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Research Article

Biocontrol measures to manage *Parthenium hysterophorus*: Current paradigms, scope and relevance

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Abstract
Parthenium hysterophorus, a noxious weed of tropical America, had relocated to Indian plains and rapidly encroached on north-western Himalayas Mountain regions. Earlier, the plant was primarily found in wastelands, but it now thrives in cultivated fields, pastures, and roadsides. *Parthenium* weed threatens human and animal health, destroys vegetation, lowers the diversity of native plant groups and causes significant financial damage to individuals and their significance in numerous nations worldwide. Parthenin, a sesquiterpene lactone found in *P. hysterophorus*, is harmful to livestock and poses a serious health risk to people, *e.g.*, dermatitis and skin rashes, emaciation, tissue rupturing, internal organ haemorrhages and death are the hazardous side effects. Several studies are being conducted to determine the most efficient and reasonable method to control this harmful weed worldwide, including physical, chemical and biological ones. The study revealed that biocontrol of *P. hysterophorus* was a cost-effective, safe and viable technique and poses no threat to non-target organisms, environment and biodiversity, *e.g.*, some allelopathic plants are used to curb the growth of congress grass. The combined effects of biocontrol agents like insects, fungi, nematodes, snails, slugs, and competitive plants decrease the density and vigour of congress grass and increase its production. The work done over the past 20 years on screening and evaluating both insect and fungal agents and the actual and potential employment of natural enemies as traditional biological control agents has been discussed. The study concludes that biological control, because of its affordability, environmental safety and sustainability, could be a significant constituent of an effective strategy for managing weed.

Keywords: Allelopathic, Biological control, Competitive plants, Nematodes, *Parthenium*

INTRODUCTION

Parthenium hysterophorus, the most notorious weed, may be found present everywhere all over the world. *Parthenium*, a perennial terrestrial weed endemic to the Americas, is widespread in equatorial regions (Saha *et al*., 2018). This harmful invasive plant is considered the nastiest weed ever discovered. Due to its lack of potent natural adversaries, allelopathic action and resistance to heat and light, it thrives luxuriantly around the year, reducing native plants and endangering natural variety (LA *et al*., 2014). It has become a big problem in the whole country, spreading to bordering countries by vehicles or through the contaminated seeds that have

been shipped (Mao *et al*., 2021a). *Parthenium* most likely arrived in India before 1910 via tainted cereal grains but was not discovered until 1956. The weeds have spread like wildfire in India since 1956 (Kaur *et al*., 2014). It takes up more than 5 million acres of the nation's land (Bhateria, 2015; Dheer *et al*., 2023).

Parthenium is a native of Central-South America, Southern North America, Central America and the West Indies. The weed has now spread to over 20 nations worldwide, including five continents and many islands (Mao *et al*., 2021b). *Parthenium* is an herbaceous perennial weed belonging to the Asteraceae family. This short-lived upright plant is well-known for its profusion in hot regions and for its vigorous growth (Rana *et al*., 2016). It develops quickly, creating an adult plant about 1.5 m tall, producing flowers early and generating many seeds throughout its lifetime (Adkins and Shabbir, 2014). In just four weeks, *Parthenium* weed can germinate, develop, and grow to seed (Masum *et al*., 2013). The weed may also flourish in various ecological settings, from sea level to a height of 3000 m. The plant spreads quickly and distinguishes itself from other weeds by being remarkably tolerant to different soil types and environmental conditions (Soni *et al*., 2023). Congress grass first bloomed in India from February to April in the western region and from August to October in the eastern region (Sridhara *et al*., 2022). The plant completes its life cycle concisely and blooms three to four times yearly because of its strong adaptive qualities (Fig.1).

Parthenium lacks natural enemies such as pests, pathogenic fungi, bacteria and viruses because it is an exotic plant (Khan *et al*., 2022). Additionally, this weed is not eaten by herbivores as it promotes unrestricted development. It is a native plant of northeast Mexico. Distinct countries have different names for *Parthenium*, including bitter weed, carrot weed, congress grass, ragweed, the scourge of India, star weed, and wild feverfew (Thejesh, 2020). Although it produces a lot of seeds, this weed is highly competitive with economically significant crops and has a considerable allelopathic effect on nearby plants (Bajwa *et al*., 2019). All kinds of crop and herbaceous plants are also invaded by *Parthenium*, which significantly reduces yield and growth as it is well recognised that *P. hysterophorus* inhibits local vegetation's growth through leaching, exuding roots, decomposing roots, decomposing wastes, *etc*. (Raghava *et al*., 2016). It may have an impact on natural diversity and lead to the extinction of local flora if left unchecked. Along with all these negative consequences, this weed also blocks orchards and public walkways and degrades the aesthetic value of housing developments, parks and gardens. *Parthenium* has developed into a significant hazard to the biodiversity of humans, plants, animals and grazing areas for livestock in the last several years due to its extensive spread to roadsides and fallow lands covered in forest in most of the valleys and hilly regions of Himachal Pradesh (Rana *et al*., 2017).

Parthenium weed has the potential to damage the envi-

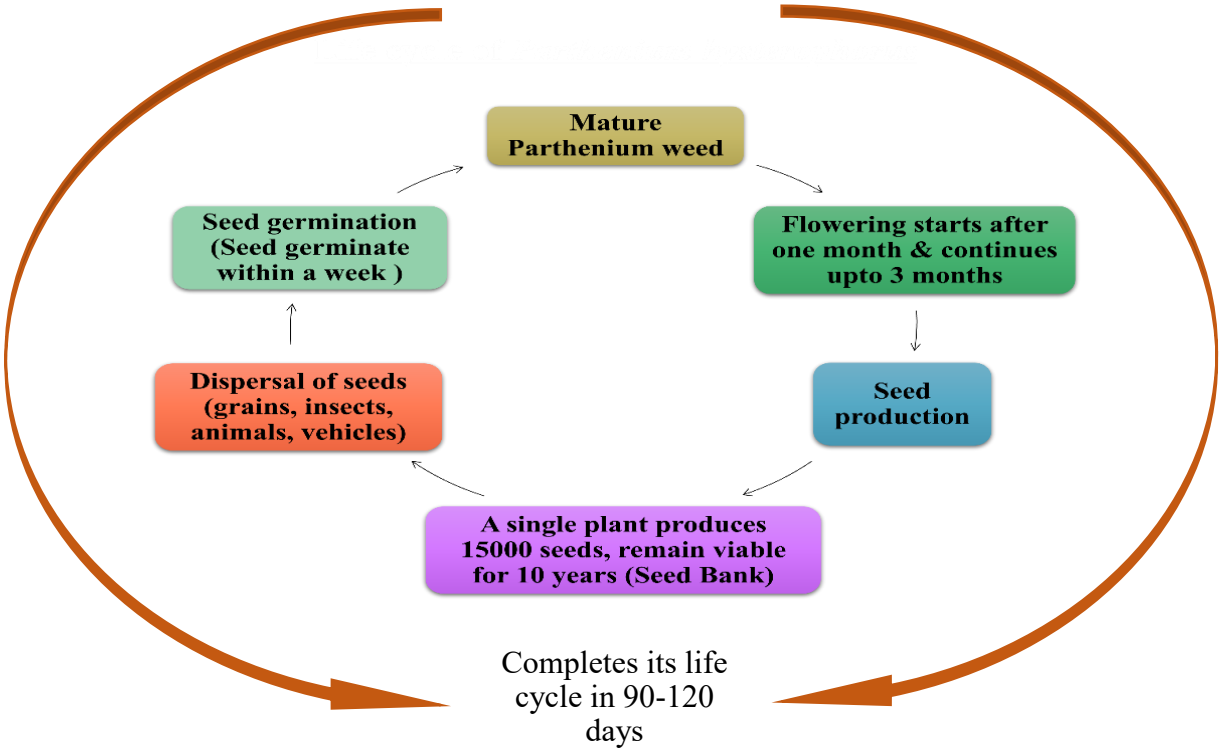

Fig. 1. *Life cycle of Parthenium hysterophorus (Source: Jamil et al., 2021)*

ronment due to its invasive propensity and allelopathic characteristics (Singh *et al*., 2017). Due to *P. hysterophorus*, which is becoming a global issue, there will be significant crop losses everywhere. Only a single weed causes most Caribbean countries to lose an average of 20% of their crop yield (Kanagwa, 2020). Due to this weed's invasive characteristics, India is currently dealing with a serious issue of decreased crop productivity and the loss of many key plants (Batish *et al*., 2012). All these examples demonstrated how *Parthenium* could alter the ecology. Because of its invasive and allelopathic characteristics, it is often recommended to stop its growth and spread and to reduce its harmful effects on crops (Tabe-Ojong *et al*., 2022). The hazardous health consequences of *P. hysterophorus* on people and animals are a major concern, and some governments in nations like Ethiopia, Australia, and Uganda have established federal institutions to aid in halting the disease's spread. Around the world, weeds can be managed using different methods, including cultural, chemical, mechanical and biological ones (Melander *et al*. 2017; Korres 2018). Using bioherbicides, nematodes, snails, insects and competing plants as natural enemies to manipulate undesirable weeds deliberately is known as biological control (Tabe-Ojong *et al*., 2022). Biological control rarely entails eliminating the undesired organism; instead, it refers to keeping its population at a lower-than-average level compared to what would happen without a biocontrol agent. Biocontrol is a feasible and cost-effective way to keep *Parthenium* inhibited since it is mostly a waste and abandoned weed (Izhar *et al*., 2023). This form of weed control, like developing alternative integrated weed management systems that are environment friendly, sustainable, and based on natural bioherbicides, is becoming increasingly popular today (Scavo *et al*., 2020). Few years ago, bacteria, host-dependent fungi and viruses were used to achieve this goal (Harding and Raizada, 2015).

Due to its invasiveness, propensity for propagation, effect on public health and adverse effects on the environment and country's economy, it is recognised as one of the worst weeds (Fig. 2). Parthenin, a sesquiterpene lactone found in *P. hysterophorus*, is harmful to livestock and poses a serious health risk to people (Jaiswal *et al*., 2022). The toxic side effects in humans are dermatitis and skin rashes, emaciation, tissue rupturing, haemorrhages within the internal organs and death (Duguma *et al*., 2019). There have been reports of contaminated meat and subpar milk from animals who consumed *Parthenium*, which is hazardous to livestock if eaten sufficiently (Gadisa *et al*., 2019).

METHODS TO CONTROL *PARTHENIUM. HYSTEROPHORUS*

Controlling *Parthenium* weed is very difficult because of its aggressive developing nature. Since the plant creates a greater risk to nature and human health, immediate action is necessary to destroy it (Kumawat *et al*., 2023). India faces a significant threat due to its quick spreading in agricultural areas. Thus, it should pay close attention to its control (Kaushik and Singh, 2020).

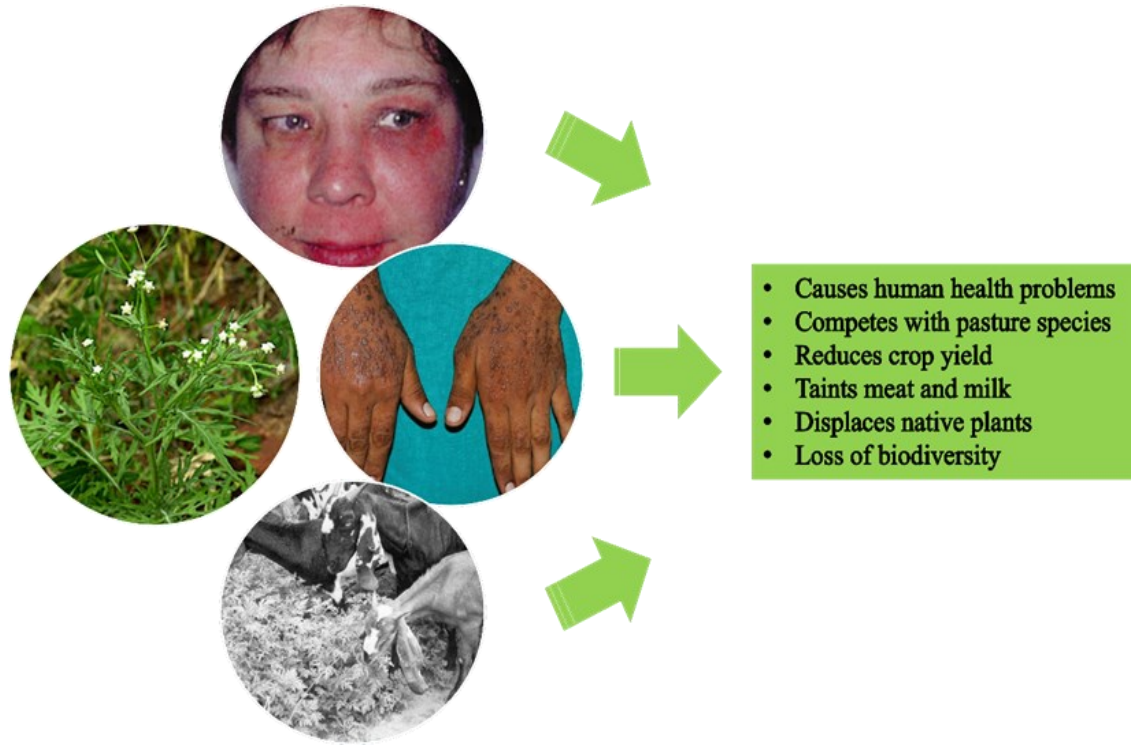

Fig. 2. *Harmful aspects of Parthenium (Source: Khanal, 2014)*

Many studies are being conducted to determine the most effective and cost-effective means to eradicate this weed globally. The methods include biological, chemical, physical, and governing the weed through appropriate use (Fig.3).

Physical control

The most effective method is to pull out *Parthenium* by hand prior to flowering and seed germination. After the weed has established seed, pulling it up will spread the infestation further (Singh *et al*., 2023). However, the perennial pasture must be seeded directly or with a crop. Some landowners successfully eradicated this harmful weed just at the rosette stage of plants and before developing seeds (Gajanan *et al*., 2015). Physical control requires manual weeding, which is tiresome and unpleasant as handling *Parthenium* weed poses health dangers (Abeita, 2016). After human removal, *Parthenium* weed populations swiftly repopulate and will grow from plants that have been trimmed or only partially removed but still have roots. Manual weeding and ploughing techniques are often used in poor nations where labour is in short supply (Kumar *et al*., 2022). Burning is another weed management technique but it is ineffective for controlling *Parthenium* (Adkins and Shabbir, 2014). However, research indicates that if the grassland is given time to recuperate earlier to introduce stock, burning for other reasons (such as removing woody weeds) would not increase *Parthenium* infestation. This has also been insufficient due to two factors, *i.e.*, (i) it consumes a significant amount of fuel and (ii) burning all nearby economically significant plants (Assema *et al*., 2017).

Biological control

The biocontrol exertion involves importing bioagents specific to the host from the weed's native nation into other countries where it has already invaded and turned intrusive (Bankar *et al*., 2023). The ecosystem, biodiversity and non-target organisms are not endangered by biological management, which is cheap and effective (Dhileepan *et al*., 2018). Since it is ceaseless, it can increase by itself, unlike additional control measures with periodic inputs. Integrating it with additional control methods is simple. Biological means are the most economical, environmentally safe and practically realistic way to control *Parthenium* (Singh *et al*., 2023). Besides increasing grass production, the combined effects of biological control agents decreased *Parthenium* weed's density and vigour (Ojija, 2022). It has been reported that *Bucculatrix parthenica*, *Epiblema strenuana*, *Listronotus setosipennis*, *Smicronyx lutulentus* and *Zyogramma bicolorata* are all effective against *P. hysterophorus* (Dinwiddie, 2014). This weed can be managed biologically by the use of fungi like *Alternaria alternata* and *Puccinia abrupta* var. *parthenicola* (Thesaurus *et al*., 2017). The most successful bioagents for controlling *Parthenium* are *Zygogramma bicolorata* Pallister and *Epiblema strenuana*, among a dozen insects and pathogens introduced in Australia and India (Sridhara *et al*., 2022).

Chemical control

In areas where the natural enemies of *Parthenium* do not exist, chemical control is an efficient approach to keep this weed under control. Chemical pesticides like glyphosate, ametryn, chlorimuron ethyl, bromoxynil,

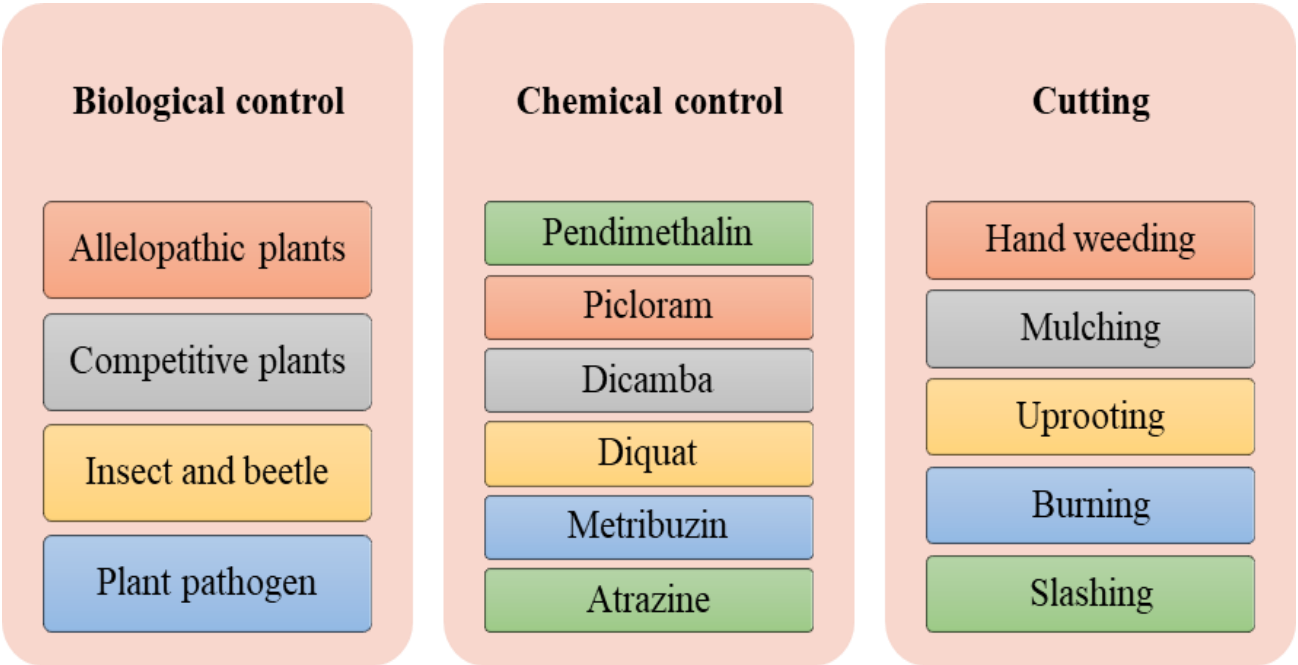

Fig. 3. *Biological, chemical and physical control of Parthenium hysterophorus (Source: Lalita et al., 2018)*

metsulfuron and atrazine are often used successfully to suppress the weed (Dukpa *et al*., 2020). The application of glyphosate 1.0-1.5% for the complete management of vegetation and metribuzin 0.3-0.5% or 2,4-D 2.0-2.5 kg a.i. to control *Parthenium* weed in grasslands and areas where uprooting is not feasible due to labour shortage and high costs (Safdar, 2015).

Different crops require various herbicides, so it is very important to consult weed scientists before applying them in diverse crops. Alachlor 2 kg a.i. can be applied as pre-emergence to suppress *Parthenium* in tomato, soybean, French bean and banana plantation. In potato, soyabean and tomato crops, metribuzin 0.50-0.75 kg may be used as a pre-emergence to suppress the *Parthenium* weed. Atrazine can also be used in maize crops to control *Parthenium*. The seeds remain viable for 2-6 years; thus, the chemicals should be used repeatedly. Spraying common salt solution at 15-20% concentration in open wastelands, across railroad tracks, along roadside embankments and in vacant lots is the least expensive technique of weed control (Sridhara *et al*., 2022).

Positive aspects of biological control

Biological control is humans' deliberate alteration of nature's adversaries to eradicate noxious weeds. The goal of biocontrol is often to control the population of unwanted organisms rather than eliminate it completely. The biological control programme entails the insertion of bioagents, particularly to a host, from the weed's native habitat into other countries where it has already established an invasive presence (Heimpel and Mills, 2017). Biological control is low-cost and does not endanger the environment, biodiversity, or unintended creatures. It is self-replicating and can propagate independently, while other control methods require periodic inputs. It is simple to include with additional control mechanisms (Strathie *et al*., 2011). Biological control of weeds can be achieved through three primary methods: augmentative biological control, classical biological control and inundative biological control (Fig.4) (Müller-Schärer and Schaffner, 2008). Classical biological control has several benefits, including being cost-effective, eco-friendly, intrinsically safe, rational and target-specific (Weyl *et al*., 2021). Therefore, biological control is the most feasible and cost-effective method to manage the *Parthenium* weed (Gnanavel and Natarajan, 2013). When it is necessary to further limit abundance, biological control stops the spread of weeds and reduces the costs associated with chemical and manual control.

Classical and bioherbicidal strategy for weed control

Since ancient times, India has seen the effects of aggressive foreign weeds on livestock, horticulture, forests, and the surrounding area. From 1996 to 2000, the advancement of classical and bioherbicide control received priority as part of a collaboration between the Indian Council of Agricultural Research (ICAR) and Commonwealth Agricultural Bureaux International (CABI) Europe UK (previously CABI Bioscience) financed by the UK Department for International Devel-

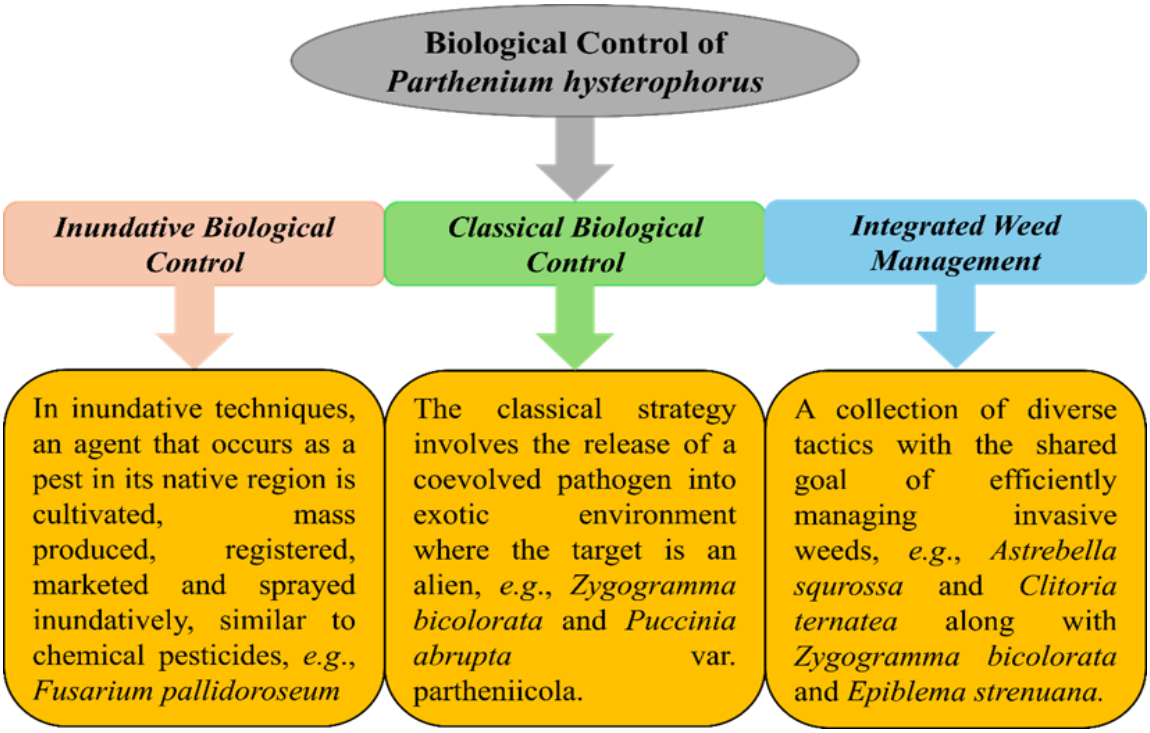

Fig. 4. *Biological control of Parthenium hysterophorus (Source: Kaur et al., 2014)*

opment (Kumar *et al*., 2008).

The bioherbicide method and classical biological control methods are the two basic biological weed management strategies (Green, 2003). In classical approach, invasive weeds are controlled by introducing a suitable exotic bioagent from the native habitat of weeds (Kaur *et al*., 2014). However, this strategy risks damaging non-target crops after dispersing the biological control agent in a new location (Cai and Gu, 2016). Therefore, the classical biocontrol method is governed by the rigorous guidelines due to possibly dangerous microorganisms' use in crop production. Biological agents such as plant pathogenic fungus are produced and utilized in the bioherbicidal approach, which is just as successful as pesticides in controlling weeds in agriculture (Kaur *et al*., 2014). Compared to the classical approach, the bioherbicide strategy is based on controlled natural enemy reproduction and human dissemination, which relies on natural adversaries' innate capacity to proliferate (Frantzen *et al*., 2001). The use of bioherbicides is favoured over classical approach because they provide a wide range of applications in gardens, lawns and agricultural systems (Cai and Gu, 2016).

Parthenium hysterophorus, the worst terrestrial social weed worldwide, is considered the primary focus of possible biological control by using insects and pathogens (Strathie *et al*., 2021). Since 1970s, various biocontrol strategies have been investigated to suppress the *Parthenium* weed. To date, two rust fungi and nine insect species are employed as biocontrol agents in Australia, China, Ethiopia, India, Nepal, Pakistan, Papua New Guinea, South Africa, Sri Lanka, Tanzania, Uganda and Vanuatu (Table 1).

Use of insects

In several nations, various insects have been used to suppress *Parthenium* weed. Among the insects, *Zygogramma bicolorata* (leaf-feeding beetle) and *Epiblema strenuana* (stem galling moth) have demonstrated promising ability to manage this weed (Kaur *et al*., 2014). In Australia, *E. strenuana* and *Z. bicolorata* imported from North America (Mexico) are released to suppress the *Parthenium* weed (Dhileepan *et al*., 2018). Decreased health, nutrients and competitiveness of *Parthenium* resulted from releases (Augustinus *et al*., 2023). However, utilizing only *Z. bicolorata* has effectively reduced the *P. hysterophorus* population. For instance, *P. hysterophorus* infestation decreased by 85 to 100% within three years of *Z. bicolorata* introduction in Bangalore, India (Dhileepan and Strathie, 2009). Similar results were obtained in Australia and central Queensland, where *Z. bicolorata* decreased flower production 100%, plant biomass 89%, plant height 65%, seedbank 86%, seedling appearance 90% and weed consistency 93% (Kumar, 2009; Kanagwa, 2020). The beetle was first brought to Australia in 1980 (Dhileepan, 2009) and then to India in 1984 (Tripathi and Tripathi, 2020). Mersie *et al*. (2019) and Weyl *et al*. (2021) noticed that the leaf-feeding insect has undergone extensive host range testing in India, Australia, Ethiopia and South Africa, indicating that the weed is entirely host-specific.

Use of fungus

Majority of these studies have focused on fungi to control the *Parthenium* weed compared to other microorganisms. The development and germination process of *Parthenium hysterophorus* may be affected due to the herbicidal properties of metabolites from several fungus species (Javaid *et al*., 2010). The International Institute of Biological Control specialists thoroughly investigated some nations, including Mexico, Argentina, Trinidad and Cuba, and discovered 26 species of fungi on *Parthenium* (Dukpa *et al*., 2020). Puccinia melampodii and P.a abrupta var. parthenicola were examined in a related study as powerful classical biocontrol agents due to their limited host ranges, rapid reproduction rates and effective aerial dissemination (Tadesse *et al*., 2005). Both harmful rusts from Mexico have undergone thorough screening and have been introduced in Australia to control *Parthenium* weed (Strathie *et al*., 2011). The most potent fungal agents to control *Parthenium* are *Entyloma compositarum*, *P. xanthii* var. *partheniihysterophorae*, *P. abrupta* var. *partheniicola* and *Plasmopara halstedii* (Kaur *et al*., 2014).

Integrated weed management

Parthenium is remarkably capable of producing numerous little seeds incessantly round the year, concluding that it is difficult to manage by using a single approach (Swati *et al*., 2013). The most effective method of long-term *Parthenium* control is integrated weed management, which integrates all practical management techniques as per the requirement and available resources (Kumar *et al*., 2022). *Parthenium* weed can withstand separately implemented management techniques in many sites; as a result, these locations need a more successful integrated approach. These integrated weed management systems must be successful and affordable in controlling weeds, simple to use and ecologically benign (Adkins and Shabbir, 2014; Tabe-Ojong *et al*., 2022). An integrated approach for managing *Parthenium* weed includes a combination of suppressive pasture plants and current biological control agents (Kumar *et al*., 2022).

Manual or mechanical removal can be done before the flowers develop since the soil remains wet during the rainy season (Tessema, 2002). In contrast to the rainy season, *Parthenium* population is lower in summer and winter and is more difficult to uproot, thus sprinkling metribuzin on wasteland and community land will be

Table 1. Biological control agents of *Parthenium* around the world (Source: Weyl *et al*., 2021)

Sr. No.	Biocontrol agent	Country where ntroduced	Year in which reported	Reference
Insects				
1.	Bucculatrix parthenica Bradley	Australia	1983	
2.	Carmenta ithacae (Beutenmüller)	Australia South Africa	1996 2014	
3.	Conotrachelus albocinereus Fiedler	Australia	1992	Cruttwell, 2000
4.	Epiblema strenuana Walker	Australia China India Papua New Guinea South Africa Sri Lanka Vanuatu	1982 1990 1985 2004 2010 & 2018 2003 2014	Strathie and Khan (2018)
5.	Listronotus setosipennis Hustache	Australia Ethiopia Pakistan South Africa Uganda	1981 2007 2019 2003 2018	Weyl *et al.* (2021)
6.	Zygogramma bicolorata Pallister	Australia Ethiopia India Nepal Pakistan South Africa Tanzania Uganda	1980 2007 1983 2009 2003 2005 2013 2018	Strathie and Khan (2018)
7.	Platphalonidia mystica (Razowski & Becker)	Australia	1991	Dhileepan and Strathie (2009)
8.	Smicronyx lutulentus Dietz	Australia Ethiopia India South Africa	1980 2015 1985 & 2018 2010	Weyl *et al.* (2021)
9.	Stobaera concinna (Stål)	Australia	1982	Strathie and Khan (2018)
Fungi				
1.	Puccinia xanthii var. parthenii hysterophorae	Australia South Africa Sri Lanka	1999 2004 2003	Dhileepan and McFadyen (2012)
2.	Puccinia abrupta partheniicola Parmelee	Australia China Ethiopia India Nepal Pakistan South Africa	1991 2007 1997 1980 2011 2019 1995	Weyl *et al.* (2021)

very helpful in decreasing the intensity of *Parthenium* in the upcoming season (Khan and Fahad, 2020). Kohli *et al*. (2006) noticed that controlling *Parthenium hysterophorus* in India will be more successful when combined with community efforts and other land management techniques rather than used alone. Similarly, in Australia, *P. hysterophorus* biomass was reduced by up to 69% because of the application of biological control agents (*Epiblema strenuana*) in combination with rivalry from buffel grass and butterfly pea (Kanagwa and his associates, 2020; Shabbir *et al*., 2015). *Zygogramma bicolorata* is the most effective bioagent, producing three overlapping generations during the rainy season. Therefore, this bioagent should be deployed and supplemented on *Parthenium*-infested areas during the rainy season. This bioagent has been

proven to effectively inhibit *Parthenium* and restore biodiversity in several places of India.

Allelopathic mechanism for *Parthenium* control

Molisch, in 1937, coined the term *allelopathy*, which describes a plant species' detrimental effects on the development, propagation and seed germination of other plant species (Mushtaq *et al*., 2020). Efforts are underway to apply several plants with allelopathic potential for weed control because natural product-based herbicides are appealing as they are bioactive even at low concentrations (Knox, 2008). Crops, grasses, broad-leaf weeds and allelopathic trees have demonstrated their herbicidal efficacy against *Parthenium* germination and growth. Generally, two strategies are used, *i.e*., (i) preserving the natural biodiversity of the area and (ii) using planting to select plants for specific areas (Temesgen *et al*., 2017). The second strategy entails purposefully manipulating natural enemies to eliminate dangerous weeds. The most genuine enemies of *Parthenium* are *Cassia auriculata*, *C. sericea*, *Mirabilis jalapa* and *C. tora* (Bashar *et al*., 2021). *Cassia auriculata* and *C. sericea* demonstrate allelopathic characteristics, impeding *Parthenium* weed germination and growth while vying for crucial resources. *Mirabilis jalapa* competes for space and resources, potentially constraining *Parthenium* weed establishment, while *C. tora's* allelopathic attributes and competitive disposition further impede *Parthenium* weed proliferation. These plants are vital in *Parthenium* weed control efforts as natural adversaries.

Challenges

Parthenium is an invasive weed with extensive ecological amplitude, profuse and rapid growth and spread, quick reproduction and health risks, so it will be the biggest issue in agriculture (Ghosh *et al*., 2023). Several approaches have been suggested to manage its growth and development, but none function effectively because they all have certain drawbacks, such as high costs, ineffectiveness, impracticability, environmental pollution, *etc.* (Kauser and Khwairakpam, 2022). There are many challenges in controlling *Parthenium* weed, like animals' movement and overgrazing, high seed production capacity and dissemination, relationship with the pastoralist way of life, adaptation to diverse climatic soil conditions, *etc.* (Barasa, 2022). The management activities' strong dependence on food for job programmes and project inputs presents another barrier to their long-term viability. Developing effective biological control methods for *Parthenium*, a highly invasive weed, presents numerous challenges. One significant hurdle is identifying a natural enemy that can target *Parthenium* without causing harm to beneficial plants. Regulatory obstacles, including the rigorous testing required to ensure the safety of introduced biocontrol agents, further impede progress. Persistent observation and investigation are needed to overcome these challenges to develop effective *Parthenium* infestation management techniques.

Future prospectives

This weed can be handled to keep it under control, but only if mankind is properly informed about the advantages and disadvantages of *Parthenium*. When there is proper knowledge, it can be used from a different perspective. Although various tools have been proposed in recent decades to suppress this harmful weed, biological control presents an economical, secure and long-term solution to control this invasive weed. Regional cooperation and shared accountability among the Asian nations where *Parthenium* has invaded and caused significant losses would save significant time and resources.

Conclusion

Parthenium hysterophorus is a dangerous weed that adversely affects human and livestock health, including the yield of crops. The harmful *Parthenium* weed grows in various ecosystems and affects soil nutrients below and above ground vegetation. It can outcompete palatable plants that are beneficial to livestock. Therefore, it is imperative to eradicate this dangerous weed. Biological control measures offer a promising avenue for addressing the issue of *Parthenium* weed. These techniques harness natural adversaries such as insects, fungi, or pathogens to suppress the proliferation of *Parthenium* while minimizing ecological harm compared to chemical alternatives.

Conflict of interests

The authors declare that they have no conflict of interest.

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