Recent advances in biological control of weeds

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Global agricultural output is still severely hampered by weed infestation, which results in large yield losses and growing reliance on herbicides. Utilizing natural enemies including insects, diseases, and competitive plants, biological control of weeds provides a sustainable and environmentally beneficial substitute for chemical weed management. Recent developments in this area have improved the effectiveness, accuracy, and reach of biocontrol methods. Novel bioagents have been identified and their host-specific interactions have been clarified thanks to the merging of molecular biology, genomics, and bioinformatics. Using endophytes, microbial consortia, and synthetic biocontrol organisms has demonstrated potential for improving weed suppression in a variety of agro-ecological settings. Biological control agent delivery and monitoring systems have also been enhanced by advancements in unmanned aerial vehicles (UAVs), artificial intelligence (AI), and remote sensing. Precision weed control has become more common thanks to these technological developments, which also reduce environmental hazards and increase biodiversity.

Keywords: *Artificial intelligence, biocontrol, environment, weeds*

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Introduction

One of the most enduring dangers to biodiversity, agricultural output, and the general well-being of ecosystems is weeds. In addition to outcompeting native plants, invasive weed species also change water regimes, interfere with food chains, and modify ecological processes. Adopting sustainable, environmentally sound methods for weed control is imperative as the drawbacks and negative effects of chemical herbicides on the environment become more apparent. Utilizing natural enemies including insects, viruses, and microbial agents, biological management provides a practical and environmentally friendly way to control invasive weeds in a variety of habitats. Weeds are so dangerous that they continue to rob millions of acres of valuable land each year in many different countries. Weeds are associated with decreased crop yields and turfgrass system values, as well as providing sources of pollen that cause allergies and aesthetic annoyances. Many weeds have spread, herbicide-resistant species have emerged, former herbivores have returned, the diversity of natural enemies has decreased, and the environment and food supply have been contaminated as a result of the unchecked use of broad-spectrum herbicides. More efficient weed management options are now required due to the negative side effects of herbicides.

Biological control of weeds is a well-known substitute for chemical weed control that lowers the hazards that herbicide residue poses to the ecosystem and the health of people and animals. The deliberate application of target-specific destructive organisms is necessary to maintain the target weed population at or below target levels without negatively affecting desirable and useful plants. With the well-established fact that biological weed control is generally host specific, recent advances have enhanced the management efficiency with the inculcation of modern aspects of mode of action, technologies and artificial intelligence.

What is biological control and its origin?

Biological control often means the introduction of organisms into an ecosystem to control one or more undesirable species (Vikas et al., 2016). These agents can inhibit the growth, reproduction, and spread of weeds and include insects, mites, fungi, bacteria, and occasionally even cattle. This approach to controlling invasive weeds is environmentally benign and sustainable, especially in places where other control strategies are unfavourable or challenging. Insects, bioagents, myco-herbicides, and toxic Rhizobacteria are examples of biological weed control methods that are both sustainable and compatible with ecosystems. Among the biological elements of sustainable agriculture are their interactions with allelochemicals and cultural behaviours. Therefore, when compared to weeds left alone, biological agents increase efficiency and limit the negative effects of weeds. Finding the right microbes or bioagents to inhibit weed development is a challenge. It seems to reason that the only environmentally beneficial method of controlling weeds is biological weed management. An effective biological control campaign against persistent weeds often requires the development and release of many agents with cumulative effects (Syrett et al., 2000). Since they might be aiming for the same part of the plant, interactions between many natural enemy species and their hosts are common in nature (Kruess, 2002). These interactions may have an inhibitory effect on plant performance (Hatcher and Paul, 2002) or a synergistic effect (Buccellato et al., 2012).

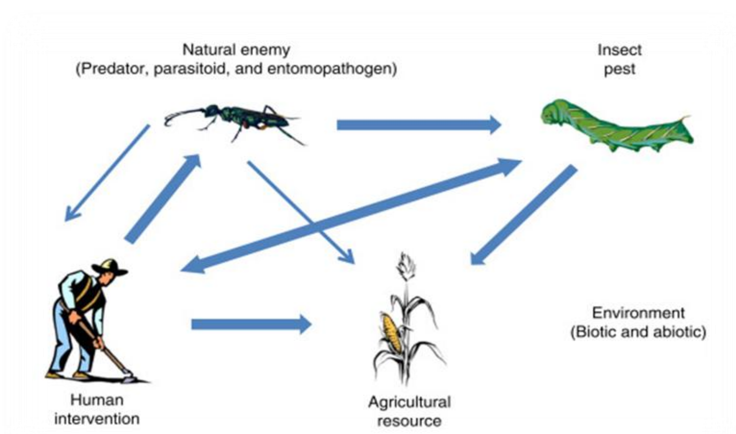

Figure 1. Biological control of weeds

Biological weed management has its roots in ancient China, when ants were employed to keep beetles away from citrus groves. In Sri Lanka, the first deliberate attempt at classical biological control was made in 1865 when scale insects were introduced to control prickly pears. From early, occasionally dangerous endeavours, this technique has undergone substantial change to become a much more regulated and scientific field.

Statistics related to losses caused by weeds

Weeds are responsible for 37% of all agricultural pest losses, followed by insects (29%), diseases (22%), and other pests like nematodes, rats, mites, birds, etc. (12%). In their initial stages of development, the majority of crops grow slowly.

Based on the study conducted at the ICAR-Directorate of Weed Research, Jabalpur, from 1,581 on-farm trials in different agro-ecological regions of the country, the actual yield loss due to weeds was estimated to be 14% in transplanted rice to as high as 36% in groundnut (Gharde et al., 2018). The projected overall annual economic loss resulting from weeds in 16 major crops was ~78,591 crore (1 crore = 10 million). But if you include all the crops, as well as the indirect consequences of weeds on biodiversity, human and animal health, nutrient depletion, grain quality, etc., the overall economic losses will be substantially greater.

An average of 6,000/ha is thought to be spent on weed control for rainy (kharif) season crops, and 4,000/ha for winter (rabi) season crops. This amounts to 33% and 22% of the overall cost of cultivation, respectively (Yaduraju and Mishra, 2018).

Mechanism

Before releasing bio-agents, we should fully understand the mechanisms involved in interactions by multiple agents against weeds.

(a) Classical Biocontrol- bringing in natural enemies from the continent where a weed is native and distributing them in afflicted areas is known as "classical biocontrol."
(b) Targeted Action- biocontrol products undergo extensive testing to make sure they exclusively target weeds and do not damage crops or other plants.
(c) Self-Sustaining- After becoming established, the biocontrol agents create populations that continue to grow, which enables them to manage the weed throughout a large portion of the afflicted region.

Characteristics of Bioagents in Biological weed control

a) Bioagents should be specific to host i.e. they should not attack the useful plants.
b) They should have high reproductive potent to increase their population with respect to weed population.
c) Hardiness should be the key feature of bioagents i.e. they should be free from their own predators and parasites and should be able to survive on their own when devoid of weed population to feed upon.
d) Environmental conditions and varying temperature should not be the constraint to their perpetuation.
e) They should be culturable or will be able for mass production under artificial conditions.
f) They should be responsive to upsurge of weed population.

Table 1. Problematic weeds in India, their entry route and bio-control agents

Weed	Weed introduced from	Bio-control agent	Insect imported from	Mode of action	Remark
Siam weed, *Chromolaena odorata*	Neotropical origin	*Pareuchaetes pseudoinsulata* (Erabidae Lepidoptera)	Trinidad & Srilanka	Caterpillar defoliate plants	It is a perennial shrub that grows very fast. It has allelopathic properties. It poses a risk of fire in woodlands. (Ambica and Jayachandran,1980)
Prickly pear, *Opuntia elatior*, *O. stricta*, *O. vulgaris*	Southern Brazill and Uruguay	*Dactylopius ceylonicus, D. opuntiae* (Dactylopiidae Hemiptera)	Brazil in 1795 USA via Sri Lanka via Australia, 1926;	sucking insect (plant drying & death)	Bringing along as a cochineal dye plant. Grew to be an Indian weed scourge. (Sushilkumar, 1993)
Parthenium hysterophorus	America and the West Indies	*Zygogramma bicolorata* (Chrysomelidae Coleoptera)	Mexico 1984	Adult beetle feeds on leaves; larvae damage foliage	It was accidentally introduced probably through importation of wheat, and it is widespread in India. (Jayanth, 1987; Sushilkumar, 2009)
Water hyacinth *Eichhornia crassipes*	South America	*Neochetina eichhorniae*, *N. bruchi* (Brachyceridae: Coleoptera)	Argentina (via USA) 1983	Feeding on petioles and the underside of leaves. Adult weevils consume and scrape leaves. Grubs enter the plant's petioles and crown through tunnels and feed there. Attached to living water hyacinth roots, the pupate is submerged.	Originally brought to Bengal in 1896 as an ornamental plant, it is now widely distributed throughout India. (Sushil kumar 2011)

Lantana *Lantana camera*	Central & South America	(Seed fly) *Ophiomyia lantanae* (Agromyzidae Diptera)	Introduced from Hawaii	The maggot feed on the seed's fleshy pulp. Due to feeding the viability of seeds is reduced.	Originating in Central and South America, this ornamental plant was first introduced in 1809. Spread extensively throughout India and developed into a significant invasive species. (GISIN-2012)
Giant salvinia/ Water fern *Salvinia molesta*	Native to South-Eastern Brazil but in 1955 entered India from sri lanka	*Crytobagous salviniae* (Curculionidae Coleoptera)	Native to Brazil, was imported from Australia in1982	weevil → destroys aquatic mats	Introduced via botanical gardens, it caused issues in Kerala. Exceptionally effective biological control (Jayanth, 1987)
Crofton Weed *Eupatorium adenophorum*	Mexico	*Procecidochares utilis* (Tephritidae Diptera)	From New Zealand	Food flow is disrupted by gall formation. Lowers the vigour and reproduction of plants	Native to Mexico; spread widely in Himalayan regions. Perennial herb forming dense thickets. Grows in hilly regions. Its effectiveness is hampered by attack of indigenous parasitoids. *P. utilis* has spread into Nepal, where it has become well distributed. (Kapoor and Malia 1978)

Some success stories of biological control of weeds

- **Water Hyacinth, *Eichhornia crassipes***

Eichhornia crassipes (water hyacinth), is a free-floating South American water weed, and one of the most invasive weeds in the world. It was initially introduced in India in the year 1896 in Bengal as an ornamental plant. Once introduced, it quickly got out of control and overgrew to cover more than 200,000 hectares of water bodies such as ponds, lakes, rivers, irrigation canals, and even overgrown rice fields. It prevents irrigation (40-95%), disrupts navigation, fishing, and hydroelectric generation, and enhances the loss of water to evapotranspiration. To control this weed, biological control was launched in India in 1982 by introduction of three exotic natural enemies on their native range (South America through USA): *Neochetina bruchi* and

Neochetina eichhorniae (weevils) and *Orthogalumna terebrantis* (mite). The weevils set in well and offered a great suppression in 2-4 years and particularly in areas such as Hebbal tank Bengaluru (Jayanth 1988) and Loktak Lake Manipur (Jayanth and visalakshi 1989). In such a way, water hyacinth was introduced in South America (1896) and was managed with the help of introduced bioagents (1982).

- ***Parthenium hysterophorus***

A typical example of a globally notorious invasive weed is *Parthenium hysterophorus* (Asteraceae) native to Central and South America and commonly known as the congress grass or Gajar Ghas in India. It was introduced accidentally in India (probably by the means of contaminated grain imports) in the middle of the 20^{th} century (approximately 1950s) and quickly dispersed throughout the country. It has today invaded approximately 35 million hectares of land including agricultural fields, wastelands and forests and is a significant threat to biodiversity, crop production, and human and animal health as it is allergenic. The weed later on proliferated to other countries that were near to India such as Pakistan, Sri Lanka, Bangladesh, and Nepal. The traditional methods of control were found to be expensive and temporary hence the focus put on biological control. Classical biological control In India, there was the initiation of classical biological control in 1983, with the importation of three insects, *Zygogramma bicolorata* (Mexico/USA region), *Smicronyx lutulentus*, and *Epiblema strenuana*. One of these, *Z. bicolorata*, was the only one that was successful and initially introduced in 1984 at Bengaluru. Although it was initially banned (1991) on host grounds it was cleared in 1999 and is now established widely becoming the most successful bioagent against *Parthenium* in India.

- ***Cactus, Opuntia* spp.**

Prickly pear (*Opuntia* spp.) cactus, which originally grew in North and South America, was intentionally introduced to India to make cochineal dye. The major ones were *O. vulgaris, O. stricta* (= *O. dillenii*), which originated in Florida (USA) and the West Indies, and *O. elatior*. With time, these species were not kept in cultivation but propagated vigorously to become serious weeds in North and South India.

Biological control agent was first introduced in 1795, when an insect, *Dactylopius ceylonicus*, was brought to India. It was erroneously presented as the actual cochineal insect *(Dactylopius cacti*) to produce dyes. *Dactylopius ceylonicus*, although commercially not successful because of low quality dye, settled upon *O. vulgaris* and successfully suppressed it in six years. Subsequently, this insect *D.ceylonicus* was intentionally introduced in Sri Lanka in 1865 from southern part of India this was the first deliberate international movement of a weed biological control agent. But it did not manage to contain *O. stricta*. In response, the *Dactylopius opuntiae* was introduced into India in 1926 via Sri Lanka and it was effective in controlling *O. stricta* and *O. elatior*. (Sushilkumar 1993).

- ***Lantana camara***

Lantana camara native to Central and South America, was also introduced in India in 1809 as an ornament. It grew quickly, became invasive and became a threat to biodiversity, forest regeneration, and ecological balance. Lantana invasion became a global issue because it emerged as one of the most invasive species across the world with millions of hectares of India and other nations affected by it. The first attempts of the biological control started in the world with successful introduction in Hawaii, Fiji, and Australia (1902-1910). Systematic work began in 1916, when Dr. Rao described native insect fauna. In 1921, the first exotic agent, *Ophiomyia lantanae* was introduced in Hawaii (origin: Mexico) although it was not very successful at control. Subsequently, some exotic insects were introduced for the control. Notably, the introduction of *Teleonemia scrupulosa* (Mexico) was done in 1941 (Australia). It spread extensively but only partially controlled them because of parasitism. Other agents such as *Uroplata girardi* and *Octotoma scabripensis* also established, and made a small contribution to suppression.

Recent trends in biological control of weeds

1. Expanded use of viruses

- TMGMV strain U2 is the first commercially registered virus-based bioherbicide that has been authorized for the control of tropical soda apples in the United States. Viruses were rarely utilized in this manner before; therefore, this is noteworthy. (Charudattan et al., 2024).
- The search for more plant viruses that may be safe and targeted weed killers is gaining momentum.

2. Fungal and Microbial Agents / Extracts

- Among the more effective bioherbicides are still mycoherbicides, which are derived from fungi. There are currently more than 16 fungal bioherbicide agents in research or in use worldwide (Roberts et al., 2022).
- Also, more research on bacteria, essential oils, allelochemicals, and plant extracts as sources of bioherbicidal activity.

3. Improving Efficacy via Formulation & Environmental Tolerance

- The low field-effectiveness of many bioherbicides because of environmental conditions (UV, humidity, soil moisture, etc.) has been a recurring problem. In order to address them, recent study has concentrated on improved formulations (carriers, surfactants, etc.), timing, and application techniques.
- Knowing the effects of environment and microclimate (temperature, CO_2, etc.) on how biocontrol agents interact with weeds.

4. Customized & Localized Solutions

- The development of bioherbicides suited to certain weed species and regional agroecological zones is gaining more attention. Region-specific strains or agents are becoming more common rather than "one size fits all."
- Additionally, incorporating biological control agents into larger systems (such as conservation agriculture or cropping systems) so that biological weed suppression complements crop rotation, soil cover, etc (Shalini et al., 2024).

5. Integration with Precision Agriculture & Technology

- Use of photography, drones, remote sensing, AI, and machine learning to detect weeds, determine the best time and location for applying bioherbicides (or spot treating), and cut down on waste.
- Site-specific technologies to reduce effects of non-targets. This contributes to the cost-effectiveness and scalability of bioherbicides (Azghadi et al., 2025).

Table 2. Crop specific recent advances in biological control of weeds

Crop	Weed or weed type	Biological advancement	Mechanism/agent
Maize (corn)	*Striga hermonthica* (witchweed)	Use of a fungal bio-herbicide “Kichawi Kill” (strain FoxyT14)	*Fusarium oxysporum* f. sp. *strigae* (virulence-enhanced), applied as inoculum or seed coating
Rice (Basmati, direct-seeded systems)	Broadleaf, grassy & sedge weeds in direct seeded rice; weeds like *Echinochloa*, *Cyperus* etc.	Development of non-GM herbicide-tolerant rice varieties (mutated ALS gene) allowing use of Imazethapyr; also breeding of Provisia trait lines via IRRI & BASF	Mutation breeding / trait introgression for herbicide tolerance; allows selective chemical weed control in DSR (direct seeded rice) systems which act more sustainably than full flooding & transplanting
Bt Cotton	Grassy+ broadleaved weeds in cotton cropping systems	Cultural method: mulching + integrated weed management (weed control via combinations of pre-emergence herbicides and hoeing/hand weeding)	Use of mulch (rice straw), mechanical/cultural weeding, selective herbicide application
Rice/ Maize/ Millet/ Sorghum (Sub-Saharan Africa)	Parasitic weeds (*Striga*)	Microbial bioherbicide / strain for seed coating; village production of inoculum; on-farm production of secondary inoculum	*Fusarium oxysporum* f.sp. *strigae* strain DSM 33471; seed coating formulation; local production of inoculum; bioherbicidal action includes inducing germination, nutrient leakage, etc.
General/ Multiple Crops	Weeds in organic/ reduced chemical systems (corn, soybean etc.)	Robotics / AI / precision spot-spraying / directed energy systems; image recognition; lightweight models for weed detection	Computer vision + AI models; robotics for spot application; directed energy or UV / laser or fine spraying; weed detection via spectral bands etc.

Use of AI and Remote sensing in biological weed control

The potential for improved weed management is ensured by the combination of drones, artificial intelligence, and multiple sensors, such as RGB (red-green-blue), hyperspectral, and multispectral. Remote sensing devices can be utilized to address the majority of the major or minor issues brought on by weed infestation in a variety of agricultural chores. Spectroscopy, optics, computers, photography, satellite launching, electronics, communication, and a number of other disciplines are all included in this multidisciplinary science. These machine learning-based solutions can also help address future issues including herbicide resistance, climate change, supply and demand, sustainability, and food security. The prospective and useful applications of remote sensing and unmanned aerial vehicle technologies in weed management practices are summarized in this paper, along with how they will address upcoming obstacles (Roslim et al., 2021).

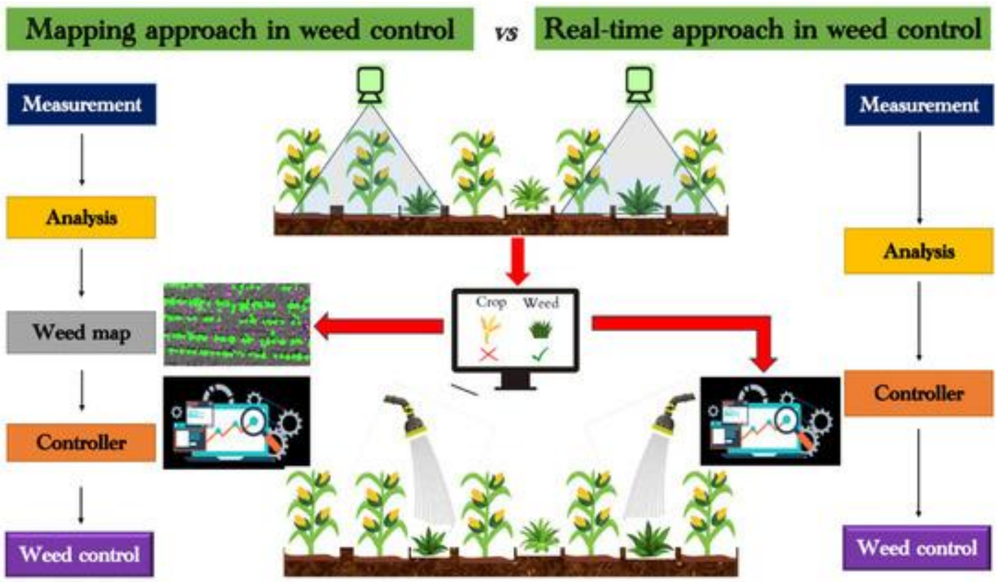

Figure 2. Mapping approach Vs Real time approach in weed control (Source: Vijaykumar et al., 2025)

Table 3. Application of AI and Remote sensing in biological weed control

Aspect	Description	Applications	References
Weed Identification & Mapping	AI models (CNNs, deep learning, machine vision) trained on satellite, UAV (drone), or hyperspectral images detect weed species and densities in real time. This enables site-specific release of biocontrol agents rather than blanket application.	Deep convolutional neural networks (CNNs) have been used to detect *Parthenium hysterophorus* and *Echinochloa crus-galli* from drone images for targeted biocontrol.	(Jin et al., 2023, *Computers and Electronics in Agriculture*); (Guo et al., 2024, *Remote Sensing of Environment*)
Monitoring Biocontrol Agent Performance	Remote sensing helps track the spread, survival, and impact of biological control organisms such as insects, fungi, or pathogens over time. Vegetation indices (NDVI, SAVI, EVI) can measure weed stress after biocontrol release.	NDVI-based UAV surveys monitored the suppression of *Striga hermonthica* in maize after application of *Fusarium oxysporum* bioherbicide.	(Mwangi et al., 2023, *Precision Agriculture*)
Predicting Weed - Biocontrol Interactions	Machine learning models (Random Forest, SVM, LSTM) predict the optimal environmental conditions for biocontrol agent effectiveness (e.g., temperature, humidity, soil type).	AI models predict the success rate of *Puccinia abrupta* infection on *Cirsium arvense* using meteorological and remote sensing data.	(Kaur et al., 2023, *Agricultural Systems*)

Optimizing Timing and Application of Biocontrol Agents	AI algorithms integrate weather forecasts, crop stage, and weed growth models to determine when and where to apply bioherbicides or release insects for maximum impact.	A decision-support system (AI + RS) developed for *Alternaria cassia* bioherbicide application in soybean fields in the U.S. optimized spray timing by 30%.	(Riaz et al., 2024, *Frontiers in Agronomy*)
Drone-based Precision Delivery	AI-guided drones equipped with sprayers can apply microbial bioherbicides precisely over infested patches detected via remote sensing, reducing cost and improving safety.	AI-driven drones applied *Colletotrichum gloeosporioides* bioherbicide patches in tea plantations against *Ageratum conyzoides*.	(Zhang et al., 2024, *Biosystems Engineering*)
Early Warning and Decision-Support Systems	RS data combined with AI models create weed risk maps, predicting future infestations and helping integrate biocontrol in an Integrated Weed Management (IWM) framework.	A hybrid AI-RS model was used in India to predict *Parthenium hysterophorus* invasion zones, supporting biological control planning with *Zygogramma bicolorata*.	(Singh et al., 2023, *Environmental Monitoring and Assessment*)
Evaluation of Ecological Impact	Satellite-based imagery tracks changes in vegetation diversity and ecosystem recovery after biocontrol introduction, helping evaluate non-target effects and ecological safety.	Long-term Landsat and Sentinel-2 data analyzed post-introduction of *Cactoblastis cactorum* for prickly pear control.	(Kumari et al., 2024, *Ecological Indicators*)

Conclusion

From conventional pathogen-based suppression, biological weed control has developed into a multidimensional, technologically integrated strategy that prioritizes ecological balance, sustainability, and accuracy. The effectiveness, stability, and field usability of bioagents have been greatly increased by recent developments, including the development of new microbial and viral bioherbicides, the use of allelopathic plant extracts, and better formulations. Agent delivery and environmental tolerance have been further enhanced by the combination of formulation science, nanotechnology, and biotechnology. By facilitating early detection, precise species identification, and site-specific administration of biological agents, the development of artificial intelligence (AI), remote sensing, and precision agricultural tools has completely changed the way weeds are managed. These developments decrease non-target impacts, improve soil health, and encourage sustainable crop production in addition to lowering reliance on synthetic herbicides. The combination of digital intelligence and biological innovation is essentially ushering in an era of eco-smart weed management, which will ensure environmental stewardship and sustained agricultural productivity.

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