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Review article

Unlocking the potential of bioherbicides for sustainable and environment friendly weed management

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A B S T R A C T

Bioherbicides might be used to manage weeds as opposed to synthetic chemical herbicides, reducing environmental risks and advancing sustainable agriculture in the meantime. Bioherbicides employ different mechanisms of action to control weeds. Microbial bioherbicides may infect and damage weed plants, disrupt their growth, or produce compounds inhibiting weed development. Plant-derived bioherbicides often target specific biochemical processes crucial for weed survival. It can be applied through conventional spraying equipment, seed treatments, or soil incorporation. Bioherbicide development faces several challenges. One major hurdle is the complex diversity of weed species across different regions, requiring tailored bioherbicide solutions. The regulatory approvals for bioherbicides can be lengthy and costly, hindering widespread adoption. Scaling up production processes and ensuring product stability also pose challenges. By reducing reliance on chemical herbicides, bioherbicides can mitigate environmental pollution, protect non-target organisms, and promote sustainable agricultural practices. The development of locally adapted bioherbicides and strategic collaborations between researchers, industries, and policymakers could further enhance their prospects in a particular country. In addition, the knowledge gaps need to be addressed prior to adopting bioherbicides in agriculture. These review intended to explore the existing state of knowledge about the categories of bioherbicides, their formulation procedure, application approaches and mode of action to control weed. The bioherbicides that are currently on the market, their effects on weed physiology, and possible factors affecting their efficacy are all included in this review. Moreover, this review offers a perspective on existing challenges and future opportunities for adopting the bioherbicides in sustainable and eco-friendly agriculture.

1. Introduction

Weed management is a critical task in present-day agriculture and are mainly based on chemical herbicide. Growers have actually no other way to escape chemical dependence because of shortage of agricultural labors due to their migration to cities and other developed countries, and increasing wage costs in agriculture [1,2]. This is a most common scenario in all developing countries, while in developed countries herbicides are already widely used to control weeds. Over and unjudicial use of herbicide in crop field may sometime destroy the off targeted flora and fauna. In some cases, herbicide-resistant weeds have evolved as a result of an over-reliance

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on herbicides with similar mode of action. At present more than 500 unique cases (species x site of action) of herbicide resistant weeds have been reported globally, and have evolved resistance to 21 out of 31 known herbicide sites of action and to 168 different herbicides [3].

In this backdrop, development of alternative weed control techniques warrants due attention in order to lessen herbicide dependency. Biological weed control or bioherbicides is an additional remedy for weed problems, particularly in agriculture. This review aims to determine the role that bioherbicides play in weed control, including how they fit into existing systems, to understand the variables that affect their effectiveness in conventional and alternative management systems, and to evaluate the potential for creating bioherbicide-based weed management strategies.

2. Bioherbicide: conceptual preview

A bioherbicide is a herbicide derived from living organisms like bacteria, fungi, or natural agents, used to control weed growth. Unlike synthetic herbicides, bioherbicides employ biological agents that disrupt essential plant processes, such as metabolism, photosynthesis, and growth hormones [4]. They offer targeted and eco-friendly weed control, posing fewer risks to non-target organisms and ecosystems.

Bioherbicides have an advantage of reduced environmental impact, making them suitable for sensitive areas like organic farms, gardens, parks, and water bodies. They have shorter environmental persistence and are biodegradable, minimizing soil, water, and air pollution. However, they may work more slowly and require multiple applications, differing from chemical herbicides.

In conclusion, bioherbicides are environmentally friendly, minimally affect desired plants, and support eco-friendly weed management, reducing the need for chemical herbicides [5]. See Fig. 1 for their contribution to weed management and mechanism of action. The contribution of bioherbicide in the weed management system with the mechanism of actions of bioherbicide in killing the weeds is stated in Fig. 1.

3. Categories of bioherbicides

Bioherbicides represent a diverse array of weed management tools, characterized by their origin, mode of action, and application. They offer promising alternatives to conventional herbicides, promoting sustainable agricultural practices and minimizing environmental impacts. Here are the examples of various types and categories of bioherbicides with their effectiveness and potential in weed control.

3.1. Microbial bioherbicides

Microbial bioherbicides harness the power of living microorganisms, such as bacteria, fungi, or viruses, to combat weed growth. These remarkable organisms possess unique properties that enable them to suppress weed development or induce diseases in weeds. By targeting weeds at different growth stages and interfering with their physiological functions, microbial bioherbicides have shown significant promise [4,7]. The fact that the costs of research and development for microbial bioherbicides are substantially cheaper than those of synthetic herbicides makes them an excellent choice for controlling agricultural weeds. Unlike weed resistance, which is rapidly evolving, there has not yet been any developed resistance to any microbial bioherbicide [8]. Compared to resistance to a chemical pesticide, resistance to a live microorganism may develop more slowly. Africa is seeing some success with a marketed mycoherbicide that was chosen in a lab to fight the parasitic weed *Striga hermonthica* [8].

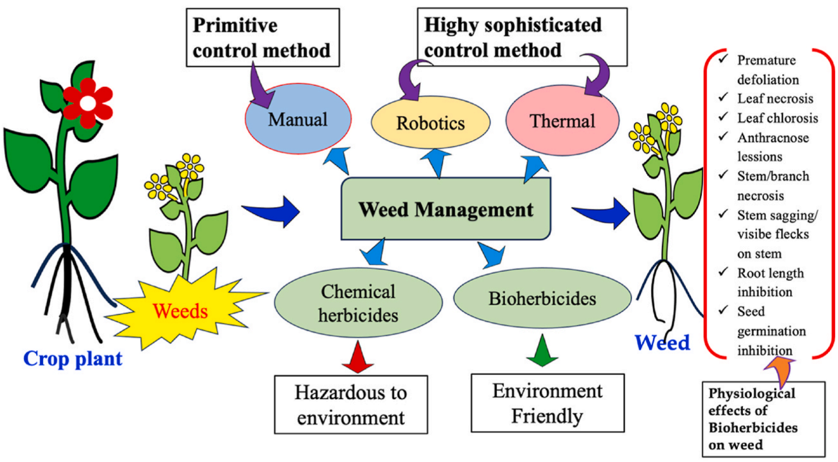

Fig. 1. Graphical representation of contribution of bioherbicides in weed management system and the mechanism of actions of bioherbicide in killing the weed (Modified from Chakraborty & Ray [6]).

3.2. Plant extract bioherbicides

Derived from specific plant parts like leaves, roots, or seeds, plant extract bioherbicides contain natural compounds with herbicidal properties. These bioherbicides leverage the bioactive constituents present in plants to disrupt weed growth and metabolism effectively. Notable examples include extracts from neem, clove, cinnamon, parthenium weed, or vinegar, all of which have demonstrated potent herbicidal effects [6,9]. One well-known example of a bioherbicide that may reduce weeds without reducing yield is phytotoxic water extracts from *S. bicolor* [10]. By using sorghum water extract, the biomass of *E. crus-galli* was reduced by 40 %, which increased rice production by 18 % [11].

3.3. Biochemical bioherbicides

Biochemical bioherbicides are formulated using specific compounds extracted or synthesized from natural sources. These compounds interfere with the biochemical processes of weeds, inhibiting their growth and development. Examples include specific enzymes, plant hormones, or secondary metabolites that exert herbicidal effects [6,12]. A byproduct of ethanol production effectively regulated *Stellaria medium* L. and *P. annua* and reduced the germination of *Oxalis corniculata* L [13]. It has long been known that corn gluten meal (CGM), a byproduct of wet-milling corn, had inherent herbicidal properties [13].

3.4. Biocontrol agents

Biocontrol agents, another type of bioherbicide, employ living organisms, such as insects, nematodes, or predatory animals, to manage weed populations. These organisms act as natural enemies of the weeds, either by consuming them or disrupting their growth. Biocontrol agents are particularly useful for managing invasive weeds or controlling weed populations in natural ecosystems [14,15]. Traditional approaches are not always effective in controlling some weeds. After applying a herbicide, they either swiftly resprout or eventually develop resistance to the herbicide. Nevertheless, as the weed spreads, biocontrol agents reappear.

3.5. Seed-based bioherbicides

Seed-based bioherbicides control weeds during crop germination and early growth by applying specific ingredients to seeds before planting. They protect emerging crops from weed competition and help desired plants establish [16]. Bioherbicides are versatile and eco-friendly weed control methods that use natural organisms or compounds with various modes of action. They require careful selection and application based on weed species, methods, and environmental conditions for optimal and sustainable results. Bioherbicides are expected to play a bigger role in the future of weed management in agriculture and natural ecosystems.

3.6. Allelochemicals as bioherbicides

Allelochemicals are naturally occurring compounds produced by certain plants that can inhibit the growth and development of surrounding competing plants, providing an eco-friendly solution for weed management. Various allelochemicals with bioherbicidal properties have been identified (Table 1), including juglone from black walnut trees, sorgoleone from sorghum, benzoxazinoids from rye, 2-phenylethyl isothiocyanate from mustard plants, catechin from various plants, and eucalyptol from eucalyptus trees [17]. These allelochemicals have shown effective inhibition against a wide range of target weeds, both grasses and broadleaf species, offering potential for sustainable weed control strategies in agriculture and environmental conservation. Moreover, the natural origin of allelochemicals reduces the risk of harmful effects on non-target organisms and minimizes chemical residues in the environment. Further research and development in this field could lead to the formulation of novel bioherbicides with increased efficacy, environmental safety, and cost-effectiveness, contributing to sustainable agriculture practices and weed management [17].

Table 1
Identified allelochemicals which can be used to develop bioherbicides.

Common Name	Chemical Name	Source	Target Weeds	Reference
Avenacin A-1/Oat triterpenoid saponin	3β-{[β-D-glucopyranosyl-(1 → 2)-[β-D-glucopyranosyl-(1 → 4)]-α-L-arabinopyranosyl] oxy}-16β,23-dihydroxy-30-oxo-12β,13-epoxyoleanan-21β-yl 2-(methylamino)benzoate	Oats (*Avena sativa*)	Various Broadleaf	[20]
Juglone	5-Hydroxy-1,4-naphthoquinone	Black walnut trees (*Juglans nigra*)	Various Weeds	[21]
Coumarins	2*H*-1-Benzopyran-2-one	Mulberry (*Morus alba*)	Various Weeds	[22]
Sorgoleone	2-Hydroxy-5-methoxy-3-alkyl-1,4-benzoquinone	Sorghum (*Sorghum bicolor*)	Grass and Broadleaf Weeds	[23]
Caffeic acid	3,4-dihydroxy-cinnamic acid	*Parthenium hysterophorus*	Crab grass, Goose grass	[12]
Phenethyl mustard oil	2-Phenylethyl isothiocyanate	Mustard plants	Various Weeds	[24]
Catechin	(2R,3S)-2-(3,4-dihydroxyphenyl)-3,4-dihydro-2H-chromene-3,5,7-triol	Various plants	Broadleaf Weeds	[25]
Eucalyptol	1,8-Cineole or 1,3,3-Trimethyl-2-oxabicyclo [2.2.2] octane	*Eucalyptus* trees	Various Weeds	[26]

Allelochemicals have several advantages, making them an appealing option for novel herbicide classes. The development of bio-herbicides derived from allelochemicals presents a chance to utilize natural compounds for plant defense and indicates a potential means of managing weeds that have developed resistance to herbicides. Home gardeners are nonetheless concerned about the centuries-old reports of black walnut's allelopathic effects on nearby plants. It is believed that Plinius Secundus, often known as Pliny the Elder, was the first to document the phytotoxic properties of black walnut. The allelochemical generated by black walnut trees (*Juglans nigra*), juglone (5-hydroxy-1,4-naphthoquinone), has been researched for possible uses in a variety of agricultural applications [18]. Numerous members of the large dicotyledonous plant family Lamiaceae are notable for their allelopathic activities in both natural and artificial environments. Therefore, Lamiaceae plants may provide supplies of substitute herbicides [19].

3.7. Essential oil as bioherbicides

Natural volatile molecules called essential oils are extracted from a variety of plant components, including the leaves, bark, flowers, fruits, seeds, roots, and whole plants. Due to their high phytotoxic action against several weed species, terpenoids, namely mono and sesquiterpenes, are the primary active constituents of essential oils and may be good candidates for future bioherbicide formulations. Chlorosis, burning of leaves, decreased plant development, suppression of mitosis, membrane depolarization, loss in chlorophyll content, cellular respiration, and oxidative damage were all aspects of essential oils' phytotoxic potential [27]. The essential oils from *Cistus ladanifer* L. were discovered by Verdeguer et al. [28] to prevent *A. hybridus*, *Portulaca oleracea* L., *C. album*, *Conyza Canadensis*, and *Parietaria judaica* L. from germinating and growing [27].

4. Attainable benefits of bioherbicides

Bioherbicides offer a range of benefits that make them a promising alternative to traditional chemical herbicides in sustainable agriculture. Derived from natural sources such as fungi and plants, bioherbicides are eco-friendly, reducing the reliance on harmful chemical inputs and contributing to biodiversity and ecosystem health [5,29]. Their targeted action allows for precise control of specific weed species while sparing beneficial plants, making them a valuable component of integrated weed management systems [30]. Additionally, bioherbicides pose no risks to human health or beneficial organisms, unlike chemical herbicides, and break down into non-toxic compounds, preventing pesticide residue build-up in the environment and maintaining soil and water quality [30]. In the face of herbicide-resistant weeds, bioherbicides offer effective control options and can complement other management strategies such as crop rotation and tillage [5,30]. Embracing bioherbicides can lead to a more environmentally responsible and productive agricultural landscape, demonstrating their potential to revolutionize sustainable crop production [31].

5. Bioherbicides production

Bioherbicides manufacturing involves a series of crucial steps, as outlined below.

5.1. Target identification

The initial and fundamental step in bioherbicide manufacturing is the precise identification of the target weed or weeds. Different weed species may necessitate distinct approaches or active ingredients for effective control [32].

5.2. Isolation, selection and cultivation of active ingredients

In the case of living organisms being chosen as the active ingredient, they are isolated or collected from their natural habitat. Once the target weed is identified, scientists and researchers meticulously select the active ingredients for the bioherbicide. These ingredients can consist of living organisms, such as bacteria, fungi, or viruses, or they may be specific compounds derived from plants or other natural sources [33]. Subsequently, scientists cultivate or grow these organisms under controlled laboratory conditions to obtain a sufficient quantity for the manufacturing process.

5.3. Formulation development

During this crucial stage, the selected active ingredients are skillfully combined with other formulation agents. These agents are added to enhance the stability, effectiveness, and delivery of the bioherbicide as discussed earlier [32]. The formulation of bioherbicides plays a pivotal role in their efficacy and ease of use. A well-designed bioherbicide contains a combination of ingredients which are categorized into three groups.

5.3.1. Active ingredients

The cornerstone of any bioherbicide formulation lies in its active ingredients, which directly target and control weed growth. These active components may consist of living organisms like bacteria, fungi, viruses, or specific compounds derived from natural sources such as plants. Their mechanisms of action disrupt weed growth, damage weed cells, or interfere with metabolic processes, ultimately reducing the weeds' ability to survive and compete with desired plants [34].

5.3.2. Formulation agents

The formulation agents, are integrated into the bioherbicide to enhance its performance and stability. The following formulation agents are commonly used.

a) ***Water:*** Serving as a diluent and carrier for the active ingredients, water promotes even distribution of the bioherbicide and facilitates its absorption by plants.
b) ***Oils:*** Vegetable oils or mineral oils are often incorporated into the formulation to improve its adhesion and spreading properties. This enables better coverage of the bioherbicide on weed leaves, maximizing its overall effectiveness.
c) ***Surfactants:*** Surfactants are added to lower the surface tension of liquids, enabling the bioherbicide to spread more effectively on weed surfaces. They aid in adherence to weed leaves and improve absorption.
d) ***Additives:*** To extend the stability and shelf life of the bioherbicide formulation, additives like preservatives, stabilizers, or emulsifiers are included. These additives prevent the bioherbicide from degrading or separating over time [34,35].

5.3.3. Adjuvants

Adjuvants are supplementary substances that do not directly target weeds but significantly enhance the bioherbicide's application process. Key adjuvants include.

a) ***Spreader-Stickers:*** These adjuvants ensure even distribution of the bioherbicide over the weed's surface and improve its adherence, preventing runoff or wash-off by rainfall.
b) ***Penetrants:*** Penetrants enhance the bioherbicide's ability to infiltrate the waxy cuticle of weed leaves, facilitating better absorption into the plant tissues.
c) pH AdjusterspH adjusters are utilized to modify the acidity or alkalinity of the bioherbicide solution. Adjusting the pH optimizes the bioherbicide's effectiveness and compatibility with other ingredients [34–36].

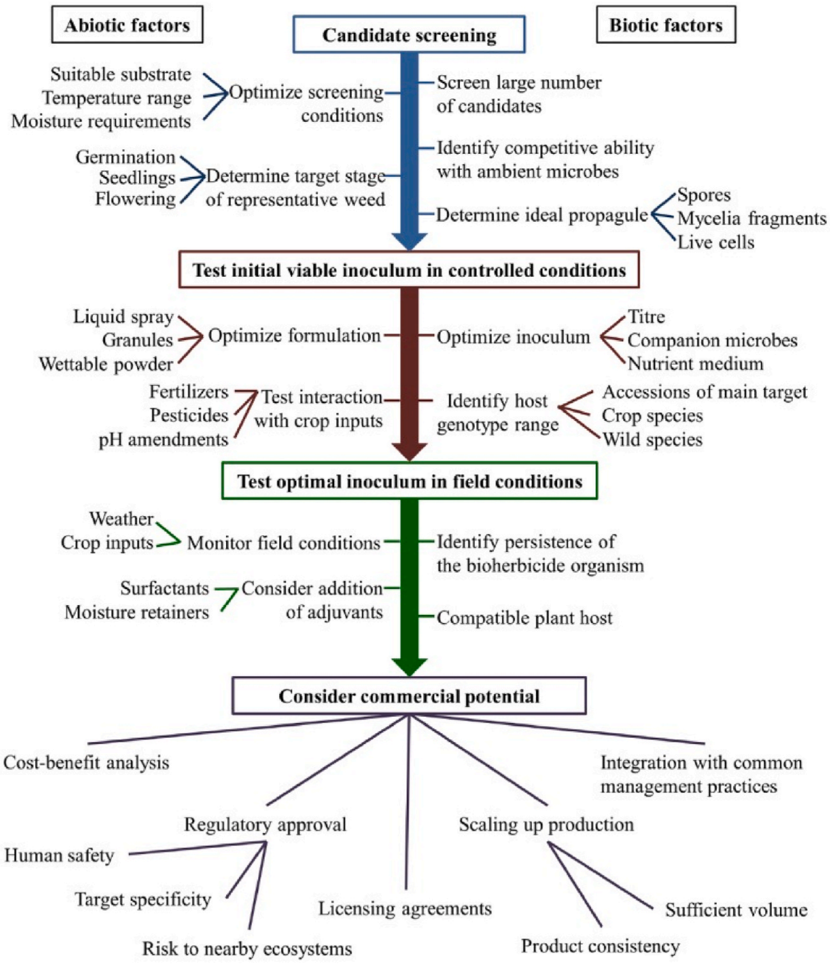

Fig. 2. Steps and factors involved in bioherbicide development [39].

Properly formulated bioherbicides hold great promise for sustainable and eco-friendly weed management in both agricultural and non-crop settings. By carefully selecting the right combination of active ingredients, formulation agents, and adjuvants, bioherbicides can effectively control weeds while minimizing adverse effects on the environment and non-target plants. As research in bioherbicides advances, their integration into integrated weed management strategies offers a potential pathway for a greener and more sustainable future.

5.4. Quality control

Stringent quality control measures are implemented throughout the manufacturing process to ensure that the bioherbicide adheres to specific standards of effectiveness, safety, and consistency. Comprehensive tests and evaluations are conducted by scientists and technicians to assess the potency, stability, and purity of the bioherbicide.

5.5. Packaging and distribution

Upon successful completion of quality control checks, the bioherbicide is packaged into suitable containers, such as bottles or bags, in preparation for distribution. Proper labeling and detailed instructions are provided to ensure safe and effective usage.

The manufacturing process may vary depending on the specific type of bioherbicide being produced and the manufacturer's procedures [37]. The ultimate objective is to develop bioherbicides that effectively target weeds while remaining environmentally safe and benign to non-target plants [38]. The production of bioherbicides demands meticulous research, scientific expertise, and strict adherence to regulatory guidelines to ensure their quality and efficacy. Mathur and Gehlot [39] describe the details of different steps and factors to be considered during bioherbicides production (Fig. 2).

6. Bioherbicides in the market

Despite the limited commercial availability of bioherbicides on a global scale, there exists a notable array of bioherbicide examples currently in practical application, as depicted in Table 2. These bioherbicides offer promising solutions to address weed challenges in diverse agricultural and non-crop settings. A few widely-used bioherbicides with their uses are given below -

DeVine: Devine is a bioherbicide that contains the fungus *Phoma macrostoma*. It is used to control broadleaf weeds in soybean and other crops [40].

BioAster: BioAster is a bioherbicide that contains the fungus *Phoma exigua*. It is used to control Canada thistle in alfalfa and other crops [41].

MycoLogic: MycoLogic is a bioherbicide that contains the fungus *Colletotrichum truncatum*. It is used to control velvetleaf and other broadleaf weeds in soybean and other crops [41].

Agralawn: Agralawn is a bioherbicide that contains cinnamon oil, clove oil, and other essential oils. It is used to control crabgrass

Table 2
A list of registered bioherbicides available in the market (Modified from Morin [42]).

Product name	Registration		Active ingredient	Target weed (s)
	Year	Country		
Di-Bak® Parkinsonia	2018	Australia	*Lasiodiplodia pseudotheobromae, Neoscytalidium novaehollandiae, Macrophomina phaseolina*	*Parkinsonia aculeata*
WeedLock	2017	Malaysia	Plant extract (*Solanum habrochaites)*	Multiple weeds
BioWeed		USA	Sea weed, *Ascophyllum nodosum*	Multiple weeds
Bioweed™	NA	Australia	Pine oil (10 % concentration) + sugar	Herbaceous and grassy weeds
Bialaphos®	2016	Eastern Asia	*Streptomyces hygroscopicus*	Multiple weeds, Broad-spectrum and post-emergence bioherbicide
Katana®	2016	USA	Pelargonic acid	Broadleaf and grassy weeds
Barrier H	2015	Europe, Japan, USA	22.9 % citronella oil	Ragwort
Bio-Phoma™	2016	Canada	*Phoma macrostoma*	Numerous broad-leaved weeds
Phoma™	2012	USA		
Sarritor®	2009	Canada	*Sclerotinia minor*	*Taraxacum officinale* and other broad-leaved weeds
NaturCur	2009	USA	Black walnut extract	Horseweed, Parslane, Tall morning glory
Lubao No. 1	2003	China	*C. gloeos poroides f. sp. cuscutae*	*Cuscutae australis*
Chontrol™	2004	Canada, USA	*Chondrostereum purpureum*	*Populus* and *Alnus* spp.
MycoTech™	2005	Belgium, Canada	*Chondrostereum purpureum*	Deciduous tree species
Collego™	1982	USA	*Colletotrichum gloeosporioides* f. sp. *aeschynomene*	*Aeschynomene virginica*
LockDown™	2006			
Camperico™	1997	Japan	*Xanthomonas campestris pv. poae*	Turf grass weeds
BioMal	1992	USA	*C. gloeosporioides (Penz.) Sacc. f. sp. malvae*	*Malva pusila*
DeVine™	1981, 2006	USA	*Phytophthora palmivora*	*Morrenia odorata*

and other grassy weeds in lawns [31].

BioWeed: BioWeed is a bioherbicide that contains the seaweed extract *Ascophyllum nodosum*. It is used to control a variety of weeds in crops such as corn, soybean, and wheat [6].

BioSafe: BioSafe is a bioherbicide that contains citric acid and other organic acids. It is used to control weeds in lawns, gardens, and other non-crop areas [41].

7. Techniques and approaches for bioherbicides application

The efficacy of bioherbicides varies depending on the application method employed, making it essential for users to understand the different techniques available. Selecting the most appropriate application method depends on various factors, including the type of bioherbicide, the target weed species, and the crop plants involved. Adhering to the instructions provided by the bioherbicide manufacturer is crucial to ensuring both effective and safe application [43,44]. Effective weed management through bioherbicides necessitates a thoughtful choice of application method. As research continues to advance, bioherbicides hold the promise of becoming even more effective and essential tools for integrated weed management strategies. The key methods used for applying bioherbicides and their proper implementation are described below-

7.1. Foliar application

Foliar application stands as one of the most common methods for utilizing bioherbicides. This approach involves directly spraying the bioherbicide onto the leaves of target weeds or crop plants. By utilizing sprayers or appropriate equipment, the bioherbicide is evenly distributed over the foliage. Upon application, the bioherbicide is absorbed through the leaves and stem, and subsequently translocate to the roots, effectively disrupting the growth and development of weeds [45].

7.2. Soil application

Applying bioherbicides directly to the soil surrounding crop plants constitutes soil application. This can be achieved through spraying or applying the bioherbicide in granular or powdered form onto the soil surface. To enhance its efficacy, the incorporation of the bioherbicide into the soil can be facilitated through tilling or watering, allowing it to come into contact with weed seeds or young weed plants in the soil. As weeds germinate or grow, they encounter the bioherbicide, which impedes their growth and development [45].

7.3. Seed treatment

Seed treatment involves applying bioherbicides to seeds before planting. This method entails coating the seeds with a bioherbicide solution or powder. Once the treated seeds are sown into the soil, the bioherbicide serves to protect emerging crop plants from weed competition by inhibiting weed growth around the seeds.

7.4. Pre-emergence and post-emergence application

Bioherbicides can be applied either before the weeds emerge (pre-emergence) or after the weeds have already sprouted (post-emergence). Pre-emergence application involves applying the bioherbicide to the soil or crop plants before weed growth commences. Conversely, post-emergence application is carried out when the weeds are already visible, and the bioherbicide is directly applied to the weeds.

7.5. Spot treatment

Spot treatment is a selective application method in which the bioherbicide is applied only to specific areas where weeds are present, rather than treating the entire field. This targeted approach proves effective for managing isolated patches of weeds while minimizing exposure of crop plants to the bioherbicide.

8. Principles for mixing different ingredients

Effective development of bioherbicide formulations hinges on adhering to essential principles during the mixing of different ingredients. Compatibility is paramount, requiring careful selection of components that blend harmoniously to avoid undesirable reactions or reduced efficacy [6,46]. Concentration is another critical factor, with optimal levels ensuring effectiveness against target weed species while safeguarding non-target plant safety [47,48]. Stability is key to maintaining bioherbicide effectiveness over time, necessitating formulation designs that consider factors like temperature, pH, and light exposure to enhance shelf life [49]. Synergistic effects are also explored, as certain ingredient combinations can exhibit greater combined action than their individual contributions, thereby enhancing overall efficacy [47,48]. Safety is of utmost concern, with thorough assessments of toxicity and risks associated with components ensuring that bioherbicides control weeds effectively while minimizing adverse impacts on the ecosystem [6]. These principles collectively provide efficient weed control solutions, promoting sustainable and environmentally friendly agricultural practices.

9. Bioherbicides mode of action

Bioherbicides have emerged as a promising alternative for effectively controlling weeds through various mechanisms. Several common modes of action have been identified.

9.1. Growth inhibition

Certain bioherbicides contain compounds that disrupt the growth and development of weeds. These bioherbicides specifically target essential proteins or hormones crucial for weed growth, resulting in a significant slowdown or complete cessation of further weed development [50]. The target sites were described by Teicher [51] in weed physiology within the thylakoid membrane, where the bioherbicides affect the metabolism of the weeds and finally kill these (Fig. 3).

9.2. Cell structure disruption

Other bioherbicides focus on damaging the cell structure of weeds. By compromising the outer protective layer of weed cells, these bioherbicides render the weeds more susceptible to desiccation or invasion by harmful microorganisms. Consequently, the weakened weed struggles to survive and reproduce effectively [51].

9.3. Metabolic process interference

Bioherbicides can also interfere with the metabolic processes of weeds [51]. Teicher [51] also illustrate the target sites within the mitochondria of weeds, where the bioherbicides affect their metabolism (Fig. 3). By disrupting the weed's ability to convert nutrients into energy or perform other vital functions, these bioherbicides debilitate the weed, hindering its growth and spread.

9.4. Disease induction

Some bioherbicides utilize living microorganisms, such as bacteria or fungi, to induce diseases in weeds. These microorganisms infect the weeds and multiply, leading to the development of diseases that weaken or kill the weeds. This approach leverages natural enemies of weeds to control their populations effectively[29] [7].

The specific mode of action of a bioherbicide depends on the substances or microorganisms it contains. Moreover, bioherbicides are typically formulated to target specific types of weeds while minimizing any impact on desired plants or the environment [52]. In summary, bioherbicides disrupt weed growth, damage their cells, interrupt metabolic processes, or induce diseases, ultimately reducing the weeds' ability to survive and compete with desired plants [16,17].

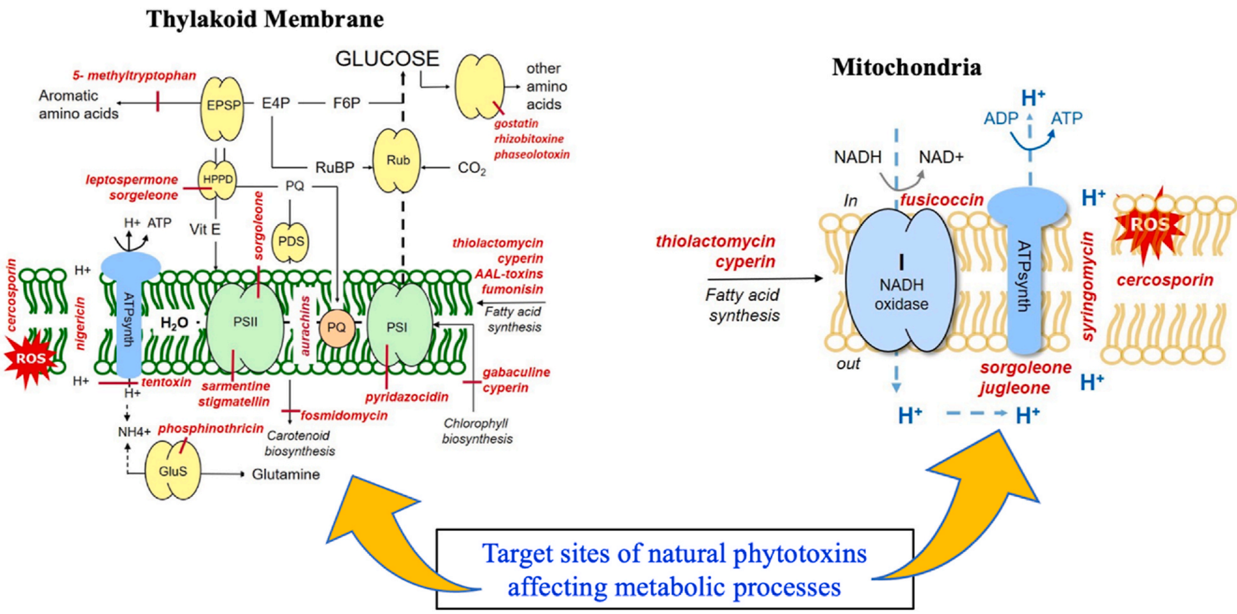

Fig. 3. Target sites of natural phytotoxins affecting metabolic processes within the thylakoid membrane and mitochondria (adopted from Teicher [51]).

10. Successful, challenges and prospects of bioherbicide development in asia

The advancement of bioherbicides in Asia, like any other region, presents a unique set of obstacles [53]. Some of the primary challenges specific to bioherbicide development in Asia include.

10.1. Biodiversity and complexity

Asia boasts remarkable biodiversity with a vast array of plant species, including numerous weed varieties. This complexity makes it difficult to identify and develop bioherbicides that can precisely target specific weed species without harming non-target plants. Thorough research and extensive testing are necessary to ensure the bioherbicides' effectiveness and specificity.

10.2. Climate variability

Asia encompasses diverse climates, ranging from tropical to temperate regions. These differing climates influence weed growth and behavior, making it challenging to design bioherbicides that consistently perform well across all regions and seasons [59].

10.3. Funding and research infrastructure

Sufficient funding and research infrastructure are critical for bioherbicide development. In some Asian countries, there might be limited financial resources and scientific capabilities dedicated to this research area, impeding progress and innovation.

10.4. Regulatory hurdles

Developing and commercializing bioherbicides requires compliance with regulatory frameworks to ensure safety and effectiveness. In certain Asian countries, the regulatory processes for bioherbicides might be less established or more stringent, leading to delays and additional costs in product development and registration.

10.5. Adoption and awareness

Convincing farmers and agricultural stakeholders to adopt bioherbicides can be challenging, especially if they are accustomed to using conventional chemical herbicides. Raising awareness about the benefits and safety of bioherbicides and providing education and training on their proper use are crucial for widespread adoption.

10.6. Scaling up production

Scaling up bioherbicide production to meet the demands of vast agricultural areas can be a complex task. It may require specialized facilities and technologies, and ensuring a stable and cost-effective supply can be challenging.

10.7. Competition with chemical herbicides

Chemical herbicides have been extensively used in Asian agriculture for decades, and they are often readily available and affordable [2]. Convincing farmers to transition from familiar chemical herbicides to bioherbicides may require incentives and government support.

10.8. Pest resistance

Similar to chemical herbicides, there is a risk of weeds developing resistance to bioherbicides over time. Employing strategies that minimize the chances of resistance development, such as rotating different control methods, is essential.

Despite these challenges, the development of bioherbicides in Asia holds great promise for sustainable and environmentally friendly weed management [53,54]. Collaborative efforts between governments, research institutions, and private enterprises are vital to overcome these obstacles and realize the potential benefits of bioherbicides for agriculture and environmental conservation in the region.

10.9. Prospect of bioherbicide in asia

Bioherbicides offer Asia a promising, eco-friendly solution for sustainable weed management and environmental conservation [30,53]. The region's rich biodiversity requires tailored solutions, and bioherbicides can provide targeted weed control without harming non-target plants. These natural alternatives reduce environmental impact, minimize pollution, and preserve beneficial organisms.

Asia's diverse climates make bioherbicides adaptable to various regions, offering customized solutions. Traditional knowledge can lead to region-specific bioherbicides, tapping into indigenous plants and natural substances with herbicidal properties. Their adoption reduces chemical residues in produce and benefits both farmers and consumers concerned about food safety [30].

Bioherbicides spare beneficial organisms, unlike chemical herbicides, which can disrupt ecosystems. They also open doors for research and collaboration, accelerating progress in the field. Government support and policy incentives promote sustainable practices, encouraging the use of bioherbicides in agriculture. Moreover, Asian countries have export potential, meeting the global demand for organic, eco-friendly products.

Despite the potential, challenges like research costs, production scaling, farmer adoption, regulation, and pest management strategies need attention. However, with joint efforts from governments, research institutions, and private enterprises, the future of bioherbicides in Asia holds promise, fostering sustainable agriculture and environmental stewardship.

10.10. Case studies on successful usages of bioherbicide

A Bioherbicide in Organic Weed Control in Vineyards

Crop: Grapes (*Vitis vinifera*)
Bioherbicide: Acetic Acid (vinegar-based)
Location: California, USA.
Description: In this case study, researchers and vineyard managers explored the use of acetic acid as a bioherbicide to control weeds in organic vineyards. Acetic acid, a natural compound found in vinegar, acts as a contact herbicide, desiccating weed foliage upon application. It is an attractive option for organic growers seeking effective weed control without synthetic chemicals. The study found that targeted application of acetic acid reduced weed competition around grapevines, resulting in increased vine growth and yield. Additionally, the bioherbicide showed minimal negative impacts on the surrounding environment and maintained the vineyard's organic certification.

B Bioherbicide for rangeland weed management

Target Weed: Leafy spurge (*Euphorbia esula*)
Bioherbicide: Extract from *Artemisia absinthium* (wormwood)
Location: Rangeland ecosystem (USA)
Description: In a rangeland area infested with leafy spurge, researchers investigated the potential of using *Artemisia absinthium* (wormwood) extract as a bioherbicide for weed control. The extract was applied as a spot treatment on patches of leafy spurge infestations. After multiple applications over two growing seasons, the wormwood-based bioherbicide showed significant suppression of leafy spurge, promoting the establishment of native grasses and improving forage availability for livestock. The study demonstrated the feasibility of using plant-based bioherbicides for managing invasive weeds in rangeland ecosystems [55].

C *Colletotrichum gloeosporioides* as a bioherbicide for congress weed control

Target weed: *Parthenium hysterophorus*.
Bioherbicide: *Colletotrichum gloeosporioides*.
Location: India.
Description: Congress weed (*Parthenium hysterophorus*) is a highly invasive weed that can be difficult to control with traditional herbicides. However, *C. gloeosporioides*, a fungus, has been used as a bioherbicide to control congress weed [5]. The bioherbicide approach to weed management involves the use of selected microorganisms for attacking specific weeds and controlling their growth. *C. gloeosporioides* has been shown to be effective in controlling congress weed, and it has the added benefit of being non-toxic to humans and animals. The use of the bioherbicides, *C. gloeosporioides* is an emerging weed control strategy towards sustainable agriculture.

D Weed control in Citrus groves

Target Weed: Strangler fig (Moraceae)
Bioherbicide: *Phytophthora palmivora*.
Location: Florida, USA.
Description: Strangler fig is a major weed problem in citrus groves in Florida. In a study conducted in Florida, *Phytophthora palmivora*, a fungal bioherbicide, was found to be effective in controlling strangler fig, with a control rate of up to 80 % [56]. The fungus was originally isolated from strangler vine (*Morrenia odorata*) in Florida and was used to control the same species in citrus orchards [57]. The bioherbicide approach to weed management involves the inundative use of selected microorganisms for attacking specific weeds and controlling their growth [55]. *P. palmivora* showed the ability to control the weed [58]. DeVine, a formulation of the fungus *P. palmivora*, was registered with the EPA in 1981 and again in 2006. Although this product was re-registered in 2006, it is no longer commercially available.

11. Limitations of bioherbicides

The use of bioherbicides in agricultural weed management is limited by several factors. Effectiveness constraints are a significant issue, as bioherbicides may not adequately control all weed species and can be influenced by environmental conditions, leading to slower action compared to chemical herbicides [41]. Additionally, bioherbicides often exhibit high host specificity and limited efficacy against certain types of weeds, making them less versatile in weed control [6,41]. Practical constraints in field use, such as availability, cost, and specialized production techniques, further hinder their widespread adoption [55,60]. Continuous research and development efforts are crucial to address potential weed resistance and enhance the potency of bioherbicides over time [6,41]. Integration with other weed management strategies is often necessary for optimal weed control, highlighting the complementary rather than standalone nature of bioherbicides [6,30]. While bioherbicides are most effective in annual cropping systems and offer environmental benefits, their limitations underscore the need for ongoing research and development to improve their efficacy and accessibility [55]. Despite these challenges, bioherbicides remain a valuable tool in weed management, particularly in situations involving herbicide-resistant weeds and environmentally sensitive areas, contributing to integrated weed management strategies [6,41].

12. Concluding remarks and future perspectives

Bioherbicides are eco-friendly tools for sustainable weed management. Despite considerable research, there are only a few commercially available bioherbicides worldwide due to limitations in their development. Potential bioherbicides may be developed from pathogens, natural products, and extracts of natural materials. Fungal and bacterial pathogens are two important sources of bioherbicides. Environmental factors influence the formulation performance of bioherbicides as inoculum production is dependent on sporulation of the formulation. Several technological limitations have been identified that could prevent the widespread use of bioherbicides, including pathogenic strains, formulation method, and the interaction of these two parameters. A higher level of allelopathy might be obtained by imparting or increasing the production of allelochemicals in crops using more advanced genetic manipulation. Bioherbicides represent a promising avenue for sustainable weed management in agriculture. While facing challenges in development and implementation, their environmentally friendly nature and potential benefits make them an attractive option for weed control in crop fields and non-cropped areas. These strategies will be of especially great value to organic production systems and to regions where cosmetic pesticide bans are in place.

Enhancing the formulation of bioherbicide active ingredients is a critical component that determines a bioherbicide product's efficacy; so, going forward, it should receive significant attention. Researchers should have to give more emphasis on isolation and identification of novel allelopathic substances originating from natural sources. Once their bioactivity has been confirmed in both laboratory and field settings, then these compounds have to recommend for further development of bioherbicides for sustainable agriculture. In many situations, it is not practical to employ allelochemical extracts directly as bioherbicides in the field due to their high cost and quick degradation. This issue may be solved if the chemical industry developed better bioherbicide formulations to increase their efficacy and, if it is more practical, synthesized the necessary allelopathic substances instead of sourcing them from the natural sources.

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Data will be made available on request.

CRediT authorship contribution statement

A.K.M. Mominul Islam: Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Conceptualization. **Sarker Mohammad Rezaul Karim:** Writing – original draft, Supervision, Resources, Conceptualization. **Sinthia Afsana**

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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