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A global perspective on the biology, impact and management of *Chenopodium album* and *Chenopodium murale*: two troublesome agricultural and environmental weeds

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Abstract

Chenopodium album and *C. murale* are cosmopolitan, annual weed species of notable economic importance. Their unique biological features, including high reproductive capacity, seed dormancy, high persistence in the soil seed bank, the ability to germinate and grow under a wide range of environmental conditions and abiotic stress tolerance, help these species to infest diverse cropping systems. *C. album* and *C. murale* grow tall and absorb nutrients very efficiently. Both these species are allelopathic in nature and, thus, suppress the germination and growth of native vegetation and/or crop plants. These weed species infest many agronomic and horticultural crops and may cause > 90% loss in crop yields. *C. album* is more problematic than *C. murale* as the former is more widespread and infests more number of crops, and it also acts as an alternate host of several crop pests. Different cultural and mechanical methods have been used to control these weed species with varying degrees of success depending upon the cropping systems and weed infestation levels. Similarly, allelopathy and biological control have also shown some potential, especially in controlling *C. album*. Several herbicides have been successfully used to control these species, but the evolution of wide-scale herbicide resistance in *C. album* has limited the efficacy of chemical control. However, the use of alternative herbicides in rotation and the integration of chemicals and biologically based control methods may provide a sustainable control of *C. album* and *C. murale*.

Keywords *Chenopodium* spp. · Common lambsquarters · Integrated weed management · Herbicide resistance · Weed biology · Environmental protection

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Introduction

Weeds are one of the largest biological constraints to sustainable crop production globally. *Chenopodium* genus consists of 250 species and subspecies around the world (Krak et al. 2016). Some of these species are cultivated for food and grains, but some others are noxious weeds of agro-ecosystems. About 25 *Chenopodium* species are recognised as weeds in different parts of the world (WSSA 2018). Two of the most prominent, out of these weed species, are *Chenopodium album* L. and *Chenopodium murale* L. Both of these species are annual weeds and propagate by seeds (Anonymous 2017). The word "*Chenopodium*" is derived from the Greek words "khen" (goose) and "pous" (foot) and describes the leaf shape (like goosefoot) of most of the species belonging to this genus (Anonymous 2017). *C. album* has been listed amongst the ten most widely distributed and problematic weed species in the world (Holm et al. 1977; Anonymous 2017). It is one of the

major weeds of several agronomic and vegetable crops including wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), chickpea (*Cicer arietinum* L.), canola (*Brassica napus* L.), maize (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], potato (*Solanum tuberosum* L.), tomato (*Lycopersicon esculentum* Mill.), sugar beet (*Beta vulgaris* L.), and peanut (*Arachis hypogaea* L.) (Conn and Thomas 1987; Shawn et al. 1999; Bhowmik and Reddy 1988; Tanveer et al. 2009; Sarabi et al. 2013; Jabran et al. 2017). *C. murale* is also a fast-growing annual, cosmopolitan weed species (Qasem 1992, 1997). It has been reported to infest more than 25 crops in different parts of the world (Dmitrovic et al. 2015). Some of the major crops infested by *C. murale* include wheat, maize, potato, cauliflower (*Brassica oleracea* L.), garlic (*Allium sativum* L.), onion (*Allium cepa* L.), and spinach (*Spinacia oleracea* L.) (Fennimore et al. 2001; Qasem 2006, 2007; Miri and Rahimi 2009; Hayyat et al. 2016). *C. album* and *C. murale* cause substantial yield losses in the above-mentioned crops due to severe competition right from the early growth stages of crops. Both of these weed species are also known to be very efficient in nutrient uptake and assimilation while growing in crops (Bhowmik and Reddy 1988; Qasem 1992; Blackshaw et al. 2003).

Chenopodium album and *C. murale* are widespread in different regions of the world (Holm et al. 1977). These species adapt under a wide range of environmental conditions including the soil moisture, soil pH, and temperature (Holm et al. 1977; Medina 1996; Khanna-Chopra and Sabarinath 2004; Tanveer et al. 2009). Both of these species possess unique biological features which help them to tolerate sub-optimal and/or harsh conditions. These features include high seed production, rapid and vigorous growth, tall growing habit, quick life cycle, seed dormancy under unfavourable conditions, high longevity and viability of soil seed bank and the ability to germinate under a wide range of environmental conditions (Bhowmik 1982; Tanveer et al. 2009). *C. album* and *C. murale* are allelopathic weed species which release several phytotoxic secondary metabolites (allelochemicals) in their rhizosphere to suppress the germination and growth of the neighbouring plant species (Reinhardt et al. 1994; Batish et al. 2006; Rezaie et al. 2008; Rezaie and Yarnia 2009). This allelopathic effect not only suppresses the growth of competitive vegetation but also provides *C. album* and *C. murale* defence against biotic and abiotic stresses (Mallik and Tesfai 1988; Ibrahim et al. 2007; Ghareib et al. 2010). *C. album* also acts as an alternate host of several crop pests including fungi, viruses, nematodes and insects (Abe and Ui 1986; Moran and Whitham 1988; De Waele et al. 1990; Sharma et al. 1998; Anonymous 2017). The strong biological and eco-physiological features of both weed species enable them to interfere strongly with crop growth and development.

A wide range of management options have been employed for *C. album* and *C. murale* in different cropping systems.

Numerous studies have shown that cultural methods, i.e. high planting density, narrow row spacing, mulching, cover crops, crop rotations, intercropping and nutrient management, offer effective control of both species (Balyan et al. 1988; Burgos and Talbert 1996; Blackshaw et al. 2004a, b; Santos et al. 2004; Saberali 2008; Corre-Hellou et al. 2011; Heidari et al. 2011; Sharma and Banik 2013; Weber et al. 2017). Similarly, hand weeding, hoeing, earthing-up, mowing, stale seedbed and reduced tillage proved effective in controlling *C. album* and *C. murale* in different cropping systems (Jaiswal 1994; Gogoi and Kalita 1995; Randall 1996; Fennimore and Jackson 2003; Gruber and Claupein 2009; Farooq and Nawaz 2014). Modern weed control methods such as solarisation and flaming have also shown promising results for soil seed bank reduction of both species (Ascard 1995; Arora and Yaduraju 1998). The use of allelopathy and biological control has also shown some potential against *C. album* and *C. murale*; however, a wide-scale field application of these approaches remains a challenge (Scheepens et al. 1997; El-Khatib 2000; Cheema et al. 2001; Netland et al. 2001; Qasem 2002; Bhowmik and Inderjit 2003; Campiglia et al. 2012; Ogut et al. 2012). All these non-chemical approaches offer varying degrees of success, depending upon the cropping system and agro-climatic conditions.

Many of the above-mentioned approaches are not applicable in different parts of the world due to economic, social and/or geographical constraints (Bajwa et al. 2015). Therefore, the use of herbicides has remained inevitable for economical, efficient and effective control of *C. album* and *C. murale* (Curran et al. 2012). A wide range of pre- and post-emergence selective herbicides has been used to control *C. album* and *C. murale* in different crops, and most of them provided effective control (> 80%). However, over-reliance upon herbicides has led to herbicide resistance evolution in *C. album* (Heap 2018). In many countries, it has evolved resistance against major photosystem II (PS-II) inhibitor and acetolactate synthase (ALS) inhibitor herbicides including triazines, metamitron, linuron, thifensulfuron-methyl and imazamox. However, it is fortunate that no case of herbicide resistance has been reported in *C. murale*. Keeping in view the widespread infestations of *C. album* and *C. murale* and herbicide resistance problem in *C. album*, no single method is successful in controlling these problematic weed species. Some studies have shown that the integrated use of different chemical and non-chemical options provides a sustainable and effective control of these species (Maliwal and Gupta 1989; Jabran et al. 2008, 2010; Pannacci and Covarelli 2009; Rao et al. 2009; Dobariya et al. 2014). However, this area has potential for more research that will help in the sustainable management of these two problematic weeds.

Chenopodium album and *C. murale* are strong competitors due to their adaptive morphology and physiology under a wide range of environmental conditions. *C. album* is more

diverse and adaptable and it also has evolved resistance against several herbicides. Therefore, it is more problematic in agro-ecosystems as compared to *C. murale*. However, *C. murale* has more flexible life cycle and superior ability to tolerate harsh conditions which makes it a threat to crop production. Bassett and Crompton (1978) reviewed the biology of *C. album* in a Canadian scenario. However, a comprehensive review of the biology and management of *C. album* and *C. murale* is lacking, especially in the context of modern agriculture. This review provides detailed and updated information on biology, ecology and management of both species. It also highlights key differences in the biological traits and ecological interactions of both species. This information will help to devise future management plans for these weed species which are problematic both in their native and introduced range. The research gaps highlighted here provide future research directions for the researchers and students working in weed science.

Global distribution and habitat

Chenopodium album and *C. murale* are widely distributed across the world (Fig. 1). *C. album* has been reported to be native to western Asia; however, it is not fully clear (Anonymous 2017). Its native range includes most of Europe, from where Linnaeus described the species. Plants native in eastern Asia are included under *C. album* but often differ from European specimens. It is widely naturalised elsewhere, e.g. North Africa, Australasia, North America and Oceania. It prefers temperate as well as tropical areas (Anonymous 2017). Preferred soil conditions for its growth range from strongly acidic to alkaline and it also prefers calcareous soils (Medina 1996). *C. album* has a wide distribution over semi-arid areas. High temperature, strong sunlight during summers, high evaporation, little precipitation and increased salinity in the soil surface are some suitable conditions for its growth (Srivastava 1967; Medina 1996).

Chenopodium murale is native to Eurasia and prefers moist soils to grow. Its growth reaches to peak in winter season but only in the regions that are not too cold as *C. murale* cannot tolerate frost. It can be found on roadsides, wastelands and cropping systems (El-Khatib 2000). *C. murale* prefers to grow in sub-tropical, temperate and cool climate (Holm et al. 1977). It grows well in nitrogen-rich areas of the Mediterranean region. Invasion and colonisation of *C. murale* is significant in highly fertilised and irrigated conditions. It can tolerate drought stress but do not grow well under shade (Anonymous 2017). Both *Chenopodium* species are widespread due to their adaptive ability to different environmental conditions.

Biology

Weed biology is very important to understand the actual impact of any weed species and mechanism of its invasion and for its effective management (Bhowmik 1997; Bajwa et al. 2016). Although *C. album* and *C. murale* are closely related species and possess several common botanical features, certain differences in their morphology and ecology are responsible for their differential adaptability and spread.

Botanical description and life cycle

Chenopodium album and *C. murale* are annual flowering plant species (Anonymous 2017). *C. album* normally grows from 0.1 to 1.5 m tall, but in some cases, its plants can grow up to 3.0 to 3.5 m tall (Bassett and Crompton 1978). Its stem is smooth, erect, longitudinally grooved, striped and red, green or purple in colour (Anonymous 2017). The flowers form dense clusters and are inconspicuous, are green and have no petals (Bassett and Crompton 1978). *C. album* flowers during the whole summer but predominantly in autumn. The flowers are hermaphrodite and usually are wind-pollinated (Lamp and Collet 1990). A mature plant of *C. album* produces about 20,000 pollen grains in a season. Seeds are very small, disc-shaped with an acute notch. They are orbicular, glossy black, brownish-green or brown, 1.5 mm in diameter and smooth (Verma 2017). The life cycle of *C. album* starts with its early emergence in spring. Seedlings can emerge from a soil depth of less than 1 cm (Bassett and Crompton 1978). At seedling stage, it has two long cotyledons and ovate shaped opposite true leaves. Later, these leaves become alternate, purplish and get covered with whitish granules. Mature plants have triangular-shaped broad leaves with irregular toothed margins. These are about 15 cm long, smooth, stalked, rhombic and covered with small white scales, especially on the lower surface (Srivastava 1967). *C. album* has a short vegetative phase and completes its life cycle rapidly to produce a large number of viable seeds (Huang et al. 2001).

Chenopodium murale is an herbaceous plant with the ability to grow in a wide range of soil types (Mitic et al. 2012). The plant grows up to 0.6 m tall and the stem is about 3–10 cm long, usually branched, pubescent particularly on immature parts, and rarely dense (Anonymous 2017). Leaves are variable, 1.5–9.0 cm long, 0.8–5.0 cm wide, rhombic-ovate, pubescent, irregular and with toothed margins. Flowers form a small, glomerule-dense group in the form of cyme. Seeds are black, not much shiny, 1.2–1.5 mm in diameter and horizontal (Mitic et al. 2012). Flowers are green when immature but become reddish at maturity. These are hermaphrodite and are pollinated by wind. The brownish fruit encloses the seeds and falls with the seeds (Lamp and Collet 1990). The germination of *C. murale* occurs from spring to autumn. Cotyledons

are long but with a round tip. The first pair of leaves are opposite which become alternate later at maturity just like *C. album* leaves (Anonymous 2017). In contrast to *C. album*, the mature plant of *C. murale* is bushy and has an unpleasant smell when crushed.

Seed biology and germination ecology

Chenopodium album self-propagates by seeds in most of the soil types and has a strong taproot (Bassett and Crompton 1978). Being very small, the seeds of *C. album* easily cause contamination in crop grains harvested from common fields, thus contributing to its propagation (Holm et al. 1977). A mature plant of *C. album* can produce more than 70,000 seeds which are not dispersed by any specific way and most of them shatter on the soil surface near the plants (Bassett and Crompton 1978). These seeds have zero buoyancy but are washed away by surface water and can travel long distances due to their light weight and small size (Curran et al. 2012). Birds and animals also cause seed dispersal. Two different morphs of seeds are produced by *C. album* (Yao et al. 2010). Some of the seeds have a brown seed coat which can germinate immediately after dispersal from the parent plant. The rest of the seeds have a black seed coat which remain dormant (Yao et al. 2010). Total seed protein, mass, seed morphology, germination ability and dormancy behaviour of both morphs are quite different (Yao et al. 2010). Soil seed bank accumulation makes *C. album* a successful weed species. Toole and Brown (1946) reported that *C. album* could germinate even after 39 years. Stokes and Rowley-Conwy (2000) described that an excessive concentration of present seeds in Europe is from the Bronze Age. Seeds produced during short days have more viability as compared to those produced during long days (Bassett and Crompton 1978; Medina 1996). Little is known about the soil seed bank dynamics of *C. murale.*

Germination of *C. album* starts in late autumn and continues to mid spring. Germination may occur across a wide range of temperatures (5–30 °C) which allows its establishment in diverse geographic conditions (Bhowmik 1982; Tanveer et al. 2009). *C. album* is a salt-tolerant species having the ability to germinate and grow successfully under saline conditions (Yao et al. 2010). In China, more than 50% seeds of *C. album* were brown coloured and germinated normally under a very high sodium chloride concentration of 300 mM (Yao et al. 2010). Bhowmik (1982) reported that *C. album* biotypes, susceptible and resistant to triazines, grew better at 25 °C than at 30 °C. The susceptible biotype produced more dry matter at 42 days after planting and flowered earlier and faster than the resistant biotype. The results demonstrated that the susceptible type exhibited its competitive superiority over the other biotypes. Regardless of the temperature, the competitive advantage of the susceptible biotype explains its

ecological fitness as a superior biotype over the resistant biotype in agro-ecosystems.

As compared to *C. album*, *C. murale* has only one type of seeds, i.e. black. The growth season of *C. murale* ranges from late autumn through summer and it has a high rate of seed dispersal (Anonymous 2017). The number of seeds produced reaches to 24,000 seeds per plant (Holm et al. 1977). *C. murale* can grow under the temperature range of 5–45 °C (Khanna-Chopra and Sabarinath 2004). The ability to survive and reproduce under heat stress makes *C. murale* a strong and well-adapted species (Sundaram et al. 2009). *Chenopodium album* and *C. murale* possess unique biological features which enable them to adapt to a wide range of environmental conditions. *C. album* is more vigorous and flexible in its growth pattern and adaptability, and therefore, it is widespread across the agro-ecosystems.

Impacts on crop production

Chenopodium album and *C. murale* interfere directly with crop production through resource competition and their allelopathic effects. Both these species successfully adapt to harsh edaphic environments, especially saline and dry conditions. Moreover, these species act as an alternate host of several important crop pests and, therefore, impact crop growth and yields indirectly.

Competition

Chenopodium album is a competitive weed species which infests potentially all crops, especially annual row crop (Williams 1964; Holm et al. 1977). Several studies have reported substantial yield losses caused by *C. album* in different crops (Table 1). It has been reported as a major weed of maize crop in several European countries (Demjanová et al. 2009; Glowacka 2011; Keller et al. 2014). At initial stages, maize growth is relatively slow allowing *C. album* to absorb more nutrients which ultimately causes reductions in crop yield (Keller et al. 2014). *C. album* caused up to 100% yield losses in maize, depending upon the environmental factors over the period of 2 years (Fischer et al. 2004). In a weed–crop competition study, *C. album* density increased with increasing weedy duration in black seed (*Nigella sativa* L.) crop (Nadeem et al. 2013). Increased competition durations also caused an increase in *C. album* biomass and a substantial decrease in black seed crop yield (Nadeem et al. 2013). Moechnig et al. (2003) used an empirical model to characterise the competitive ability of *C. album* and *Setaria faberi* Herrm in a maize crop. Several parameters indicated *C. album* as the dominant competitor of maize. Another study suggested that *C. album* plants need to be controlled no later than a three-leaf stage and kept below 40 plants m^{-2} to avoid
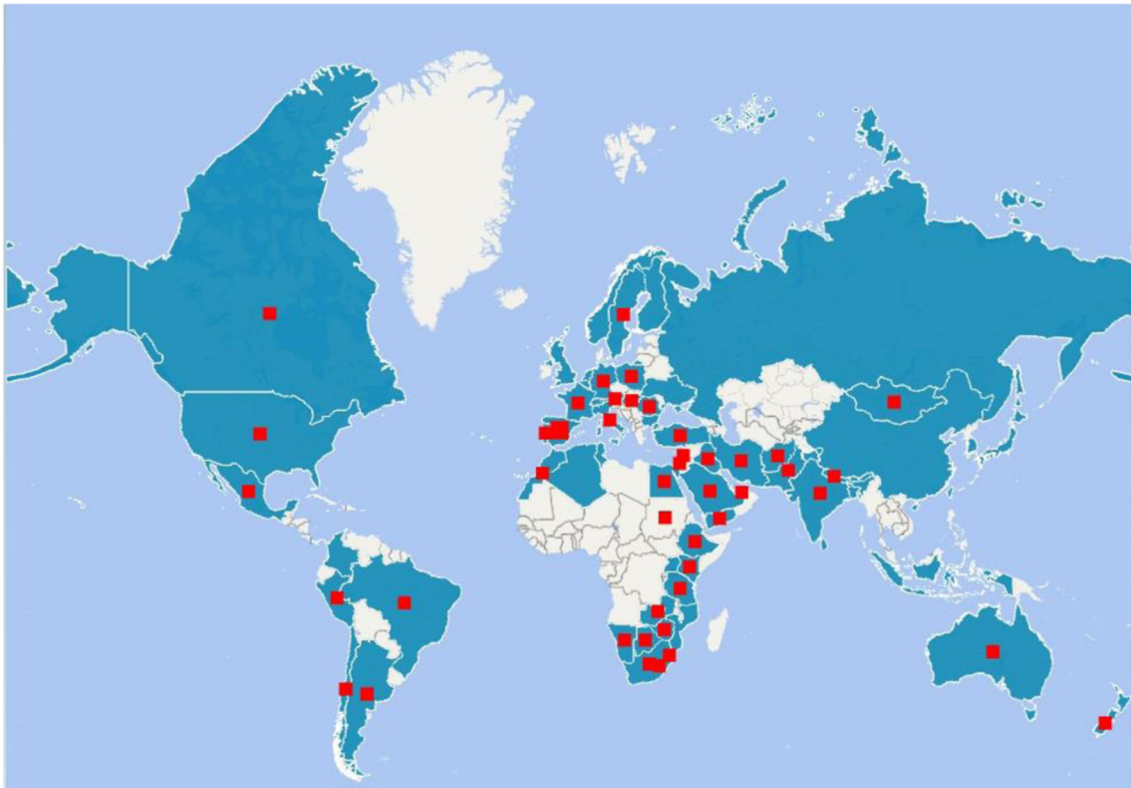
Fig. 1 The present distribution of *Chenopodium album* and *Chenopodium murale* in different countries across the world (Anonymous 2017). Dark blue shade represents the areas of *C. album* distribution and red rectangles represent the areas of *C. murale* distribution

economic yield losses in maize (Golebiowska and Kieloch 2016). In tomato, *C. album* did not affect tomato shoot dry weight at the vegetative stage but decreased the weight at the early fruit stage. Season-long interference of *C. album* plants reduced marketable tomato fruit number and marketable fruit weight ranging from 17% at 16 plants per m to 36% at 64 plants per m in a row (Bhowmik and Reddy 1988).

Chenopodium murale is also a very competitive weed species, but studies on its competition dynamics in cropping systems are lacking. Vigorous growth, high reproductive capacity, adaptive ability and efficient use of resources make *C. murale* a successful competitor in natural vegetation and crops. It is also a universal weed which has been reported to infest a large number of crops across more than 57 countries (Holm et al. 1977). Some studies have reported yield losses caused by *C. murale* in different crops (Table 1). *C. murale* was reported to efficiently absorb major nutrients, including nitrogen, phosphorus and potassium in tomato crop (Qasem 1992). In a greenhouse experiment, *C. murale* substantially suppressed the growth and yield of chilli pepper (*Capsicum annum* L.) (Omezine 2017).

It is clear from the above-mentioned information that *C. album* and *C. murale* strongly impact the crop growth and yield through resource competition. These weed species should be kept below economic threshold levels to avoid substantial crop yield losses.

Allelopathic effects

Plants can affect the growth and development of neighbouring plants negatively or positively by releasing secondary metabolites/allelochemicals in the environment (Farooq et al. 2013). *C. album* and *C. murale* are known to be allelopathic weed species. These species release allelochemicals into the soil which cause germination and growth inhibition of neighbouring plants. The extracts from various plant parts of *C. album* contain major allelochemicals, including alkaloids, aldehydes, apocarotenoids, steroids, flavonoids, clerogenic acid xyloids and saponins (Rezaie et al. 2008). These compounds could decrease yield extensively by affecting the major physiological processes of crop plants (Farooq et al. 2013).

Different studies have reported the negative effects of *C. album* allelochemicals on the germination and early seedling growth of wheat, radish [*Raphanus raphanistrum* subsp. *sativus* (L.) Domin], carrot (*Daucus carota* subsp. *sativus*), squash (*Cucurbita moschata* L.) and safflower (*Carthamus tinctorius* L.) (Qasem 1995; Batish et al. 2006; Rezaie and Yarnia 2009). Caussanel and Kunesch (1979) reported that *C. album* inhibited the root elongation and growth of maize seedlings by releasing an allelochemical, oxalic acid. Bhowmik and Doll (1982) also found similar results for soybean. The presence of residual material of *C. album* in soil resulted in growth reduction of wheat and other crops (Bhatia

Table 1 Yield losses due to *Chenopodium album* and *Chenopodium murale* in different crops

Crop	Yield loss (%)	Reference
Chenopodium album		
Barley	23	Conn and Thomas (1987)
Barley	36	Conn and Thomas (1987)
Wheat	16	Holm et al. (1977)
Wheat	40	Oad et al. (2007)
Wheat	23	Siddiqui et al. (2010)
Maize	12	Beckett et al. (1988)
Maize	58	Sibuga and Bandeen (1980)
Maize	70	Sarabi et al. (2013)
Soybean	15	Shurtleff and Coble (1985)
Soybean	20	Crook and Renner (1990)
Soybean	61	Conley et al. (2003)
Sugar beet	48	Schweizer (1983)
Sugar beet	86	Holm et al. (1977)
Sugar beet	93	Kropff and Spitters (1991)
Tomato	17	Bhowmik and Reddy (1988)
Chenopodium murale		
Garlic	78	Qasem (1996a)
Tomato	33	Qasem (1997)
Onion	92	Edim (2009)

et al. 1984; Reinhardt et al. 1994, 1997). *C. album* exudates were reported to suppress the growth of nitrification bacteria and *Rhizobium* spp. (Mallik and Tesfai 1988).

Chenopodium murale is also reported to be strongly allelopathic due to the presence of allelopathic lipids, essential oils, alkaloids, flavanols, glycosides, coumarins and saponins (El-Sayed et al. 1999; Ibrahim et al. 2007; Ghareib et al. 2010). Plant residues of *C. murale* released the phenolic compounds such as ferulic acid, protocatechuic acid, syringic acid and *p*-coumaric acid, which negatively affected the nodulation and growth of pea (*Pisum sativum* L.) and chickpea (Batish et al. 2007a). *C. murale* inhibits the germination and growth of several agronomic and vegetable crops (Datta and Ghosh 1982; Qasem 1995). Al-Johani et al. (2012) observed that the aqueous extracts of *C. murale* negatively affect the plant height, tillers, leaves and fresh and dry weight of barley. Similar results were reported for rice (*Oryza sativa* L.) crop which was affected by toxic phenolic compounds released by *C. murale* (Alam and Shaikh 2007). The seeds of *C. murale* have also been reported to possess certain allelochemicals (Qasem 1990). *C. murale* affected the wheat growth negatively by releasing the phenolic acids (benzoic, vanillic, *p*-coumaric and ferulic acids) in the rhizosphere (Batish et al. 2007b). It was also suggested that *C. murale* roots that remain in the soil even after eradication of the aerial plant parts may release some chemical compounds harmful to the growth of associated crops (Batish et al. 2007b).

The allelopathic potential of these species contributes significantly towards their interference with crop production. Understanding the modes of release of major allelochemicals of *C. album* and *C. murale* will help in evaluating their interference mechanism.

Alternate host of crop pests

Chenopodium album acts as an alternate host of several crop pests and pathogens (Bassett and Crompton 1978; Curran et al. 2012). It has been reported to harbour some fungi (*Stagonospora atriplicis* Lind and *Polymyxa betae* Keskin) that host disease-causing viruses (Abe and Ui 1986; McKenzie and Dingley 1996). *C. album* also hosts beet yellows virus, peanut stunt cucumovirus, potato viruses M and S and prunus necrotic ring spot virus which cause diseases in sugar beet, peanut, potato and *Prunus* spp., respectively (Stevens et al. 1994; Gillaspie and Ghabrial 1998; Sharma et al. 1998).

Chenopodium album was also reported as an alternate host for a root-knot nematode (*Meloidogyne hapla*) which caused severe disease in carrot (Bélair and Benôit 1996). This weed species also hosts potato root-knot nematode (*Ditylenchus destructor*) enabling it to survive between the crop seasons (De Waele et al. 1990). The sugar beet root aphid (*Pemphigus betae* Doane) has also been reported to complete its life cycle on cottonwood tree (*Populus angustifolia* James) and the roots of *C. album* (Moran and Whitham 1988). Similarly, the beet leafhopper (*Circulifer tenellus* Baker) and the common stalkborer (*Papaipema nebris* Guenée) also use *C. album* as an alternate host before damaging the sugar beet, tomato and maize crops (Anonymous 2017).

There is no information available on the role of *C. murale* as an alternate pest host; however, this aspect is worth to explore. Such information will be valuable for integrated pest management in any cropping system.

Management

Extensive research has been done on the management of *C. album* and *C. murale* around the world, but still these species are amongst the most problematic weeds in different crops. It is due to their rapid growth, strong interference ability and evolutionary adaptations. The following methods are used to control these weed species mainly in cropped areas with varying degrees of efficacy.

Cultural and mechanical strategies

Management of weeds through cultural methods is considered as 'many little hammers' approach, which can be used as an alternative of chemical control (Bhowmik and Inderjit 2003;

Bajwa et al. 2015, 2017a). A variety of cultural methods have been reported to control *C. album* and *C. murale*. These weeds can be controlled by crop rotations, tillage and cover crops (Weber et al. 2017). Crop rotation proved effective to manage *C. album* in wheat crop (Balyan et al. 1988). The introduction of perennial crops in a wheat-based annual cropping system reduced the soil seed banks of *C. album* and *C. murale* (Archibold 1981). Mulch of hairy vetch notably inhibited the establishment of *C. album* without affecting the establishment of maize crop (Teasdale 1993). Heidari et al. (2011) reported that high crop density and narrow row spacing in sugar beet reduced *C. album* emergence and density. A double row planting pattern of maize crop was found to be more effective in suppressing *C. album* as compared with a single row planting pattern (Saberali 2008). However, this practice may not be feasible to adopt under field conditions in most cases. Manual weeding of *C. album* 20 days after sowing of Indian mustard (*Brassica juncea* L.) was found to be effective in terms of minimising the crop yield losses (Gogoi and Kalita 1995). Similarly, earthing-up and hand weeding controlled *C. album* in potato (Jaiswal 1994). Mowing also provided about 50% control of *C. album* (Randall 1996).

The emergence of *C. murale* could be greatly suppressed by intercropping legumes in maize (Sharma and Banik 2013). Intercropping of barley with pea substantially reduced *C. album* density and biomass and increased the barley yield (Corre-Hellou et al. 2011). Green manure cover crops such as oregano (*Origanum vulgare* L.), dill (*Anethum graveolens* L.), anise (*Pimpinella anisum* L.) and fiddleneck (*Lacy phacelia* L.) suppressed *C. album* in maize (Dhima et al. 2009). The use of cereals as cover crops can also inhibit the germination and seedling growth of *C. album* and *C. murale* (Przepiorkowski and Gorski 1994; Burgos and Talbert 1996). The use of some aromatic crops for green manuring also provided up to 92% control of *C. album* and other broad-leaved weeds of maize (Dhima et al. 2006). The barley and rye (*Secale cereale* L.) cover crops provided about a 79% control of *C. murale* (Weber et al. 2017).

Manipulating tillage and sowing methods can also help to manage *C. album* and *C. murale*. Reduced tillage systems reduced the germination of small-seeded weeds like *C. album* and *C. murale* (Gruber and Claupein 2009). The infestation of *C. album* was reduced in a zero-tillage system as compared to a conventional tillage system (Mishra and Singh 2012). The density of *C. album* was the lowest in a wheat crop when grown after the puddled-transplanted rice (Farooq and Nawaz 2014). The stale seedbed method has also been reported to be effective in controlling *C. album* and *C. murale* (Fennimore and Jackson 2003). Thermal approaches like solarisation and flaming have also been used to control *C. album* and *C. murale* (Ascard 1995). Solarisation reduced the germination of *C. album* and *C. murale* by up to 100% from the soil seed bank (Satour

et al. 1991; Arora and Yaduraju 1998). Flaming at 2–4 and 6–12 leaf stages reduced *C. album* density by 95% (Ascard 1995).

Chenopodium album responds efficiently to mineral fertilisers and, therefore, competes with crop plants (Di Tomaso 1995; Blackshaw et al. 2003, 2004a). The emergence of *C. album* and *C. murale* can be decreased by up to 50% by optimum placement (band placement) and timing of nitrogenous fertiliser, particularly in no-till cropping systems (Blackshaw et al. 2004b). Another study showed that yield losses due to *C. album* interference were high in lettuce (*Lactuca sativa* L.) when phosphorus was broadcasted as compared to band placement beneath lettuce rows (Santos et al. 2004). Therefore, it is important to keep fertiliser management in mind while designing an integrated management strategy for *C. album* and *C. murale*.

Allelopathy

Allelopathy has been proposed as a potential weed management tool in agro-ecosystems (Bhowmik and Inderjit 2003; Farooq et al. 2013; Bajwa 2014; Rehman et al. 2018). Some laboratory and field studies have shown that the application of allelopathy in different ways can help to control *C. album* and *C. murale*. Anjum and Bajwa (2007) reported that the sunflower (*Helianthus annuus* L.) leaf extracts inhibited the germination and growth of *C. album* in a sunflower crop. A combined application of sorghum and sunflower extracts in sunflower crop reduced *C. album* density by up to 84% and increased the crop yield by 16% (Awan et al. 2009). The foliage application of sorghum water extracts reduced *C. album* density and biomass by 15–47 and 49%, respectively, in a wheat crop (Cheema and Khaliq 2000). Cheema et al. (2001) reported that the application of sorghum water extracts in mungbean [*Vigna radiata* (L.) R. Wilczek] reduced *C. album* density by 18–32% and improved the crop yield by 18%. Some of the major allelochemicals reported in the sorghum water extracts included *p*-coumaric acid, *m*-coumaric acid, syringic acid, benzoic acid, ferulic acid, gallic acid, phydroxybenzoic acid, vanillic acid, caffeic acids, protocateuic acid, phydroxybenzaldehyde and sorgoleone (Ahmad et al. 1991). These allelochemicals were associated with germination and growth inhibition of *C. album* (Ahmad et al. 1991).

The aqueous extracts of eucalyptus (*Eucalyptus camaldulensis* Dehnh) also suppressed the growth of *C. album* seedlings (Khan et al. 2007). The aqueous extracts of wheat and rye reduced radicle growth of *C. album* (Younesi et al. 2008). Similarly, leaf and stem extracts of a medicinal plant, heart-leaved moonseed [*Tinospora cordifolia* (Thunb.) Miers], also inhibited the germination and seedling growth of *C. album* and *C. murale* (Batish et al. 2007a; Abdul Raoof and Siddiqui 2012). El-Khatib (2000) reported that the aqueous extracts of camelthorn (*Alhagi graecorum* Boiss.) effectively

suppressed *C. murale* germination and growth. Qasem (2002) screened 30 medicinal plants to identify their herbicidal activities against *C. murale*. About eight of the tested species were found to be highly toxic against *C. murale* (Qasem 2002). The inhibitory effect increased with an increasing concentration of the extracts.

Residue mulches of hairy vetch (*Vicia villosa* Roth), subterranean clover (*Trifolium subterraneum* L.) and oat (*Avena sativa* L.) effectively controlled the density of *C. album* in black pepper (*Piper nigrum* L.) and tomato (Campiglia et al. 2012). Rye and buckwheat (*Fagopyrum esculentum* Moench) residues reduced the emergence and growth of *C. album* and *C. murale* and some other weed species by releasing phytotoxic compounds (Putnam and DeFrank 1983). Growth of *C. album* was suppressed when a mulch of two *Brassica* spp. was used that released a large amount of potent allelochemical glucosinolates (Peterson et al. 2001). The use of allelopathic rye as a cover crop in soybean suppressed *C. album* effectively (Bernstein et al. 2014). Barnes and Putnam (1983) reported that a spring-planted rye crop reduced the density of *C. album* by 40–98% over the non-treated control. Similarly, Dyck and Liebman (1995) reported that the incorporation of crimson clover (*Trifolium incarnatum* L.) residues reduced the density of *C. album*. It also reduced *C. album* biomass by 36–65% and increased the maize yield (Dyck and Liebman 1995). Wheat straw residues and leachates also reduced the germination and growth of *C. album* (Ramakudzibga 1991). Overland (1966) reported similar results from barley crop residues. The use of white mustard (*Sinapis alba* L.) residues significantly controlled the population of *C. album* (Alcantara et al. 2011).

The application of allelochemicals through mulching, residue incorporation and foliage spray has provided an effective control of *C. album* and *C. murale*. However, further research is required to optimise the nature and dose/rate of allelopathic materials under field conditions.

Biological control

Chenopodium album and *C. murale* have several natural enemies (insects and pathogens) in their native range. Some of them have been successfully tested as a biological control agent for *C. album* but none for *C. murale*. A plant pathogenic fungus [*Ascochyta caulina* (P. Karst) v.d. Aa and v. Kest] has shown very promising results against *C. album* (Scheepens et al. 1997; Netland et al. 2001). Major phytotoxins extracted from this fungus were ascaulitoxin, trans-4-amino-D-proline and the aglycone of ascaulitoxin (Netland et al. 2001). All these toxins showed high efficacy and herbicidal activity against *C. album* under glasshouse conditions (Netland et al. 2001). These toxins cause severe necrosis in the leaves and stems, leading to mortality of *C. album* plants (Kempenaar et al. 1996).

In another study, Vurro et al. (2001) tested the toxins and spores of *A. caulina* alone and in combination with herbicides and reported a synergistic effect which provided effective control of *C. album*. Ghorbani et al. (2002) reported that a high nitrogen supply improved the efficacy of *A. caulina* toxins against *C. album*. At high nitrogen availability, an increase in the necrotic lesions was observed, which caused greater biomass reduction of *C. album* plants. Recently, another fungus (*Phoma chenopodiicola* Gruyter, Noordel. & Boerema) has been proposed as a potential biocontrol agent for *C. album* (Evidente et al. 2015). Major phytotoxins associated with this species include chenopodolin, chenopodolans A–C, chenopodolin B, chenopodolan D and chenisocoumarin (Cimmino et al. 2013a, 2013b; Evidente et al. 2015). Similarly, the fungus species, *Stagonospora vitensis*, also caused necrosis and mortality in *C. album* (Ogut et al. 2012). Although these biocontrol agents have shown promising results under controlled conditions, their application under field conditions and commercialisation is challenging (Shabbir et al. 2018).

Chemical control

Herbicides provide the most effective and economical control of *C. album* and *C. murale*, similar to most of the weed species. Various herbicides have been used successfully to control *C. album* and *C. murale* over the years (Table 2). The application 2,4-D and dicamba in wheat provided maximum control of *C. album* (Malik et al. 1992). Flourodifen and oxadiazon applied as post-emergence in onion controlled *C. album* and *C. murale* (Porwal and Singh 1993). The combinations of bromoxynil with pendimethalin provided effective control of *Chenopodium* and other broad-leaved species in wheat (Tag-El-Din et al. 1989). In a 3-year study, cinmethylin applied pre-emergence alone at 0.6, 0.8 and 1.0 kg a.i ha^{-1} or in combination with metribuzin at 0.3 kg ha^{-1} controlled over 90% *C. album* and *Amaranthus retroflexus* L. and many grass species (Bhowmik 1988). Monks et al. (1993) controlled *C. album* effectively in soybean with thifensulfuron. *C. album* along with other broad-leaved weeds was controlled effectively by pre-emergence application of flumeturon + pendimethalin followed by early post-emergence application of glyphosate in an ultra-narrow row cotton crop (Culpepper and York 2000). Post-emergence application of mesotrione (150 g ha^{-1}) in maize provided an excellent control (95%) of *C. album* (Pannacci and Covarelli 2009).

Chenopodium murale was effectively controlled (80%) by bromoxynil plus MCPA (450 + 130 g ha^{-1}) in wheat crop (Hayyat et al. 2016). The application of oxadiazon and oxyflourfen as post-emergence in garlic at the 4–6 leaf stage effectively controlled *C. murale* and resulted in higher garlic production (Qasem 1996b). Trabulsi and Abul-Hayja (1982) reported that dinitramine, diphenamid and metobromuron were effective against *C. murale* in tomato. Methabenzthiazuron

Table 2 Chemical control of *Chenopodium album* and *Chenopodium murale*

Herbicide	Dose (g a.i ha^{-1})	Time of application	Crop	Control (%)	References
Chenopodium album					
Cinmethylin	600	PRE	Soybean	95	Bhowmik (1988)
Cinmethylin + metribuzin	700 + 300	PRE	Soybean	100	Bhowmik (1988)
Fluchloralin	1000	PPI/PRE	Field mustard (*Brassica compestris* L.)	36–45	Brar et al. (1991)
Nicosulfuron + 2,4-D	35 + 280	PRE	Maize	97	Glenn et al. (1997)
Flumioxazin	110	PRE	Peanut	99	Shawn et al. (1999)
Prometryn	1500	PRE	Potato	46	Eleftherohorinos et al. (2000)
Isoxaflutole	35	PRE	Maize	100	Chomas and Kells (2004)
Flumetsulam	53	PRE	Maize	100	Chomas and Kells (2004)
Pendimethalin	1100	PRE	Maize	98	Chomas and Kells (2004)
Metachlor	1400	PRE	Maize	75	Chomas and Kells (2004)
Imazapyr + imazapic	20 + 60	POST	Maize	64	Alister and Kogan (2005)
Clomazone	240	POST	Tomato	80	Nurse et al. (2006)
Halosulfuron	18	POST	–	95	Isaacs et al. (2006)
Mesotrione	150	POST	Maize	95	Pannacci and Covarelli (2009)
Pendimethalin + atrazine	1680 + 1530	PRE	Maize	91	Stewart et al. (2012)
Rimsulfuron + S-metolachlor/benoxacor + dicamba	15 + 684 + 360	PRE	Maize	100	Stewart et al. (2012)
Nicosulfuron + prosulfuron + dicamba	25 + 10 + 140	POST	Maize	98	Stewart et al. (2012)
Glyphosate	900	POST	Maize	94–100	Stewart et al. (2012)
Foramsulfuron + dicamba/diflufenzopyre	70 + 200	POST	Maize	100	Stewart et al. (2012)
Fluroxypyr + MCPA	450 + 30	POST	Wheat	80	Hayyat et al. (2016)
Triasulfuron	30	POST	Wheat	81	Hayyat et al. (2016)
Chenopodium murale					
S-metolachlor	720	PRE	Spinach	97	Fennimore et al. (2001)
Oxadiazon	750	PRE	Onion	57	Qasem (2006)
Oxyfluorfen	600	PRE	Onion	68	Qasem (2006)
Diphenamid	3750	PRE	Onion	–	Qasem (2006)
Paraquat	20	POST	Onion	60	Qasem (2006)
Oxyflourfen	2000	PPI	Cauliflower	82	Qasem (2007)
Nitrofen	1400	POST	Cauliflower	87	Qasem (2007)
Trifluralin + isoproturon	300 + 500	PRE	Canola	–	Miri and Rahimi (2009)
Bromoxynil + MCPA	450 + 30	POST	Wheat	81	Hayyat et al. (2016)
Clopyralid	525	POST	Wheat	50	Hayyat et al. (2016)

a.i, active ingredient; *PPI*, pre-plant incorporation; *PRE*, pre-emergence; *POST*, post-emergence; –, not available

provided an effective and economical control of *C. murale* in potato (Maliwal and Jain 1991). In wheat, *C. murale* was effectively suppressed by trisulfuran (Biljon et al. 1988). Pendimethalin as pre-emergence proved very effective against *C. murale* and helped to improve the crude protein contents in grains (Maliwal and Gupta 1989). Application of chlorotoluron at the 3–4 leaf stage provided 90% control of *C. murale* and

enhanced grain yield of wheat by 30–70% (Fazali and Muhammad 1991). Cyclotate in sugar beet and tebutryn in cumin were also reported to be very effective against *C. murale* (Chaudhary and Gupta 1991).

Herbicide resistance Continuous and non-judicious use of herbicides has led to resistance evolution in *C. album*.

Fortunately, there is no registered case of herbicide resistance in *C. murale*. Globally, 47 herbicide resistance cases in *C. album* have been reported to date (Table 3) and almost half of them are from the United States of America (USA; Heap 2018). *C. album* is resistant to several PS-II and ALS inhibitor herbicides. The most common and widespread resistance in this species is against atrazine (33 cases) and in maize crops (35 cases; Heap 2018). The first case of herbicide resistance (against atrazine) in *C. album* was reported in 1973 from Canada (Bandeen and McLaren 1976). In the USA, most of the triazine-resistant populations of *C. album* were found to be present in the east of the 'Dairy belt', where maize has been grown for several years in the same place without rotation and triazines were used consistently to control weeds (Curran et al. 2012). Triazines can persist longer in the soil which increases the selection of resistant biotypes (Curran et al. 2012).

The expansion of reduced or no-till farming practices resulting in less use of mechanical control has also contributed significantly towards herbicide resistance evolution in *C. album* (Norsworthy et al. 2012). *C. album* has also evolved resistance against some ALS inhibitors (thifensulfuron-methyl, tribenuron-methyl and imazamox) and synthetic auxin (dicamba, aminopyralid and clopyralid) herbicides (Heap 2018). *C. album* was less sensitive to the ioxynil as compared to other broad-leaved weed species in an onion crop (Dejam et al. 2010). It was also more tolerant to oxadiazon as compared to oxyfluorfen (Mirshekari and Karimi 2015).

Herbicide management to avoid resistance Herbicide resistance evolution in *C. album* has been rapid and consistent. However, a careful selection of herbicides and their judicious use may help to manage herbicide-resistant populations of *C. album*. Wrubel and Gressel (1994) reported that a mixture of chloroacetamide and triazine was effective to prevent resistance in *C. album* for 20 years. Parks et al. (1995) reported that in maize, atrazine-resistant biotypes of *C. album* could be managed by integration of mechanical cultivation and the application of herbicides at reduced rates. Similarly, tank mixtures of the reduced doses of nicosulfuron and mesotrione ensured above 90% control of *C. album* and other broad-leaved weeds in maize (Skrzypczak et al. 2011). However, the use of reduced doses of herbicides (lower than recommended rates) carries a huge risk of non-target site herbicide resistance evolution and, therefore, must be avoided. A tank mixture of imazethapyr and bentazone controlled triple resistant biotypes (atrazine–pyrazon–pyridate) of *C. album* in common bean (*Phaseolus vulgaris* L.) (Solymosi and Lehoczki 1989). In a recent study, Rahman et al. (2014) suggested a post-emergence application of bromoxynil, mesotrione, nicosulfuron and pyridate for the effective control of both dicamba-susceptible and resistant *C. album* biotypes.

The herbicide resistance issue should be tackled by reducing the reliance on the sole use of chemicals. Further research is needed to explore suitable herbicide combinations and their rotational use against *C. album* and *C. murale*.

Integrated management

Integrated weed management (IWM) strategies are more reliable and always effective in every cropping system (Sanyal et al. 2008; Bajwa et al. 2015, 2017b). *C. album* has been successfully managed by using IWM approaches. For instance, the

Table 3 Global status of the herbicide resistance in *Chenopodium album*

Herbicide	Site of action	Crops	Countries
Atrazin	Photosystem II (PS-II) inhibitor	Maize, potato, sugar beet, soybean	Belgium, Canada, Czech Republic, France, Italy, Netherlands, New Zealand, Poland, Portugal, Slovenia, Spain, Switzerland, USA
Metribuzin	PS-II inhibitor	Maize, potato, sugar beet, soybean	Belgium, Bulgaria, Greece, Norway, Sweden, USA
Simazine	PS-II inhibitor	Maize, potato, sugar beet, soybean	Czech Republic, Germany, United Kingdom (UK), USA
Metamitron	PS-II inhibitor	Maize, potato, sugar beet	Belgium, Poland, Sweden
Cyanazine	PS-II inhibitor	Maize, sugar beet, soybean	Czech Republic, USA
Lenacil, prometon, terbutryn, terbuthylazine	PS-II inhibitor	Maize, sugar beet	Czech Republic
Linuron	PS-II inhibitor	Not available	Norway
Terbacil	PS-II inhibitor	Potato, mint (*Mentha spicata* L.)	USA
Thifensulfuron-methyl	Acetolactate synthase (ALS) inhibitor	Soybean, barley, wheat,	Canada, USA
Tribenuron-methyl	ALS inhibitor	Barley, wheat	Canada, Finland
Imazamox	ALS inhibitor	Soybean	USA
Aminopyralid, clopyralid, dicamba	Synthetic auxin	Maize	New Zealand

Source: The table is based on information from Heap (2018)

application of pendimethalin along with two hoeings effectively controlled *C. album* in fenugreek (*Trigonella foenum-grpcum* L.) (Maliwal and Gupta 1989). The application of sorghum and brassica extracts along with a reduced dose of pendimethalin controlled *C. album* (42–91%) with a 40% increase in canola yield (Jabran et al. 2008, 2010). Pannacci and Covarelli (2009) reported that harrowing along with the reduced rates of nicosulfuron (one-third of the labelled dose of 140 g a.i ha^{-1}) and mesotrione (two-thirds of the labelled dose of 60 g a.i ha^{-1}) effectively controlled *C. album*. Rao et al. (2009) reported that a pre-emergence application of atrazine (1.5 kg ha^{-1}) followed by hand weeding 30 days after sowing (DAS) of maize gave the highest control of *C. album* with the highest net monetary benefit. However, this is a specific relation between control rate and the cost of hand weeding.

Another study showed that *C. album* can be effectively controlled by pre-emergence application of alachlor (3 kg a.i ha^{-1}) along two hand weedings (20 and 40 DAS; Alok and Bhagwan 2007). Similarly, Dobariya et al. (2014) reported that hand weeding and intercultural operations at 30 DAS with a pre-emergence application of atrazine (0.5 kg a.i ha^{-1}) in maize provided excellent control of *C. album*. Vurro et al. (2001) reported that the simultaneous application of the spores or toxins of fungus, *A. caulina*, and reduced doses of metribuzin and rimsulfuron provided better control of *C. album* as compared to sole applications of bioherbicides or chemical herbicides. In another study, Ogut et al. (2012) reported that the biocontrol agents (*A. caulina* and *S. vitensis* fungi) in combination with the reduced dose of nicosulfuron (12.5% of the recommended dose) provided an effective control of *C. album*. Research on integrated management of *C. murale* is very limited and should be done in the future.

Conclusions and future research directions

Chenopodium album and *C. murale* are widespread problematic weeds in different parts of the world. These species infest many crops and cause substantial yield reductions. Both these weed species produce a large number of seeds which may become dormant under unfavourable conditions. The seed bank of these species is highly persistent. The germination ability under a wide range of environmental conditions, vigorous growth habit, tall stature, high nutrient uptake capacity and the abiotic stress tolerance makes *C. album* and *C. murale* amongst the most competitive and difficult-to-control weeds in the cropping systems. These species also release several allelochemicals in their surroundings and, therefore, suppress the native vegetation and crop plants. Although significant research has been done on chemical and non-chemical control methods for these species, their rapid adaptive evolution makes the management task difficult. *C. album* has evolved resistance against many herbicides which are commonly used to control it. Therefore, more

research needs to be done on different aspects of biology and interference of *C. album* and *C. murale* to establish proper management tools for these species.

Future research on these two species should investigate their seed biology, the germination ecology and the morphophysiological traits contributing towards their invasiveness. Moreover, the role of allelopathy in crop interference of these species should also be elucidated under field conditions. Research on understanding the molecular bases of herbicide resistance in *C. album* may be further strengthened. Economic threshold levels of *C. album* and *C. murale* in different crops should be studied under different geographical conditions. It is clear from this review that IWM strategies are more successful in controlling *C. album*. However, the potential of different control methods should also be tested in combinations against *C. murale*. Innovative and non-conventional approaches such as the use of crop competition, biological control agents, allelopathy, solarisation, the precision control methods based on sensory and robotics techniques and strategic tillage should also be tested against these species under field conditions.

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