ silicone surfactants and their effects on sulfonylurea herbicide activity* [PhD thesis, Virginia State University].
32. Julien, M. H. (1992). Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds (3rd ed.). Wallingford, Oxford: CAB International.
33. Julien, M. H. (1998). Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds (4th ed.). Wallingford, Oxford: CAB International. (In press).
34. Kaur, R., Kaur, S., Deol, J. S., Sharma, R., Kaur, T., Brar, A. S., & Choudhary, O. P. (2021). Soil properties and weed dynamics in wheat as affected by rice residue management in the rice-wheat cropping system in South Asia: A review. *Plants, 10*(953). https://doi.org/10.3390/plants10050953
35. Kaur, S., Kaur, T., & Bhullar, M. (2017). Control of mixed weed flora in wheat with sequential application of pre- and post-emergence herbicides. *Indian Journal of Weed Science, 49*(1), 29–32.
36. Khan, M. H., Hassan, G., Khan, N., & Khan, M. A. (2003). Efficacy of different herbicides for controlling broadleaf weeds in wheat. *Asian Journal of Plant Sciences, 2*(3), 254–256.
37. Khan, M., & Haq, N. (2002). Wheat crop yield loss assessment due to weeds. *Sarhad Journal of Agriculture*, 18, 443–448.
38. Kudsk, P. (1997). Formulation and adjuvants. In J. E. Jensen, J. C. Streibig, & C. Andreasen (Eds.), *Weed Science Compendium*, 99–116.
39. Kudsk, P., & Mathiassen, S. K. (2007). Analysis of adjuvant effects and their interactions with variable application parameters. *Crop Protection,* 26, 328–334.
40. Kumar, A., Kumar, S., Singh, B., & Dhaka, A. (2013). Evaluation of herbicides alone and in combination for weed control in wheat. *Indian Journal of Weed Science, 45*(3), 210–213.
41. Kumar, S., Angiras, N. N., & Rana, S. S. (2011). Bio-efficacy of clodinafop propargyl + metsulfuron methyl against complex weed flora in wheat. *Indian Journal of Weed Science, 43*(4), 195–198.
42. Lee, N., & Thierfelder, C. (2017). Weed control under conservation agriculture in dryland smallholder farming systems of southern Africa. *Agronomy for Sustainable Development*, 37, 48. https://doi.org/10.1007/s13593-017-0453-7
43. Leinonen, P., & Närkki, V. (2004). Lay-down working chart improves efficacy of hand weeding. In Proceedings of the 6th EWRS Workshop on Physical and Cultural Weed Control (p. 124).
44. Loddo, D., McElroy, J. S., & Giannini, V. (2021). Problems and perspectives in weed management. *Italian Journal of Agronomy, 16*, 1854. https://doi.org/10.4081/ija.2021.1854
45. Malik, R. K., & Singh, S. (1995). Littleseed canarygrass (Phalaris minor) resistance to isoproturon in India. *Weed Technology,* 9, 419–425.
46. Malik, R. S., Yadav, A., & Kumari, R. (2013). Ready-mix formulation of clodinafop propargyl + metsulfuron-methyl against complex weed flora in wheat. *Indian Journal of Weed Science, 45*(3), 179–182.
47. Melander, B., Lattanzi, B., & Pannacci, E. (2015). Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. *Crop Protection*, 72, 1–8.
48. Mennan, H., & Işik, D. (2004). The competitive ability of Avena spp. And Alopecurus myosuroides Huds. Influenced by different wheat (Triticum aestivum L.) cultivars. *Turkish Journal of Agriculture and Forestry, 28*(4), 245–251.
49. Montazeri, M. (1995). Interaction of tribenuron methyl and graminicides in wheat. *In Proceedings of the 1995 Brighton Crop Protection Conference–Weeds* (pp. 753–756). Brighton, UK.
50. Moran, V. C., & Hoffmann, J. H. (Eds.). (1996). *Proceedings of the 9th International Symposium on Biological Control of Weeds.* Stellenbosch: University of Cape Town Press.
51. Nandula, V. K., Poston, D. H., Reddy, K. N., & Kroger, C. H. (2007). Formulation and adjuvant effects on uptake and translocation of clethodim in bermudagrass (Cynodon dactylon). *Weed Science*, 55, 6–11.
52. National Statistics and Information Authority of Afghanistan (NSIA). (2020). Afghanistan Statistical Year Book. https://www.almendron.com/tribuna/wp-content/uploads/2021/08/47ediment47s47-statistical-yearbook-2019-1st-version.pdf

53. Oad, F., Siddiqui, M., & Buriro, U. (2007). Growth and yield losses in wheat due to different weed densities. *Asian Journal of Plant Sciences, 6*(1), 173–176.
54. Pandey, J., & Singh, R. (1997). Weed control in wheat is key to higher production. *Indian Farming, 47*(8), 4–7.
55. Pannacci, E., & Tei, F. (2014). Effects of mechanical and chemical methods on weed control, weed seed rain, and crop yield in maize, sunflower, and soybean. *Crop Protection*, 64, 51–59.
56. Pannacci, E., Lattanzi, B., & Tei, F. (2017). Non-chemical weed management strategies in minor crops: A review. *Crop Protection*, 96, 44–58.
57. Patil, R. R., & Dhonde, M. B. (2009). Weed management in wheat. *Journal of Maharashtra Agricultural Universities, 34*, 149–151.
58. Pawar, J., Singh, R., Neelam, Kabdal, P., Prabhakar, D., & Kumar, S. (2017). Optimization rate of pinoxaden + clodinafop-propargyl for weed control in wheat. *Indian Journal of Weed Science, 49*(2), 136–138.
59. Pisal, R. R., & Sagarka, R. K. (2013). Integrated weed management in wheat with new molecules (Triticum aestivum L.). *Indian Journal of Weed Science, 45*(1), 25–28.
60. Ramesh, K., & Beena, K. (2008). Persistence of clodinafop-propargyl in soil and wheat crop. *Environment and Ecology*, 26, 2149–2151.
61. Rao, A. N., & Nagamani, A. (2007). Available technologies and future research challenges for managing weeds in dry-seeded rice in India. *In Proceedings of the 2151 Asian-Pacific Weed Science Society Conference* (pp. 2–6). Colombo, Sri Lanka.
62. Rao, A. N., & Nagamani, A. (2010). Integrated weed management in India. *Indian Journal of Weed Science, 42*(4), 123–135.
63. Rasmussen, I. A. (2004). The effect of sowing date, stale seedbed, row width and mechanical weed control on weeds and yields of organic winter wheat. *Weed Research*, 44, 12–20.
64. Rasmussen, J., & Svenningsen, T. (1995). Selective weed harrowing in cereals. *Biological Agriculture & Horticulture*, 12, 29–46.
65. Rasmussen, J., Mathiassen, H., & Bibby, B. M. (2010). Timing of post-emergence weed harrowing. *Weed Research*, 50, 436–446.
66. Rasool, R., Bhullar, M. S., & Gill, G. S. (2017). Growth stage of Phalaris minor Retz. And wheat determines weed control and crop tolerance of four post-emergence herbicides. *Spanish Journal of Agricultural Research, 15*(1), 2171–2179.
67. Rathi, A. S., Kumar, V., Singh, V. P., & Singh, D. K. (2008). Integrated weed management in irrigated wheat. *Progressive Agriculture, 8*, 74–75.
68. Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature*, 460, 999–1002.
69. Rueda-Ayala, V. P., Rasmussen, J., & Gerhards, R. (2011). The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Research*, 51, 478–488.
70. Rueda-Ayala, V. P., Weis, M., Keller, M., Andújar, D., & Gerhards, R. (2013). Development and testing of a decision-making based method to adjust automatically the harrowing intensity. *Sensors*, 13, 6254–6271.
71. Safina, S., & Absy, R. (2017). Broadleaf weed control with some recent postemergence herbicides in bread wheat (Triticum aestivum L.) in Egypt. *Egyptian Journal of Agronomy, 39*(1), 41–50.
72. Saha, M., Banerjee, H., & Pal, S. (2016). Relative efficacy of herbicides in wheat. *Indian Journal of Weed Science, 38*(2), 127–128.
73. Samedani, B., & Meighani, F. (2022). Effect of cover crops residue on weed control and yield in conservation tillage (Lycopersicon esculentum Mill.) production. *Weed Biology and Management*. https://doi.org/10.1111/wbm.12254
74. Sanyal, D. (2008). Introduction to the integrated weed management revisited symposium. *Weed Science*, 56(1), 140. https://doi.org/10.1614/0043-1745
75. Sanyal, D., Bhowmik, P. C., & Reddy, K. N. (2006). Influence of leaf surface micro-morphology, wax content, and surfactant on primisulfuron droplet spread on barnyardgrass (Echinochloa crus-galli) and green foxtail (Setaria viridis). *Weed Science,* 54, 627–633.
76. Sasode, D. S., Gupta, V., Joshi, K., Arora, A., Dixit, J. P., & Panse, R. (2017). Management of diverse weed flora of wheat by herbicide combinations. *Indian Journal of Weed Science, 49*(2), 147–150.
77. Scott, R. C., Shaw, D. R., O'Neal, W. B., & Klingman, T. D. (1998). Spray adjuvant, formulation, and environmental effects on synergism from post-applied tank mixtures of SAN 582H with fluazifop-P, imazethapyr, and sethoxydim. *Weed Technology,* 12, 463–469.
78. Sharma, S. D., & Singh, M. (2000). Optimizing foliar activity of glyphosate on Bidens frondosa and Panicum maximum with different adjuvant types. *Weed Research*, 40, 523–533.
79. Shivran, H., Yadav, R. S., Singh, S. P., Godara, A. S., Bijarniya, A. L., & Samota, S. R. (2020). Tillage and weed management effect on productivity of wheat in North-West Rajasthan. *Indian Journal of Weed Science, 52*(2), 127–131.

80. Singh, A. K., Kumar, R., Singh, A. K., & Kumari, A. (2011a). Bio efficacy of sulfosulfuron on weed flora and irrigated wheat (Triticum aestivum L.) yield. *Environment and Ecology*, 29, 834–838.
81. Singh, A. P., Bhullar, M. S., Yadav, R., & Chowdary, T. (2015). Weed management in zero-till wheat. *Indian Journal of Weed Science*, 47, 233–239.
82. Singh, A. P., Bhullar, M. S., Yadav, R., & Chowdhury, T. (2015). Weed management in zero-till wheat. *Indian Journal of Weed Science, 47*(3), 233–239.
83. Singh, R. K., Bohra, J. S., Srivastava, V. K., & Singh, R. P. (2008). Effect of diversification of rice-wheat system on weed dynamics in rice. *Indian Journal of Weed Science, 40*, 128–131.
84. Singh, S. (2007). Role of management practices on control of isoproturon-resistant littleseed canarygrass (Phalaris minor) in India. *Weed Technology*, 21, 339–346.
85. Singh, S., Sharma, S. D., Punia, S. S., & Singh, H. (2005b). Performance of tank mixture of metribuzin with clodinafop and fenoxaprop for the control of mixed weed flora in wheat. *Indian Journal of Weed Science, 37*, 9–12.
86. Storkey, J., Helps, J., Hull, R., Milne, A. E., & Metcalfe, H. (2021). Defining integrated weed management: A novel conceptual framework for models. *Agronomy,* 11(4), 747. https://doi.org/10.3390/agronomy11040747
87. Subramanian, E., & Martin, G. J. (2006). Effect of chemical, cultural and mechanical methods of weed control on wet-seeded rice. *Indian Journal of Weed Science, 38*, 218–220.
88. Surin, S. S., Singh, M. K., Upasani, R. R., Thakur, R., & Pal, S. K. (2013). Weed management in rice (Oryza sativa)–wheat (Triticum aestivum) cropping system under conservation tillage. *Indian Journal of Agronomy, 58*(3), 288–289.
89. Verma, S. K., Singh, S. B., Meena, R. N., Prasad, S. K., Meena, R. S., & Gaurav. (2015). A review of weed management in India: The need for new directions for sustainable agriculture. *The Bioscan, 10*(1), 253–263.
90. Wang, K. H., Waisen, P., Leslie, A. W., Paudel, R., Meyer, S. L. F., & Hooks, C. R. R. (2022). Relationships between soil tillage systems, nematode communities and weed seed predation. *Horticulturae*, 8, 425. https://doi.org/10.3390/horticulturae8050425
91. Webb, M., & Conroy, C. (1995). The socioeconomics of weed control on smallholder farms in Uganda. *In Proceedings of the Brighton Crop Protection Conference – Weeds* (pp. 157–162). Farnham, UK: British Crop Protection Council.
92. Yadav, D. B., Yadav, A., & Punia, S. S. (2019). Long-term effects of green manuring and herbicides on weeds and productivity of the rice-wheat cropping system in North-Western India. *Indian Journal of Weed Science, 51*(3), 240–245.
93. Zabkiewicz, J. A. (2000). Adjuvant and herbicidal efficacy – present status and future prospects. *Weed Research, 40*, 139–149.
94. Zawierucha, J. E., & Penner, D. (2001). Adjuvant efficacy with quinclorac in canola (Brassica napus) and turf grass. *Weed Technology*, 15, 220–223.
95. Zimdahl, R. L. (2013). Fundamentals of weed science. Academic Press.
96. Zimdahl, R. L. (2018). Fundamentals of weed science. Academic Press.