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REVIEW ARTICLE

Biology and management of wild oat in Australia

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ABSTRACT

Wild oat (*Avena* spp.) is one of the most serious weeds in Australian winter season crops such as wheat, barley, chickpea, *etc. Avena fatua* and *A. ludoviciana* are the dominant species of wild oat in cropping regions of Australia. Propagation of wild oat can occur through seeds. Dissemination of wild oat occurs by agricultural machinery, use of the contaminated seeds and crop residues, *etc.* Seed recruitment of wild oat in the soil occurs through high seed production and the shattering ability of plants. Wild oat has evolved resistance to many herbicides and continuous use of same herbicide could increase the resistance build-up in many populations on a large scale in Australia. The use of herbicides with different modes of action can provide cost-effective and sustainable control of wild oat. Non-chemical weed management practices, such as sanitation, residue burning, tillage operation, crop rotations, and improved crop competition approaches could reduce the infestation of this weed. For sustainable control of wild oat, integrated strategies involving chemical and non-chemical tactics may prove useful. Knowledge regarding the understanding of wild oat ecology could aid in strengthening the integrated management of this weed.

Keywords: *Avena fatua*, *Avena ludoviciana*, Herbicide resistance, Integrated weed management, Weed biology, Wild oat

INTRODUCTION

Wild oat (*Avena* spp.) is one of the most important weeds in the winter growing crops. The wild oat is included in the list of the world's top 10 worst weeds, causing yield reductions in cereals by up to 70% (Beckie *et al.* 2012; Holm *et al.* 1991). The extent of its problematic and cosmopolitan nature can be assessed from the fact that it causes an enormous yield reduction in more than 20 crops across 55 countries (Sharma and Born 1983; Holm *et al.* 1977). The genetic diversity in the populations of wild oat is considered to cause its wide adaptation and distribution.

Avena spp. has been claimed to be the weeds of agricultural systems for at least 4000 years (Malzew 1930), dating back to the Roman and Greek empires (Van Der Puy 1986). Malzew (1930) reported that wild oat originated in South West Asia. Nugent *et al.* (1999) and Kirby (2000) claim the origin of wild oat in Asia or the Mediterranean region. There is no clear and accurate information about the introduction of *Avena* spp. in Australia. However, it has been suggested that it was introduced into Australia as a contaminant of grains (Nugent *et al.* 1999; Kirby 2000). From the United Kingdom, *Avena* spp. entered Tasmania as a contaminant of cereals (Paterson 1976). It was introduced to Western Australia through settlement in Australia by 1830 and became a terrible weed in the fields of New South Wales in 1895 (Maiden 1985).

WILD OAT SPECIES

Along with cereal crops like wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and oats (*Avena sativa*), wild oat species belong to the family Poaceae. In Australia, there are three main species of wild oat, namely *Avena fatua* L. (wild oat), *Avena sterilis* ssp. *ludoviciana* (Durieu) Gillet and Magne, generally referred to as *A. ludoviciana* (sterile oat) and *Avena barbata* Pott ex Link (slender oat), which combinely cause the reduction in crop productivity and increase the cost of weed management, resulting

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in an annual monetary loss of AU$ 28 million to the Australia grain growers (Llewellyn *et al*. 2016). An increase in cropping intensity in most parts of Australia encouraged *A. fatua* and *A. ludoviciana* to be the dominant weed species and about 80% of wild oat populations in Australia contain both of these species (Storrie 2019; Fernandez Quinantilla *et al.* 1990). Southern Australia faces the dominance of *A. fatua*, while in southern Queensland and northern New South Wales, *A. ludoviciana* is the most dominant species (Nugent *et al.* 1999). *Avena barbata* is mainly a weed of non-agricultural land and mostly found along roadsides (Nugent *et al.* 1999; Cousens 2003). In the eastern region of Australia (New South Wales and Queensland), *Avena* spp., when assessed in terms of the infested areas, secured the highest ranking in the regional ranking of the top residual winter weeds in different crops (Llewellyn *et al*. 2016). As *A. fatua* and *A. ludoviciana* are the dominant weed species in Australia, these two species are mainly focused in this article.

WEED BIOLOGY

Botanical description

Although the two major species (*A. fatua* and *A. ludoviciana*) are quite similar morphologically, there are some variations, especially, during the reproductive growth stages which may be helpful to distinguish them from each other (Mennan and Uygur 1996; Holm *et al.* 1977; Thurston 1951). The growth habit and life cycle of *A. fatua* resemble with winter cereals; however, environmental conditions cause great flexibility in its life cycle (Medd 1996; Edgar 1980). Although *Avena* spp. are very similar to wheat and barley, these can be identified by their collar region before flowering. The leaf twist of wheat and barley is clockwise, while wild oat leaves twist anticlockwise (Paterson 1976). Florets of *A. fatua*, which are having hairy, bent, and twisted awns, resemble similarly with *A. ludoviciana* (Edgar 1980). The plants of *A. fatua* have loose and drooping panicles and open branches bearing spikelets whereas the panicles of *A. ludoviciana* plants are spreading and loose (Edgar 1980). The panicles of *A. fatua* are heavier than *A. ludoviciana* because its spikelets bear more and large florets (Edgar 1980). Keeping in view the similarities and differences in the botanical features of wild oat species, suitable management strategies may be devised effectively.

Propagation and dispersal of seed

Propagation of both species of *Avena* occurred exclusively through seeds (Holm *et al.* 1977). *Avena fatua* and *A. ludoviciana* are prolific seed producers (Storrie 2019; Storrie 2007). However, several studies suggested the variation in the seed production potential of both species. Environmental conditions also affect seed production in different wild oat species. *Avena fatua* can produce a large number of seeds *i.e.* up to 1000 seeds/plant (Rauber 1977). In a pot study, *A. fatua* was found to produce 480 seeds/ plant under well-watered conditions (Sahil *et al.* 2020). However, in the case of *A. ludoviciana*, a single plant was reported to produce up to 400 seeds/ plant (Sahil *et al*. 2020). Another Australian field study showed that under the conditions of low competition, *A. ludoviciana* can produce about 2,500 seeds/plant when emerged at the start of the winter season (Mahajan and Chauhan 2021a). Information regarding the seed retention or shattering behaviour of both the species in a crop is of great importance as seeds of *A. fatua* shatter individually while the spikelets of *A. ludoviciana* are too hard to break easily, thus, its seeds shatter in pairs at plant maturity (Sahil *et al*. 2020; Moss 2015; Mahajan and Chauhan 2021b). The reinfestation of these weed species in the fields is mainly caused by their shattering behaviour and thus, affects the severity of competition to the crop in the next season. Flowering in *A. fatua* occurs later than *A. ludoviciana* (Stace 1997; Holm *et al.* 1977), while the seed shattering of *A. ludoviciana* occurs 15-20 days before the harvesting of wheat (Balyan and Malik 1989). Seeds of *A. fatua* are elongated, large, and with hairs on them. Therefore, no report claims natural seed dispersal of *A. fatua* by water or wind. Dispersal is mainly through contaminants of winter crop seeds. In a study on weed dispersal, Wheeler *et al.* (2001) showed normal progress of patches of *A. fatua* by 1–3 m per year; however, the potential progress may reach up to 30 m in agricultural lands. Dispersal of wild oat species by anthropogenic activities also has great importance. In mixed farming systems, agricultural machinery (Thurston and Phillipson 1976), use of contaminated seed (Elliott and Attwood 1970), straw (Wilson 1970) or transportation of fodder (Thomas *et al*. 1984) are the major sources of dispersal of wild oat. Thus, prolific seed-producing nature, high seed viability, formation of a persistent seed bank, and effective dispersal nature enable *Avena* spp. to adapt successfully to a wide range of agroecosystems.

Dormancy

Dormancy in the seeds of both wild oat species maintains seed viability in the soil for several years. Due to the various interactions of *A. fatua* with the environment and high genetic variability, its dormancy behaviour is difficult to generalize (Holm *et al*. 1977). Seed recruitment of wild oat in the soil through shattered seeds by plants and their persistence in the soil through dormancy are the major factors that maintain the weed seed banks in the soil (Mahajan *et al*. 2021b; Jensen 2004). However, several studies claimed that persistence in the seed bank does not correlate with seed dormancy (Thompson *et al*. 2003; Honda 2008). It was suggested that the dynamics of the seed bank can be understood by determining the effects of environmental conditions on seed decay and seed longevity of *Avena* spp. (Vázquez-Yanes and OrozcoSegovia 1996). As reported by Fennimore *et al*. (1998), low temperatures increase the extent of dormancy in wild oat seeds, and dormancy is released when temperatures start increasing. Under unfavourable conditions for the seedling, the persistence of *A. fatua* becomes longer in the soil seed bank with the help of dormancy (Wu and Koetz 2014). Furthermore, under field conditions, seed dormancy and viability are dependent on the seed burial depth as the seed loss is increased with burial depth (Miller and Nalewaja 1990; Mahajan and Chauhan 2021c). In a study conducted by Miller and Nalewaja (1990), the seed viability of *A. fatua* was shown to be decreased by 80% soon after burial. However, 7% of seeds remained viable after 9 years of burial and a small portion of seeds were found viable even after 14 years of burial (Miller and Nalewaja 1990). A recent study conducted in eastern Australia reported that seeds of *A. fatua* and *A. ludoviciana* decayed in the soil within 3 years irrespective of burial depth (Mahajan and Chauhan 2021c). Thus, seed persistence and viability are correlated to environmental factors and soil conditions (Demo 1999).

Germination

The germination process shows complex patterns of variation both within and between populations of *Avena* spp. (Marshall and Jain 1970). Rains boost the germination of *A. fatua* seed bank. Approximately 40% of the seed bank germinates with the opening rain and a further 30% of seed bank germinates later in the season (Nugent *et al.* 1999). Germination remains continued from autumn to spring, consequently, the seed bank is replenished by enough seed production from the smaller and later cohorts. In reference to the suitable temperature for germination, *Avena* spp. shows a large range of temperature *i.e*. 10-26.5°C for germination. However, low temperatures favour the germination of *A. ludoviciana* more than that of *A. fatua* (Fernandez-Quintanilla *et al*. 1990); while germination of *A. fatua* is favored by relatively higher temperatures. There was a similar rate of germination for both species up to 10–18°C. However, at a temperature of more than 20°C, *A. fatua* germinated at a higher rate as compared to *A. ludoviciana*, the opposite trend occurred below 10°C (Fernandez-Quintanilla *et al.* 1990). Uremis and Uyagur (1999) reported 30, 2, and 10 °C as the maximum, minimum, and optimum temperatures, respectively, for germination of *A. ludoviciana*. Different wild oat species show spatial and temporal variation in the time of emergence (Aibar *et al.* 1991). Germination of *A. fatua* occurs from autumn to spring season while winter to early spring is the best time for germination of *A. ludoviciana* (Medd 1996). The knowledge regarding longevity of weed seeds within the soil and the timing of weed emergence under local conditions make a better understanding of a timely and efficient weed management strategy. Mahajan and Chauhan (2021c) found that a shallow depth of 2-5 cm favours the emergence of *A. ludoviciana and A. fatua* compared with the surface and 10 cm soil depth. Poor gas exchange and the absence of a light trigger around the buried seeds at 10 cm depth might be the reason for the lower emergence (Benvenuti and Macchia 1998; Benvenuti 2003). Fatal germination also might be a reason for the lower emergence of deeply buried seeds, as the seeds which germinate at a depth of 10 cm are likely to be died prior to reaching the soil surface (Davis and Renner 2007).

CLIMATE CHANGE AND WILD OAT

Generally, the distribution and prevalence of weed species within the crop and weed communities are affected by changes in climatic factors, such as atmospheric CO_2, rainfall, temperature, *etc*. (Chauhan *et al*. 2014). As wild oat populations have great genetic diversity, there are possibilities that with climate change, these will achieve more competitive advantage over the crop plants with which they have competition (O'Donnell and Adkins 2001). It was argued that wild oat species acquired a range of mechanisms for their survival in the cropping environment, such as a persistent seed bank and variable seed dormancy (Ali *et al.* 2021). In the present climate change scenario, with frequent changes in dry and hot spells during the late winter or early spring period (Cleugh *et al.* 2011), wild oat plants mature early and shed a major part of their seeds prior to harvesting of cereal crops (Ali *et al.* 2021).

For the germination of *A. ludoviciana*, 10 °C is considered the optimum temperature (Quail and Carter 1968). In an experiment on different Australian populations of wild oat, it was observed that major variables of climate change, *i.e.*, atmospheric CO_2, temperature, and soil moisture availability, had an important influence on the growth and development of wild oat species (O'Donnell and Adkins 2001). High plant biomass and an increase in the seed number of wild oat plants have resulted from increased CO_2, however, some degree of compensation was also observed in plant biomass for moisture-stressed plants grown at 480 parts per million by volume (ppmv) CO_2 (O'Donnell and Adkins 2001). Soil moisture stress and increased CO_2 were shown to reduce the dormancy level in after-ripened caryopses, and this may cause a change in seedling emergence patterns. Management strategies of wild oat may change under changing environmental conditions and new ecotypes.

HERBICIDE RESISTANCE IN WILD OAT

Among the major challenges to the sustainability of Australia's prevalent agricultural system, herbicide resistance is the important one. Due to the over-reliance on chemical weed control strategies in Australian farming systems, herbicide resistance has evolved in 49 weed species across 12 herbicide modes of action (MOA) groups (Storrie 2019). The first herbicide resistance case in wild oat was found in Western Australia in 1985 against the Group 1 herbicides (Heap 2008). Thereafter, in 1991, another incidence of resistance against the same group of herbicides was found in South Australia and New South Wales (Heap 2008). Since then, herbicide resistance cases have increased steadily and dramatically. A survey report of the year 2003 claimed the resistance to Group 1 herbicides in 10% of all wild oat populations in northern New South Wales and southern Queensland (Widderick and Walker 2007). An investigation on herbicide resistance in wild oat species in Australia showed that those wild oat populations have a high risk for evolving resistance that has been treated with acetolactate synthase (ALS) inhibitor herbicides repeatedly over the last 15 years (Storrie 2019; Storrie 2007). The wild oat populations were reported to be resistant to Group 1, Group 2, Group 9, and Group 31 herbicides in Australia with some populations resistant to sub-groups or multiple groups (Storrie 2019). Multiple herbicide resistance (resistance to both Group 1 and 31 herbicides) has been estimated in one of three wild oat populations. A recent study conducted in Australia reported the world's first case of glyphosate-resistant (GR) *A. fatua* and *A. ludoviciana* (Chauhan 2022).

As herbicide resistance in *Avena* spp. against a large number of herbicides including glyphosate, has been reported in Australia, sole reliance on herbicides may not be an effective strategy for the management of wild oat (Chauhan 2022; Heap 2022; Storrie 2019). Therefore, integrated weed management (IWM) strategies involving cultural weed management options, such as harvest weed seed control, improved crop competitiveness, and rotational use of herbicide, may provide better weed management options. For implementing IWM strategies against herbicide-resistant wild oat populations, two scenarios could be taken into consideration: those where resistance has still to evolve and those where resistance has already evolved (Nietschke *et al.* 1996). In those cases, where herbicide resistance in wild oat has already occurred, those strategies should be adopted which annihilate the resistant populations, such as crop removal for hay, silage, or green manure, so as to avoid the dispersal of resistant seeds. In the cases where resistance is yet to be experienced, adoption of those IWM strategies should be emphasized which minimizes or avoid the selection for herbicide resistance. If a variety of pre-and post-emergence herbicides and herbicides with different modes of action are used in a rotational way, it may help in delaying the onset of herbicide resistance (Anderson 2003). Besides, the survivor of herbicide-treated weeds needs to be tested with different groups of herbicides for susceptibility and an alternative method to be evolved for preventing seed set. A range of IWM techniques has been developed for the effective management of herbicide-resistant wild oat populations; however, an effective management strategy is needed to manage the weed seed bank in the soil. The development of an IWM program must be supported by a thorough understanding of the population dynamics operating within weed seed banks (Swanton *et al*. 2008). Therefore, it is suggested to know the biology of herbicide-resistant weed species which may help in the development of sustainable management practices.

MANAGEMENT MEASURES

As the wild oat species are listed among the most noxious, widespread, and terrible weeds in modern-day agriculture in Australia (Chauhan 2022; Nietschke 1997), there is a need to gain an understanding of the management of this problematic weed in crop production systems. A range of weed control or prevention methods have been identified for the management of wild oat species. These methods must be planned in such a way that they should focus on a whole farm basis rather than crop by crop or field by field. Initially, cultural methods were found more reliable on controlling wild oat, but since the 1960's, chemical control has become the most preferred method (Combellack 1992). However, after the development of herbicide resistance in wild oat species, the focus has shifted to IWM strategies for the sustainable control of wild oat.

Preventive methods and sanitation

One of the most important strategies in managing weeds is the prevention of weed introduction and spread regardless of crop, establishment method, and ecosystem. Preventive methods involve all possible means that restrict the entry and establishment of weeds in an area (Mahajan *et al.* 2016). Many sources may cause the spread of weeds from one area or field to another. As the seeds of wild oat do not disperse naturally, poor hygienic conditions on the farm can facilitate the introduction, spread, and persistence of wild oat. In such a situation, sanitation is considered an essential component of cultural control. In mixed farming systems, the spread of wild oat can be attributed to the use of contaminated grain (Elliott and Attwood 1970), transportation in fodder (Thomas *et al.* 1984), straw (Wilson 1970), or dispersal by agricultural machinery. Dispersal of wild oat seeds may be minimized by using clean and pure seeds, cleaning the tillage and harvest machinery between fields, and covering grain trucks used to transport grain (Thill *et al.* 1994).

Crop residue burning

One of the few cultural weed control methods that can be used for the control of wild oat in Australian farming systems is the crop residue burning from cereal crops. Nietschke (1997), from a series of experiments, demonstrated that crop residue burning helps to destroy the wild oat seeds on the soil surface. Seed killing is maximum if burning occurred directly after harvesting (Wilson and Cussans 1975). The position of seeds at the time of burning and the temperature and timing of burning are the major factors that affect the extent of control by the stubble burning method (Cussans *et al.*1987). However, it can, generally, be stated that wild oat seed destruction increases with the amount of residue burnt (Nietschke 1997). Additionally, residue burning can encourage the emergence of those wild oat seeds that were not killed by the burning process, therefore there is further depletion of seed banks when these emerged weeds are killed. However, potentially overriding these factors is that burning is generally not encouraged in Australia due to the established advantages of crop residue retention. However, if crop residue burning is used judiciously and may provide benefits to the agricultural system as a whole, it may prove a viable option for the IWM strategy in the management of wild oat and prevention of herbicide resistance in wild oat in Australia.

Tillage operation

There are complex and varied influences of tillage operations on the population dynamics of *Avena* spp. (Navarrete and Fernandez-Quintanilla 1996). Germination of wild oat is encouraged with tillage operations (Chancellor 1976). Tillage is considered a key factor in affecting the persistence of wild oat (Simpson 1992). A major proportion of wild oat seeds remained on the soil surface in minimum and no-till systems where they decay at a faster rate because of continuous variations in weather conditions and also can be killed by predators (Mahajan and Chauhan 2021c). Thus, wild oat seed banks decline more rapidly in minimum and no-till systems than in conventional cultivation (McGillion and Storrie 2006; Nugent *et al.*1999). In the conventional tillage system, seeds are buried in soil which promotes seed longevity and extends the life of the seed bank by inducing dormancy, however, the seeds released from dormancy and germinate when brought to the surface in subsequent tillage operations (Widderick and Walker 2007; Nietschke 1996). Thus, pre-sowing tillage operations are supposed to increase the wild oat infestation compared with practices which involve no or minimal soil disturbance during seedbed preparation, such as direct seeding (Medd 1990). Mahajan and Chauhan (2021c) suggested the depletion of seed bank of wild oat species with no-till systems. Further, the type of tillage implements also affects the seed bank. Some authors reported the more rapid decline of wild oat seed banks by using tyned implements as compared with deep ploughing (Wilson and Phipps 1985; Wilson 1978). The adoption of conservation tillage practices, thus seems the most appropriate for the management of wild oat in Australia.

Seeding rate

Cultural weed control strategies mainly focus on reducing yield loss due to interference of weeds by exploring crop competition against weeds (Gibson *et al*. 2002). It was established in the studies that increasing the crop density might be useful to improve the competitive ability of different crops against wild oat. High seeding rates were observed to suppress wild oat in common wheat (Carlson and Hill

1985), tame oat (May *et al.* 2009), barley (O'Donovan *et al.* 1999), and canola (*Brassica napus* L.) (O'Donovan *et al.* 2004). A recent study in Australia reported that a high seeding rate in early-planted wheat suppressed the growth of wild oat in terms of weed biomass and decreased weed seed production which resulted in increased wheat yield (Mahajan and Chauhan 2022). Banisaeidi *et al.* (2014) reported that an increase in the seeding rate of spring wheat from 152 kg seeds/ha to 266 kg seeds/ha reduced the shoot biomass of wild oat resulted in increased grain yield and the number of spike/m^2. Scursoni and Satorre (2005) reported the increased competitiveness in barley by increasing seeding rates which may be used as an effective crop management strategy to reduce the effect of wild oat on crop yield losses, particularly when herbicide use is reduced and when weed populations are low. However, it needs to be remembered while choosing a high seeding rate as a weed management tool that a high seed rate of crops can increase crop competitiveness against weeds only up to a certain level. Beyond that level, an increase in seed rate may not always result in a higher economic return, especially when seed costs are high.

Time of sowing

The time of sowing plays a vital role in crop-weed competition by affecting the initial growth of crops and weeds. By delaying the sowing date of spring cereals, wild oat, that germinate prior to sowing, can be controlled by cultivation. In general, delay in sowing of wheat is recommended in the paddocks which are highly infested with weeds. This delayed sowing maximizes weed control and helps to attain a high yield (Singh *et al.* 1995; Cussans and Wilson 1976). Recent studies in Australia have shown that early cohorts of wild oat (which emerge in May) are very competitive in nature and prolific seed producers (Mahajan and Chauhan 2021c). In such cases, delayed sowing of wheat can be used as an effective tool for weed management as early cohorts can be killed by pre-sowing tillage operation or by spraying non-selective herbicides (Cussans and Wilson 1976). Mahajan and Chauhan (2022) also reported the vigorous growth and high seed production of wild oat in the early sown wheat crop in Australia. However, it was further reported that weed seed production was reduced by 40% when timely sowing of wheat was sown at a high seed rate compared with a low seed rate (Mahajan and Chauhan 2022). A delay in the sowing of wheat, due to slower early growth, often causes a yield reduction (Shah *et al.* 2020). Some authors reported that delayed sowing of crops is a less effective method of controlling the first cohort of wild oat prior to crop sowing because of the staggered germination pattern of wild oat (Nugent *et al.* 1999; Nietschke 1996). These studies suggest that delayed sowing may not be the effective option for the control of wild oat, rather, early sowing along with the use of a higher seed rate may be a better option for smothering the weed flora and high profitability. However, in fields having a history of high infestation of wild oat, delayed sowing of winter crops may help in reducing seed bank in subsequent years.

Crop rotation

The continuous cropping of the same crops in Australia has resulted in detrimental effects on productivity in recent years. These negative effects have been associated with the increased selection pressure for the establishment of certain annual weeds, particularly problematic annual grasses (Bell *et al.* 2006; Seymour *et al.* 2012). As the weed management costs to Australian grain producers exceed AU$3 billion annually, advancements in easily adoptable and economic weed management techniques are needed (Gurusinghe *et al.* 2022). Crop rotations can be used as an objective to minimize the cost and to increase weed control efficiency by interspersing crops in which control can be attained. The long-term weed population dynamics are influenced by the choice and sequencing of crops. Every crop allows a particular weed to establish its association. These particular weeds are found in different rotations, and are controlled by rotating the crops which have different cultural habits and life cycles (Kumar *et al.* 2017). Diversified and specifically timed crop rotations give a specific benefit to farmers with respect to the control of annual weeds. Including broad-leaved crops such as canola, pasture legumes or lupins in crop rotation may enhance the suppression of grass weeds by improving crop competitiveness against weeds while also making available a broad range of selective herbicides for in-crop use (Weisberger *et al.* 2019).

Martin and Felton (1993) claimed that crop rotation is the most effective way to reduce wild oat seed banks in comparison to tillage and herbicide strategies. They found that the cultivation of wheat crops for four successive years with annual applications of either flamprop-methyl or triallate did not prevent the build-up of the wild oat seed bank. However, Johnson *et al.* (2006) found that continuous cropping systems did not decrease the seed banks of wild oat to an acceptable level and thus, benefited the wild oat. In the earlier studies in northern Australia, Martin and Felton (1993), Wilson *et al*. (1977) and Philpotts (1975) reported the effective reduction in seed reserves of wild oat through clean winter fallowing in association with a rotation from wheat to sorghum. Similarly, growing crops either for green or brown manuring, or for use as hay or silage, give an opportunity to growers for effective wild oat control while providing additional income from fattening stock or selling hay or silage (Storrie 2019). However, this technique will give effective control of wild oat only on the condition that removal of wild oat plants should be done prior to seed set.

Harvest weed seed control

Modern grain harvesters, while working in harvest condition specifications, collect and clean the crop grain efficiently, separate the grain from residues (*e.g.*, crop and weed plant material), and then, spread the straw residues and chaff (including collected weed seeds) from the rear of the harvester. This process disperses the collected weed seeds uniformly in the whole field. Thus, this process becomes inadvertently and ironically an efficient process for maintaining ongoing weed infestations. To disrupt this cycle, weed seeds can be harvested from the crop fields and their return to the field may be minimised. This is known as harvest weed seed control (HWSC) (Walsh *et al.* 2018). This is an effective weed control method that involves the collection and destruction of weed seeds that are present at the time of harvesting. As with several significant innovations in agriculture, HWSC system is one of the important innovations which targets weed seeds during crop harvest, was developed with the efforts of Australian grain growers. There are currently six HWSC methods being adopted in Australian agriculture systems: chaff carts; narrow windrow burning; chaff tramlining or chaff decks; chaff lining; seed impact mills and bale direct systems.

In Australia, HWSC technique has been proven an efficient weed management technique, particularly for *Lolium rigidum* (annual ryegrass), and is widely adopted in western Australia and increasingly in southern New South Wales, southern Australia, and Victoria (Walsh and Powles 2014). Some reports showed HWSC, a less effective tool for the management of wild oat, due to its early seed-shattering character before crop harvest (Nietschke *et al.* 1996). However, Walsh and Powles (2014), while studying the potential of HWSC in Western Australian wheat crops, showed high seed retention (HWSC potential) (84%) for wild oat species. This study confirmed that high proportions of the total seed production of wild oat could potentially be targeted with HWSC systems in Australian wheat crops. In another study, it was also found that *A. ludoviciana* has limited opportunity for HWSC (Mahajan and Chauhan 2021b). HWSC is considered more effective on wild oat when it germinates later in the crop as their maturity is closer to that of the crop. Any delay in harvest may result in a decline in the collection of weed seeds in the HWSC system (GRDC 2019).

Chemical weed control

Chemical weed control is generally considered the most important and cost-effective tool for the control of *Avena* spp. (Beckie *et al*. 2002). Due to the staggered emergence of wild oat, effective control has relied upon the most on the use of pre-and post-emergence herbicides, especially where early cohorts are responsible for major yield losses (Jones and Medd 1997). In the Australian cropping system, the first herbicides (*i.e.,* diallate and barban) for control of wild oat were introduced in the late 1950s (Hutson and Roberts 1987; Medd 1992). However, the selective spray topping method was introduced in the 1990s to prevent seed sets from the later germinating species (Cook *et al.* 1999). The ACCase-inhibiting (Group 1) herbicides, aryoxyphenoxypriopionates (fops) and cyclohexandiones (dims) (Group 2) have been widely used for in-crop wild oat control in Australia since the release of the first of these herbicides in 1978 (Broster *et al.* 2011). Efficient management of wild oat species is dependent on early post-application of aceto-lactate synthase (ALS) and acetyl-CoA carboxylase (ACCase) inhibitor herbicides (Owen and Powles 2009). Cyclohexanedione (CHD) and aryloxyphenoxy-propionate (AOPP) herbicides have also been broadly used for the management of wild oat (Burton *et al.* 1989). A number of herbicides including, barban, glyphosate, difenzoquat, linuron, chlorfenprop, monolinuron, metoxuron and metribuzin, have proved effective for the management of *A. fatua* and *A. ludoviciana* (Terry 1984).

Due to the over-dependence on herbicides, wild oat species have evolved resistance to ALS inhibitor herbicides, which are the most widely used herbicides for the control of wild oat in Australia (Storrie 2007). Therefore, pre-emergence herbicides may be an alternative for the control of wild oat in wheat in Australia. New pre-emergence herbicide options can give better flexibility for the control of wild oat in wheat, especially when integrated with other weed management tools. Today, a range of herbicides have been introduced worldwide which effectively control *Avena* spp. (**Table 1**). Mahajan and Chauhan (2022) reported that the application of pyroxasulfone and tri-allate as pre-emergence herbicides provided maximum control of wild oat in the Australian wheat system. Among the post-emergence herbicides, pinoxaden, clethodim, haloxyfop, and propaquizafop provide the best alternative herbicide options for the control of wild oat species (Chauhan 2022). Irrespective of the growth stage, these herbicides provide complete control of both *Avena* species. Some herbicides (e.g. butroxydim) provided the best results when applied at earlier stages (at the 3–4 leaf stage), however, delaying their spray till the 6–7 leaf stage resulted in the survival of *Avena* species (Chauhan 2022). Although, several herbicides have provided effective control of *A. ludoviciana* and *A. fatua* over the years, the evolution of resistance in herbicide has reduced the scope of chemical weed control. Owen and Powles (2009), in a survey conducted in the Western Australian grain belt, revealed the widespread resistance in wild oat to the ACCase-inhibiting herbicide diclofop-methyl across the studied area. However, alternative ACCase-inhibiting herbicides such as clodinafop, clethodim, and pinoxaden were shown to be effective on 97% of the wild oat populations which proved relatively low resistance in wild oat populations to AOPP and CHD ACCase herbicides. Similarly, herbicides of other modes of action, such as ALS inhibiting herbicides, triallate, glyphosate, and flamprop, also showed effectiveness in controlling those wild oat populations which showed resistance to ACCase herbicide. Thus, it may be concluded that still there is the scope for chemical weed control of wild oat by selecting a diverse range of herbicides available that permits flexibility in choosing herbicides with different modes of action, acting at different stages of crop growth (pre-seeding, seeding, post-seeding, and late stem elongation). This strategy may slow the onset of resistance to any single group and therefore, is widely recommended as a means of prolonging herbicide efficacy in Australian agriculture.

Allelopathy

Allelopathy is a naturally occurring phenomenon in agricultural ecosystems which has been emphasized in recent years as a potential alternative to chemical weed management. Many studies around the globe have confirmed allelopathy as an effective weed management tool, especially in organic farming systems (Cheema *et al*. 2004; Jamil *et al*. 2009; Iqbal *et al*. 2007). Allelochemicals retard the growth of plants by suppressing their physiological functions when applied at high concentrations. The growth suppression of weeds is caused by the phytotoxic activity of allelochemicals (Farooq *et al*. 2013). Bajwa *et al*. (2013) reported the suppression of germination and growth of wild oat with the application of water extracts from some weeds and tree plants, applied either singly or in combination. Jabran *et al*. (2010), investigated the allelopathic effect of barnyard grass, winter cherry, mulberry, and sorghum on wild oat and found that the mulberry was the most inhibitory plant species with respect to germination, root, and shoot length, the number of roots and leaves, and seedling fresh and dry weight of

Table 1. Herbicides used to control wild oat

Herbicide	Dose (g/ha)	Time of application	Crop	References
Pyroxasulfone	100	PRE	Wheat	Mahajan and Chauhan (2022)
Tri-allate	800	PRE	Wheat	Mahajan and Chauhan (2022)
Butroxydim	45	POST	Resistance Screening study	Chauhan (2022)
Clethodim	60-120	POST	Resistance Screening study	Chauhan (2022); Broster *et al.* (2011)
Haloxyfop	78	POST	Resistance Screening study	Chauhan (2022)
Pinoxaden	20	POST	Resistance Screening study	Chauhan (2022)
Propaquizafop	30	POST	Resistance Screening study	Chauhan (2022)
Fenoxaprop-ethyl	60	POST	Wheat	Medd *et al.* (1992)
Flamprop-methyl	225-450	POST	Wheat	Medd *et al.* (1992)
Fenoxaprop	81	POST	Barley	O'Donovan *et al.* (2013)
Mesosulfuron	10	POST	Resistance Screening study	Broster *et al.* (2011)
Triallate	800	PRE	Resistance Screening study	Broster *et al.* (2011)
Pinoxaden	100	EPOST	Wheat	Travlos *et al.* (2011)
Mesosulfuron + iodosulfuron	7.5 + 7.5	EPOST	Wheat	Travlos *et al.* (2011)
Metribuzin	247	POST	Wheat	Mueen-ud-Din *et al.* (2011)
Clodinafop-propargyl	36	EPOST	Wheat, Barley	Scursoni *et al.* (2011)
Fenoxaprop-p-ethyl	55	EPOST	Wheat, Barley	Scursoni *et al.* (2011)
Pinoxaden	40	EPOST	Wheat, Barley	Scursoni *et al.* (2011)
Iodosulfuron + metsulfuron-methyl	3 + 3.75	EPOST	Wheat, Barley	Scursoni *et al.* (2011)

PRE: pre-emergence, POST: post-emergence, EPOST: early post-emergence wild oat. The allelopathic potential for different plants against wild oat was in the order: mulberry > winter cherry > barnyard grass > sorghum. Turk and Tawaha (2003) found that the water-soluble allelochemical substances in black mustard (*Brassica nigra* L.) inhibited the germination and seedling growth of *A. fatua*. This study also confirmed that the inhibitory effect on germination increased with increasing concentration of extract solution of the fresh plant parts. Similarly, Cheema *et al.* (2013) also found the potential effect of sunflower, sorghum, and mulberry as allelopathic crops. There is a lack of information regarding the allelopathic potential of different plant species to control wild oat in Australian conditions. So, research is needed to quantify the potential effect of allelopathy as an integrated part of weed management strategies in Australia.

INTEGRATED WEED MANAGEMENT APPROACH

Many weed management strategies have been developed for the effective management of wild oat. However, the adoption of any single technique cannot provide effective, sustainable, and season-long control of this weed as different species of wild oats vary in dormancy and growth habits. Sustainable and effective weed management strategies involve the combined use of preventive, mechanical, cultural, chemical, and biological weed control methods in an effective and economical pattern which is called IWM. This is the most suitable and effective strategy for weed management in progressive farming. No doubt, chemical weed management remains the central part of any IWM package, the inclusion of above-discussed methods may provide the best weed control results. Non-chemical weed management methods which may improve the performance of the IWM strategy for controlling wild oat species include tillage, crop rotation, crop competition, seed rate or seeding density, manipulation in sowing time, harvest weed seed control and allelopathic suppression (Mahajan and Chauhan 2022; Mahajan and Chauhan 2021b; Nalewaja 1999; Boerboom 1999; Thill *et al.* 1994). Instead of using only chemical methods, *A. fatua* can be controlled successfully with an integrated approach, and its seed production and competitive ability may be reduced by the adoption of different approaches in an integrated manner (O'Donovan *et al.* 2000). Different wild oat species have been reported to be effectively controlled by adopting appropriate combinations of different management tools (**Table 2**). By using the IWM approaches, weed biomass of *A. fatua* and *A. ludoviciana* has been reported to be reduced by up to 90% (Harker *et al*. 2009; Blackshaw *et al*. 2008; Anderson 2003). Mahajan and Chauhan (2021a) suggested that IWM could be the best strategy for the successful control of *A. ludoviciana*, and prevention of seed production is the most important action toward reducing the replenishment of seed banks.

As the wild oat species have evolved resistance to most of the selective herbicides available for their control including glyphosate in Australia and, therefore, have had the biggest impact on farm profitability. A range of IWM methods has been proven very effective for managing and reducing the herbicide-resistant populations of wild oat (Beckie 2006). Mahajan and Chauhan (2021c) emphasized the knowledge of the timing of the emergence and the emergence dynamics of *A. fatua* and *A. ludoviciana* from different depths, allows to make decisions making tools such as strategic tillage systems, making the best use of all principles of IWM and maintaining weed infestation at economically acceptable levels. Improving the competitiveness of

Table 2. Integrated weed management options for wild oat species

Integrated weed management strategy	Outcome of IWM strategy	Associated crop	References
Early sowing + effective pre-emergence herbicides, (pyroxasulfone and triallate)	Effective control of wild oat and limited production of weed seed resulting in high crop yield	Wheat	Mahajan and Chauhan (2022)
Crop competitiveness + reduction in herbicide dose	Reduction in biomass and minimal potential replenishment of the seed bank of *A. ludoviciana*	Barley	Walker *et al.* (2001)
High crop density (150 plants m^{-2}) + Reduction in herbicide dose	Reduction in biomass and seed production of *A. ludoviciana*	Wheat	Walker *et al.* (2002)
Tall cultivar + high crop density (400 plants m^{-2}) + diverse crop rotation (barley–canola–barley–pea–barley) + A 50% reduction in herbicide dose	Reduction in biomass of *A. fatua* and a 40-fold reduction in its seed production	Barley	O'Donovan *et al.* (2013)
Diverse crop rotations involving cereals and legumes + high seed rates + cover crops	Reduction in biomass and seed production of herbicide-resistant *A. fatua* resulting in high crop yields and economic returns	Canola, barley, wheat, pea, rye	Harker *et al*. (2016)

the crop by adopting multiple weed management approaches in an integrated manner has shown success in managing wild oat species in major field crops (Bajwa *et al*. 2016). So, the adoption of an appropriate IWM method could prove as a key to the successful management of wild oat species in the Australian crop production system.

CONCLUSION

Wild oat species, especially *A. fatua* and *A. ludoviciana* are the major challenge to the crop production system in Australia. The morphological features, propagation, dispersal, dormancy, and germination mechanism of these weed species enable them to survive in a wide range of environmental conditions. A range of herbicides with different modes of action and their use in rotations could provide long-term weed control by reducing selection pressure on weeds. Non-chemical methods such as sanitation, crop residue burning, optimizing seeding rate, increasing crop competition, allelopathy, harvest weed seed control, etc can be used for the management of wild oat. However, the adoption of any single technique cannot provide effective, sustainable, and season-long control of this weed as different species of wild oats vary in dormancy and growth habits. Sustainable and effective weed management strategies involve the combined use of preventive, mechanical, cultural, and chemical weed control methods in an effective and economical pattern.

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