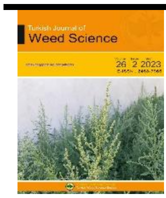

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Chenopodium album: A Review of Weed Biology, Status and The Possibilities for Biological Control

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ABSTRACT

The weed *Chenopodium album* can infest a number of agricultural systems due to its high reproductive capacity, seed dormancy, high persistence in the soil, ability to sprout and develop under adverse environmental circumstances, and other peculiar biological traits. This weed prevents the germination and/or growth of plants as well as native vegetation because of its allelopathic characteristics. Since they have the potential to reduce agricultural productivity by more than 90% and infest a wide variety of horticultural and agronomic crops, this weed poses a potential threat to food security worldwide. In consideration of these consequences, effective control measures are required. Various cultural, mechanical, and biological methods have been used to control *C. album* with variable degrees of success, depending on cropping systems and weed infestation levels. Since *C. album*'s widespread herbicide tolerance has decreased the efficiency of chemical management, biological control could be a potential management strategy. In this review, we have investigated and analyzed the up-to-date information regarding the biology, current status and possibilities of biological control of *C. album*.

Keywords: *Chenopodium album*, common lambsquarters, biological control, herbicide resistance

1. INTRODUCTION

Since the beginning of agriculture, weeds have been a constant issue. Because weeds compete with plants for resources like water, nutrients, and sunlight, they prevent crops from growing properly and significantly reduce agricultural yields (Monteiro & Santos, 2022). Weeds continue to cause yield losses ranging from 10 – 60% depending on the crop and environment. The global estimated loss potential of weeds in rice, wheat and maize indicates that weeds account for 46.2 % to 61.5% of potential losses, whereas 27.3 to 33.7% of actual losses are caused by all pests together (Yaduraju & Rao, 2013).

Chenopodium album is one of the top 10 most problematic weed species found in the world (Netland et al., 2001). The weed is native to Europe and Asia and likes subtropical, tropical, and temperate weather conditions. As a result, it remains in the group of most extensively distributed weeds around the globe (Tang et al., 2022). Most species in this genus have leaves that are shaped like goosefeet, therefore, they were given the name "Chenopodium," which comes from the Greek terms for goose (khen) and foot (pous) (CABI, 2022). The Latin word "album," which means "white," was used to name the plant for the granular substance found in its leaves (Curran et al., 2007). Because of some distinctive biological characteristics, *C. album* is able to thrive in a diverse array of environmental circumstances, including those pertaining to the moisture content, pH level, and temperature of the environment (Eslami & Ward, 2021).

There are a variety of common names for this difficult annual weed, including common lambsquarters, lambsquarters, fat-hen and white goosefoot. It competes with more than 40 crop species around the globe, and corn and soybean growers in the United States view it as a major weed (Asshleb, 2010). It causes severe harm all over the world to sugar beet, potato, and maize crops, as well as vegetables and grains. In Europe, where it is prevalent in many spring-sown crops, significant economic losses are documented (Cimmino et al., 2015). Herbicide resistance has evolved in *C. album* against various synthetic herbicides as a result of the overuse of chemical herbicides (Heap, 2022). After a number of environmental problems arose as a result of the negative effects of chemical herbicides, researchers began looking into alternative biological control systems against weeds by utilizing bioherbicides. To control weeds in the crop production system, biological control agents (BCAs), including pathogenic and non-pathogenic fungi and bacteria, may exhibit herbicidal activity (Harding & Raizada, 2015). The use of biological weed management using plant pathogens in crop production has various benefits, including the ability to target weeds selectively and with host-specificity, as well as the absence of negative environmental effects and non-target plant effects (Bo et al., 2020). Conversely, the process of identifying the exact BCAs that provide the intended impact can be challenging and time-intensive (Babendreier, 2008). Over the past 30 years, plant pathogenic microbes have been studied as a potential alternative to traditional weed management methods in Europe (Öğüt et al., 2012). Through scientific investigation, scientists have discovered several microbes that can successfully treat *C. album*. Based on the aforementioned information, it is crystal clear that *C. album* is one of the most important weeds based on the different context of modern agriculture. So, this review aims to investigate *C. album*'s biology, status and up-to-date knowledge of biological control management.

2. BIOLOGY

Weed biology knowledge is required for the development of weed control strategies that are both economically and ecologically acceptable. Plant characteristics, including morphology, seed dormancy and germination, growth physiology, and reproductive biology, are all relevant to weed biology (Qaderi, 2023). The distinct biology of *C. album* is given in the sections below.

2.1. Identification and life cycle

C. album is a weed that grows as an erect annual plant (Eslami & Ward, 2021). This plant's life cycle takes roughly 4 months to complete; however, it can take longer or shorter depending on the region, season, and photoperiod. **Figure 1** shows the life cycle of this weed. The emergence of *C. album* occurs often in the spring and summer (Tang et al., 2022), while germination begins in late autumn and lasts until mid-spring. Germination can take place at temperatures ranging from 5 to 30 °C (Bajwa et al., 2019). Despite the fact that it may grow in a variety of soil types, it thrives in rich soils and is more frequent when manured (Asshleb, 2010).

As a seedling, it has two cotyledons that are both long and linear (Coleman et al., 2018). Moreover, it has a dull green to gray hue, is oblong, and has no midvein (Plant & Pest Diagnostics, 2020). The true leaves, which are the first to develop, are shaped like ovate, and they appear in pairs that are opposite one another (Coleman et al., 2018). In an alternative configuration, the 5-sided stem is wrapped with spirally attached "goose-foot" shaped leaves. The lower surfaces of the leaves also exhibited white patches with a number of salt-containing glands (Glimn-Lacy & Kaufman, 2006). Mature leaves vary greatly in form from oval to trowel-shaped, with uneven lobes or teeth along the edge, and are 2–6 cm long. It comes in a wide range of hues, from blue-green to grey-green, and occasionally has a mealy (powdered) surface (Coleman et al., 2018). *C. album* has the ability to reach a height of up to 2 meters and has a thick taproot in addition to stems that are ridged and branch out (Eslami & Ward, 2021). The stems of mature plants have smooth or hairless surfaces, vertical grooves, and stripes of red, purple, or mild green (Curran et al., 2007; Plant & Pest Diagnostics, 2020). *C. album* is capable of flowering in any daylength; however, a photoperiod of 8 hours significantly accelerates flowering and maturity in the plant. This species is more widely spread in temperate zones and less so towards the equator because it grows larger and more vigorously under extended photoperiods (16 – 18 hours) (Kurashige & Agrawal, 2005). Despite not having enough time for a flowering hormone called "florigen" to be translocated from the mature leaves, when plants were subjected to a rapid change in day duration from long to shorter days, floral apices developed and blooming took place (Wagner et al., 2012). At the terminals of the stems, green, unnoticeable flowers grow in granular, thick clusters (Plant & Pest Diagnostics, 2020). *C. album* is mostly self-pollinating, but it is also capable of receiving pollen from other species through the wind (Aper et al., 2012). At maturity, the seed keeps its star-shaped papery covering, which is surrounded by floral segments (Coleman et al., 2018; Plant & Pest Diagnostics, 2020). The average seed output ranges from 3000 to 20,000 seeds per plant (CABI, 2022); however, over 150,000 seeds per plant have also been observed (Colquhoun et al., 2001). The seeds have a diameter of 1.5 mm, weight 1.2 mg, and range in shape from almost round to slightly oval (CABI, 2022; Eslami & Ward, 2021). When the papery casing is removed, the seeds reveal a smooth, shiny interior. The seeds are primarily black, with only around 3% of them being brown (Loades et al., 2023). The life cycle of *C. album* is brief, and it is finished quickly, resulting in a lot of viable seeds being produced (Bajwa et al., 2019). The weed has no specific seed dispersion mechanism (CABI, 2022) and relies only on seed for reproduction (Asshleb, 2010). Because the majority of *C. album* seeds fall near the mother plant, the crop grows in typical patches (Aper et al., 2010). As a result, the life cycle keeps going in this order.

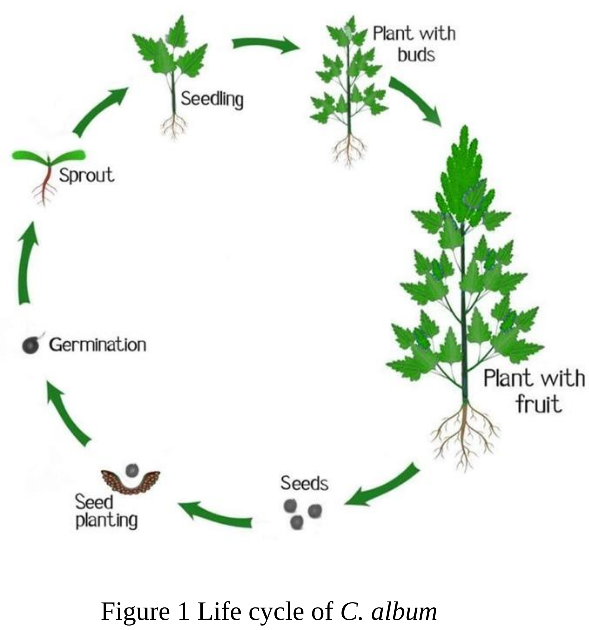

Figure 1 Life cycle of *C. album*

2.2. Seed biology and ecology

C. album has the potential to generate as many as 50 million seeds per hectare when it is heavily infested (Coleman et al., 2018). Abundant water stimulates C. album seed germination, whereas low soil moisture and high salinity inhibit it. The seeds can germinate under a wide variety of soil pH levels; therefore, this is not a limiting factor. Light also promotes the germination of these seeds (Tang et al., 2022). The seed morphologies exhibit variations in both size and seed coat color (black and brown). The internal composition is distinguished by the presence of a peripheral embryo and the variability in the thickness of the seed coat, which plays a crucial role in inducing physiological dormancy. In a broad sense, it was seen that the brown seeds exhibited a lack of dormancy and greater tolerance to salinity as compared to the dormant black seeds, which had the ability to create a long-lasting seed bank in the soil. These attributes give the species the ability to germinate in a variety of environmental situations, which may considerably increase its effectiveness as a successful weed (Loades et al., 2023). When a plant is stressed, the proportion of brown seeds it produces may rise, promoting quick germination and establishment under unfavorable conditions, such as salty soils (Yao et al., 2010). Black *C. album* seeds that have gone dormant can live for 30 to 40 years at a depth of more than 45 cm under the right circumstances (Yerka et al., 2012). Manure is seen as a potential source for transferring seed since the seeds may even survive well in the gastrointestinal systems of cows, horses and sheep (Coleman et al., 2018). Equipment transfer, animal excrement, and flowing water are a few of the ways that the disease spreads from one place to another (Coleman et al., 2018; Curran et al., 2007). In this way, increased seed production makes it easier for it to accumulate rich, long-lasting seedbanks, hence fostering the persistence of its population and fresh infestations in fields (Aper et al., 2012). Additionally, some *C. album* seeds become permeable shortly after seed dispersal, allowing them to sprout when conditions are ideal, while other seeds break their dormancy after the winter and can then germinate the following spring at typical habitat temperatures, providing a major and persistent issue for the whole crop growing season (Rahman et al., 2014; Werle et al., 2014). These special characteristics make *C. album* a serious crop competitor starting in the early development phases, which significantly lowers crop production and quality (Damalas & Koutroubas, 2022).

3. STATUS

Any weed species' status provides an overview of its distribution, interactions with crops, susceptibility to control tactics, and other factors. To get a complete understanding of the weed, must consider all of these characteristics. The sections below provide an overview of *C. album*'s current situation with regard to various crucial factors.

3.1. Geographical distribution

Its specific geographical origin is unknown, although archaeological evidence suggests that *C. album* was grown as a pseudo-cereal in Europe more than 3000 years ago (Stokes & Rowley-Conwy, 2002). Although it was reportedly a native of western Asia, plants inherent to eastern Asia are classified as *C. album*; however, they commonly vary from European examples (Bajwa et al., 2019). This weed has long been spread by humans, whether on purpose or accidentally. As a consequence, it has grown to be one of the most extensively spread weeds in the world, occurring from sea level to 3600 m and from latitude 70ºN to latitude 50ºS (Ardila-Barragán et al., 2019). *C. album* is widely distributed across the semi-arid region. A few favorable circumstances for its growth include high temperatures, intense summertime sunshine, high evaporation, minimal precipitation, and elevated salt at the soil's surface (Tang et al., 2022). It is found all over the world, in both the northern and southern hemispheres, including in Asia, North America, South America, Europe, South Africa, Australia, and India (see **Figure 2**) (Le et al., 2019). Its effectiveness as an agronomic weed in annual crops is due to *C. album*'s propensity to colonize damaged regions when the opportunity arises. Additionally, these weeds can be seen growing along highways and in places that have been disturbed by overgrazing or other human or animal activity (Eslami & Ward, 2021).

Figure 2 Distribution of the *C. album* in the current time over the entire planet (Heap, 2022)

3.2. Effects on yield

Crop production has a direct impact on the ability of the world to meet the rising demand for food, which is primarily related to population expansion. High crop yields result in an abundant food supply, which lowers the likelihood of food shortages, stabilizes prices, the trade balance, and employment (Amanullah & Khalid, 2020). The effects can be extensive when crop yields are reduced as a result of bad weather, pests, diseases, or poor farming practices. Food security is put in danger, which causes starvation and health problems. This might worsen economic disbalance, poverty, income disparities, and social unrest, which would have a knock-on effect on regional and national stability (Richardson, 2010).

According to a survey done in Canada in 1991, weeds are responsible for $984 million in losses annually on average. The survey encompassed a total of 58 commodities cultivated in Canada in order to gather data on crop loss. It should be noted that certain commodities consisted of combinations of different species (Swanton et al., 1993). Similar research on 46 crops in the USA revealed average yearly damages of $4.1 billion with existing management methods and $19.6 billion without herbicides (Bridges, 1992). A recent study revealed that the presence of weeds in corn fields in the United States and Canada resulted in a significant reduction in crop production, with an average loss of 52%. This translates to a substantial annual loss of 142 million tons of maize, valued at over US$28 billion. These yield loss estimates were derived using quantitative comparisons of corn yields between untreated plots and plots subjected to treatments that achieved weed control rates exceeding 95%. The investigations were carried out during the period spanning from 2007 to 2013 (Soltani et al., 2016).

C. album is to blame for substantial financial losses in agriculture all over the world (Kurashige & Agrawal, 2005). Through allelopathic and competitive processes, *C. album* has a direct impact on agricultural output (Bajwa et al., 2019). The release of allelochemicals into the environment by one plant directly harms another, causing allelopathy, whereas competition refers to a battle between the two plants over one or more growth factors that are in short supply (Yuan et al., 2021). Additionally, this weed serves as a secondary host for a number of significant agricultural pests, which indirectly affect crop growth and productivity (Bajwa et al., 2019).

3.2.1. Competition

The competitive weed species *C. album* threatens all crops with infestation and causes significant harm to sugar beet, potatoes, maize, grains, and vegetables worldwide (Cimmino et al., 2015). Until the canopy closes, which occurs several weeks after seeding, they are vulnerable to competition (Eslami & Ward, 2021). It has an advantage over agricultural plants because of its early emergence and quick rate of development (Coleman et al., 2018).

In this regard, the facilitation of high seed production enables the accumulation of abundant and long-lasting seedbanks, thereby enhancing the permanence of the population and facilitating the occurrence of new infestations in agricultural fields. As a result, it competes with crops over nutrients and other important elements (Aper et al., 2012). Numerous studies have documented significant yield losses brought on by the weed in various crops.

It is generally known that *C. album* competition causes significant harm to field crops. Early phases of maize development allow *C. album* to take in more nutrients, resulting in decreased crop output (Keller et al., 2014). Over the course of two years, this noxious plant reduced maize yields by up to 100%, depending on the environmental variables (Fischer et al., 2004). The weed has been shown to decrease barley yield by 36% (Asshleb, 2010). Both South Asian and European nations regularly notice the weed in wheat (and other winter crops). The grain yield and dry matter buildup were both harmed by the weed (Jabran et al., 2017). According to a field trial experiment, fat hen competition caused the wheat varietals Inqlab-91 and Punjab-96 to lose between 50 and 60 percent of their biomass (Ghosh et al., 2020).

C. album's competitive impacts on tomato, lettuce, and cabbage were investigated, and it was discovered that these three crops grew much less rapidly as a result of the weed. The weed mostly absorbs the nutritious components of these vegetables and the loss becomes more dramatic with increased exposure to the competition (Asshleb, 2010). It lowered the weight of tomato shoots in the early fruit stage but had no effect on tomato shoot dry weight at the vegetative stage. Marketable tomato fruit weight and quantity were decreased during the whole growing season by this weed, with reductions ranging from 17% at 16 plants per meter to 36% at 64 plants per meter (Bajwa et al., 2019). In the absence of management, *C. album* has the potential to absorb substantial amounts of phosphorus that would otherwise be accessible to lettuce plants (Santos et al., 2004).

3.2.2. Allelopathic effects

The weed species *C. album* has been proven to be allelopathic. This species releases allelochemicals into the soil, which hinder the development of nearby plants and trigger their germination (Bajwa et al., 2019). The existence of chemical components in the various portions of *C. album* may be the cause of its allelopathic action (Majeed et al., 2012). Major allelochemicals like alkaloids, aldehydes, apocarotenoids, steroids, flavonoids, clerogenic acid xyloids, and saponins are present in the extracts from different plant parts of *C. album* (Rezaie et al., 2008). By interfering with the key physiological functions of plants, these substances have the potential to significantly reduce yield (Farooq et al., 2013). Several studies have found that wheat, radish, lettuce, tomato, onions, maize, safflower and mustard are negatively affected by the presence of *C. album* allelochemicals during the germination and early seedling development stages (Bajwa et al., 2019).

Seven phenolic compounds have been identified from wheat and radish shoots whose germination and development were suppressed by an aqueous extract of *C. album*. They also determined that the main phytotoxin is chlorogenic acid (Majeed et al., 2012). Seven cinnamic acid amides that were isolated from *C. album* were studied for their impact on the germination and development of lettuce, cherry tomatoes and onions. They noticed that all of these plants had decreased germination and growth (Cutillo et al., 2003). The seven cinnamic acid amides that were identified from *C. album* are given in Table **1** their site of identification.

Table 1. CInnamic acid amids identified in *C. album* (Cutillo et al., 2003)

Sl no.	**Identified cinnamic acid**	**Identification site**
1	N-trans-feruloyl 4’-Omethyldopamine	*Chenopodium album*
2	N-trans-feruloyl 3'-O-methyldopamine	*Spinacia oleracea*
3	N-trans-feruloyl tyramine	*Hypecoum sp.*
4	N-trans-4-O-methylferuloyl 3’,4’-O-dimethyldopamine	*Zanthoxylum rubescens*
5	N-trans-4-O-Methylcaffeoyl 3’-O-methyldopamine	*Actinodaphne longifolia*
6	N-trans-feruloyl tryptamine	*Zea mays*
7	N-trans-4-O-methylferuloyl 4’-O-methyldopamine	-

By generating an allelochemical called oxalic acid, the weed prevented maize seedlings from growing and elongating their roots. In the case of soybeans, similar findings were also made (Bajwa et al., 2019). Oxalic acid typically has little influence on plant growth; however, it has negative impacts on seedling growth. The acid acts on active gene expression, de novo protein synthesis, breakage of nuclear DNA, cell shrinkage, and induces a rise in reactive oxygen species levels, all of which cause signal transduction that results in cell death (Pego & Fialho, 2018). Safflower height, root and shoot dry weight, root length, leaf area, and biomass all significantly decreased after treatment with *C. album* extracts compared to the control. Root dry weight and plant height were significantly decreased by 26.59 and 92.50%, respectively, by the root extract. The plant height and root dry weight were similarly reduced by the shoot extract by 71.00 and 21.23%, respectively (Rezaie & Yarnia, 2009). Mustard seed germination dropped when *C. album* extract (leaf, stem, and root) was present in higher concentrations. At increasing concentrations of extract, the plant's root and shoot length were also significantly decreased (J.R. & Y.B., 2014). Wheat and other crops grew less as a result of *C. album* residue being present in the soil. Exudates from this weed have been found to inhibit the development of Rhizobium spp. and nitrifying bacteria (Bajwa et al., 2019).

3.2.3. Indirect effects

C. album causes significant indirect costs in agriculture by serving as an alternative host to a number of economically significant pests and illnesses. Numerous illnesses that affect vegetable crops are spread worldwide by this weed (Coleman et al., 2018). Table 2 below lists a few instances of indirect losses brought on by *C. album* populations.

Table 2. *C. album* as a host for pests or infectious agents

Country	Pest/ infectious agent	Disease/ symptoms	Affected plant	Reference
Japan	*Polymyxa betae*	Rhizomania	Sugar beet and spinach	(Abe & Ui, 1986)
-	Beet leafhopper and common stalkborer	-	Sugar beet, tomatoes, corn	(Mitich, 1988)
New Zealand	*Stagonospora atriplicis*	-	-	(Mckenzie & Dingley, 1996)
USA	Peanut stunt cucumovirus (PSV)	Mild mosaic symptoms	Cowpea	(Gillaspie & Ghabrial, 1998)
USA	*Pemphigus betae*	-	Cottonwood	(Moran & Whitham, 1988)
United Kingdom	Beet yellows virus	-	Sugar beet	(Smith & Hallsworth, 1990)
South Africa	*Ditylenchus destructor*	Root-knot	Potato and groundnut	(Waele et al., 1990)
Canada	*Meloidogyne halpa*	Root-knot	Carrot	(Belair & Benoit, 1996)
India	Prunus necrotic ring spot virus (PNRSV)	Chlorotic local lesions	Agronomic crop	(Sharma et al., 1998)
Australia	Aphids	-	Vegetables	(Coleman et al., 2018)

3.3. Herbicide resistance

It is claimed that common *C. album* ranks as the fourth most significant herbicide-resistant weed on earth (Westhoven et al., 2008). As of now, 50 incidents of this plant exhibiting herbicide resistance have been reported worldwide (Table 3), with almost half of them coming from the United States. Several Photosystem II (PS-II) and Acetolactate synthase (ALS) inhibitor herbicides are ineffective against the noxious *C. album* (Heap, 2022). According to several studies, employing too many herbicides with the same mode of action without considering other weed management options is the main cause of the development of herbicide resistance (Konstantinović et al., 2015). Resistance to atrazine (34 occurrences) on maize crops is the most frequent and pervasive in this species. The first instance of herbicide resistance in *C. album* (against atrazine) was documented in Canada in 1973 (Bajwa et al., 2019). The "Dairy Belt," an area of the United States located east of the Mississippi River, contains the highest incidence of triazine-resistant *C. album*. Triazine herbicides (such as atrazine and simazine) have been widely used at high rates to control weeds in these locations, where maize is commonly cultivated for multiple years in the same field (Curran et al., 2007). Except for one Swedish population where atrazine resistance was brought on by an Ala_{251} to Val substitution, all examined atrazine resistant *C. album* populations had the identical Ser_{264} to Gly point mutation in the photosystem II protein D1 (psbA) gene (Mechant et al., 2008). The most prevalent target-site resistance mechanism in different weeds is the mutation of target proteins. Atrazine's target gene is the PsbA gene, which encodes the D1 protein (Yang et al., 2022). Weeds with the Ser_{264} to Gly point mutation displayed high levels of atrazine resistance, according to research on herbicide dose-response (Lu et al., 2019). These herbicides have a long half-life in the soil, which promotes the development of resistant biotypes (Curran et al., 2007). The ALS inhibitors thifensulfuron-methyl, tribenuron-methyl, and imazamox, as well as the synthetic auxin herbicides dicamba, aminopyralid, and clopyralid, have also developed resistance in *C. album* (Heap, 2022). Researchers demonstrated that weed resistance to ALS-inhibiting herbicides can result from at least five treatments of the same action mechanism (Konstantinović et al., 2015). Additionally, this weed poses a significant danger to farming systems all across North America because of potential glyphosate resistance (Curran et al., 2007). After 8 years of continuous glyphosate usage in a rotation of maize and soybeans, researchers found that *C. album* dominated glyphosate-based treatments (Westhoven et al., 2008). Unexpectedly, *C. album* populations that are herbicide-resistant have not yet been identified in Australia, despite cases being documented elsewhere (Coleman et al., 2018).

Table 3. The current state of herbicide resistance in *C. album* around the world (Heap, 2022)

Herbicide	Site of action	Crops	Countries
Atrazin	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	USA
Thifensulfuron-methyl	ALS inhibitor	Soybean, Barley, Wheat	Canada, USA
Tribenuron-methyl	ALS inhibitor	Barley, Wheat	Canada, Finland
Imazamox	ALS inhibitor	Soybean	USA
Florasulam, flumetsulam, imazamox, iodosulfuron-methyl-Na, thiencarbazone-methyl, thifensulfuron-methyl, and tribenuron-methyl	ALS inhibitor	Maize, Soybean, Sunflower, and Wheat	Ukraine
Aminopyralid, clopyralid, dicamba	Synthetic auxin	Maize	New Zealand

PS-II = Photosystem II; ALS = Acetolactate synthase

4. BIOLOGICAL CONTROL

The term BCA refers to the utilization of naturally occurring, highly effective strains of microorganisms or genetically modified organisms to mitigate the occurrence or intensity of plant diseases caused by pathogens (Gupta et al., 2021). BCAs are known to generate a diverse range of compounds that elicit the activation of plants' defensive mechanisms. These compounds have the ability to either enhance the formation of complex antioxidant defense pathways in host plants or trigger plant defenses by inducing biochemical alterations in plant systems, enabling them to better handle future pathogen infections (Kurjogi et al., 2021).

Due to the growing problem of herbicide resistance among populations of *C. album* in a variety of overseas crops, different management strategies are being researched (Coleman et al., 2018). With the rising cost of human labor, manual and mechanical methods for weed control are becoming more and more expensive. The weed is known for being able to thrive in a wide range of soil types, weather conditions and altitudes (Eslami & Ward, 2021).

Due to this considerable propensity for adaptation to various settings, cultural techniques are not always effective in managing it (Bajwa et al., 2019). The rise of herbicide-resistant weeds is a primary motivator for research into effective BCAs. These substances have been employed against weed species in several nations across the world (Jabran et al., 2017). Within the natural habitat of *C. album*, there are several predatory insects and infectious diseases. The majority of BCAs for *C. album* are fungi, and several of them have undergone successful testing for their specific mechanism of action (**see Figure 3**).

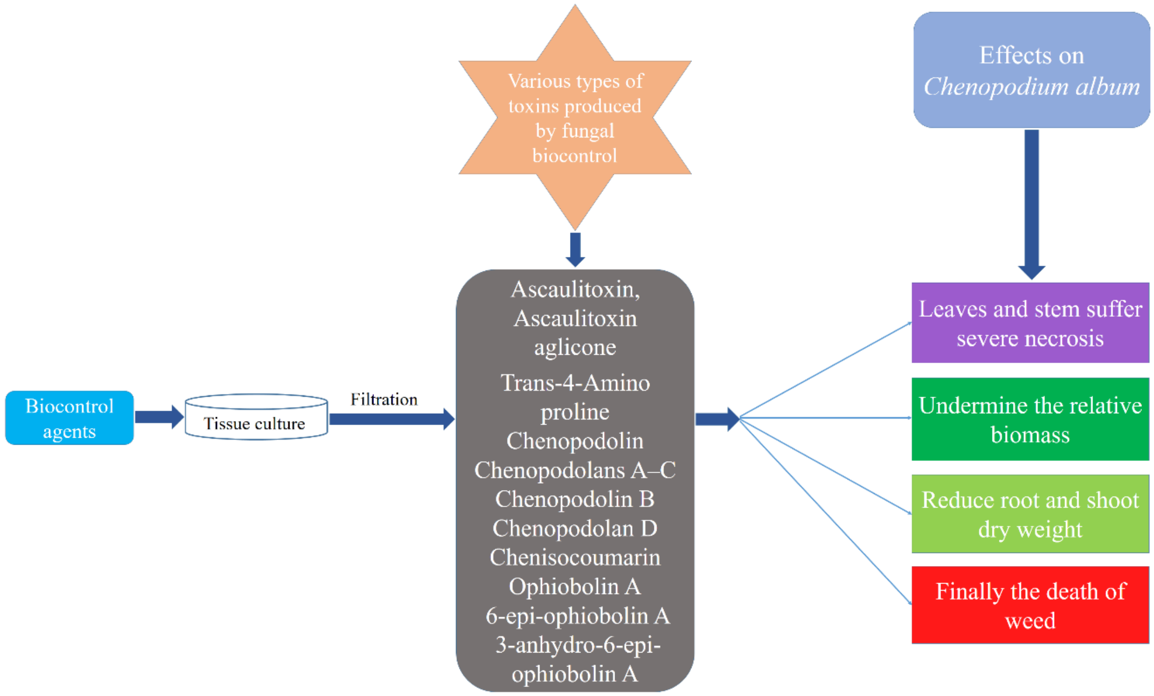

Figure 3 Basic mechanism of BCAs against *C. album*

Ascochyta caulina [(P. Karst) v.d. Aa and v. Kest], a plant pathogenic fungus, has demonstrated extremely impressive outcomes against *C. album* (Netland et al., 2001; Scheepens et al., 1997). Ascaulitoxin, Ascaulitoxin Aglicone, and Trans-4-Amino Proline are the three primary toxins that have been produced, purified, and chemically and biologically characterized from liquid culture filtrates of the fungus (A. Evidente et al., 2006; M. Evidente et al., 2015). It is a suspicion that these toxins have the capability to inhibit one or more aminotransferases or impact amino acid transporters. Such a disturbance may result in an unbalanced level of amino acids and other metabolites, which will have a detrimental effect on the growth and development of the weed (Avolio et al., 2011; Cimmino et al., 2015). Based on a number of pertinent biological and technical characteristics, including their tiny molecular size, broad-spectrum phytotoxicity to various plant species, absence of antibiotic and zootoxic activities, and complete solubility in water, their usage in combination as a natural and eco-friendly herbicide was proposed (Vurro et al., 2012). The leaves and stems of *C. album* suffer severe necrosis as a result of these poisons, which results in plant death (Bajwa et al., 2019). Herbicides and the toxins and spores of *A. caulina*, both separately and in combination, had a synergistic impact that effectively controlled the *C. album* weed. The herbicide metribuzin, sprayed at a sublethal dose, increased fungal effectiveness in terms of reducing plant growth. Additionally, the fungus and *A. caulina* toxins used together had a favorable impact on fungal activity (Vurro et al., 2001). Toxins from *A. caulina* were more effective against *C. album* when there was a lot of nitrogen available. Increased necrotic lesions were seen with high nitrogen availability, leading to a larger drop in biomass in *C. album* (Ghorbani et al., 2002). Additionally, the inclusion of yeast extract under shaken conditions might enhance toxin production (Vurro et al., 2012).

Another fungus pathogen, *Phoma chenopodiicola*, has been suggested as a means of controlling *C. album* biologically (M. Evidente et al., 2015). These harmful Sphaeropsidales are widely recognized for producing toxins (Cimmino et al., 2013, 2015).

Chenopodolin, chenopodolans A–C, chenopodolin B, chenopodolan D, and chenisocoumarin are the main phytotoxins connected to this species (Cimmino et al., 2013; M. Evidente et al., 2015). The biological action against the weed is significantly influenced by the type of side chain at C-4 in these phytotoxins, with special emphasis on its hydroxylation (M. Evidente et al., 2015). When tested on *C. album* pierced leaves, these compounds demonstrated potent herbicidal action (Akbar et al., 2017). Each of the following secondary metabolites is produced by the fungus in liquid culture. These toxins can also elicit necrosis symptoms on the leaf discs of non-host weeds since they are not limited to *C. album* (M. Evidente et al., 2015).

A novel fungus called *Alternaria alternata* is to blame for the leaf blight that can result in up to 70% mortality in *C. album* (Siddiqui et al., 2016). The disease's initial signs are brown necrotic patches that progress to form concentric rings. Then, these dots combine to create huge, erratic blotches. Infected leaves immediately droop, die, and fall off (Siddiqui et al., 2009). Under greenhouse and outdoor circumstances, it has been discovered that a formulation of *A. alternata* in a 20% canola oil emulsion may seriously infect *C. album*. Additionally, its use promotes wheat development and production (Siddiqui et al., 2016).

Researchers extracted and studied the *Drechslera rostrata* metabolite, Ophiobolin A. The superficial leaf cells of the noxious weed of wheat died as a result of this refined substance. Therefore, it can be deduced that *D. rostrata* has phytotoxic and herbicidal qualities that may be used to combat *C. album* as natural herbicides (Akbar et al., 2017). *Drechslera gigantean*'s secondary metabolites were effectively examined for their phytotoxic potential against *C. album* (A. Evidente et al., 2006). Ophiobolin A, 6-epi-ophiobolin A, 3-anhydro-6-epi-ophiobolin A, and ophiobolin I are among the phytotoxic compounds the fungus generates. Comparing these to other comparable chemicals, ophiobolin A is shown to be generally more phytotoxic (A. Evidente et al., 2006).

Stagonospora vitensis, a kind of fungus, also produced necrosis and death in *C. album*. It decreased the relative weed biomass by up to 48% (Öğüt et al., 2012). *C. album* was well controlled by the BCAs (the fungi *A. caulina* and *S. vitensis*) in conjunction with the lower dose of nicosulfuron (12.5% of the recommended dose) (Bajwa et al., 2019).

Another fungus, *Cercospora dubia*, has proven its ability to cut the dry matter weight of C. album by up to 20% at the latest 4 weeks after it was inoculated. The plants had already grown new leaves after being inoculated with a combination of spores and mycelium before necrosis took hold. Similar outcomes were attained in the USA using a regional strain of this fungus (Scheepens et al., 1997).

It's interesting to note that *C. album* seedling development can be significantly hampered by rhizospheric bacteria. At 60 and 90 days of plant development, the inoculation of bacterial isolate reduced *C. album*'s root and shoot dry weights. Additional research is needed to further improve these rhizobacteria as a possible biological agent for weed management (Khandelwal et al., 2018).

5. CONCLUSION

C. album is an extremely significant weed on a worldwide scale according to its biology, adaptability, impact on crops, rapid rates of breeding, and diversity. The seeds of this plant spread by different means around the world and contaminate crop areas. This noxious plant can spread rapidly, regardless of the light conditions. Additionally, the weed's invasive tendencies have the potential to damage biodiversity and natural habitats. The weed seriously harms a variety of crops and vegetables through the mechanisms of allelopathy and competition. The crop population might also become host to other infectious agents and pests. Due to herbicide resistance to synthetic chemical herbicides, this problem has gotten worse. As a result of all these factors, agricultural yields are decreasing and food production is impaired, which poses an imminent threat to global food security. Because of its capacity to adapt to shifting weather patterns and tolerance to chemical herbicides, urgent biological control measures are required. Numerous studies have been conducted to manage *C. album* using fungi and bacteria as BCAs. The fungus's ability to combat the spread of this plant was extremely successful. The necrosis of *C. album* plants is mostly caused by their toxins, which should be taken into consideration with utmost importance in order to control the weed. Additional investigation into the principles of molecular biology is required in order to understand the mechanism of action of toxins. Each BCA must also go through field testing in several geographic settings to ensure its global efficacy.

Ethics Approval and Consent to Participate
Not Applicable

Availability of data and material
Data for this research were online publications from the Web of Science as contained in the reference section.

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