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Bioherbicides and agroecology: challenges and opportunities for agroecological weed management

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The limited availability of herbicides for weed management, coupled with the rapid expansion of herbicide-resistant weed populations, has intensified the need to explore alternative weed management strategies, particularly for producers transitioning to and/or operating in organic farming systems. The expansion of bioherbicides in the US market has opened new opportunities in weed control and new research avenues for weed management. Bioherbicides are natural substances with herbicidal activity, and are mostly non-selective and do not translocate within plants. They are directly connected with agroecological principles by serving as sustainable, nature-derived complementarily to synthetic herbicides aiming to control weeds while preserving biodiversity, soil health, and ecological balance. Their non-selective activity requires special attention because they may also affect crops, while targeted application may be needed for safe use. Because some bioherbicides are new to the market, data on their effectiveness against troublesome weeds is limited. Therefore, bioherbicides, when integrated with precision application technologies and non-chemical tactics, may serve as a bridging strategy for systems facing herbicide resistance. This perspective discusses the challenges and opportunities of bioherbicides as a new tool for weed control, with particular attention to application technology, regulatory pathways, and ecosystem services.

KEYWORDS
agroecology, bioherbicides, natural herbicides, regulatory, weeds

1 Introduction

Weeds are among the most economically damaging agricultural pests, causing significant yield losses and increasing production costs (Storkey et al., 2021). These challenges are exacerbated by the limited and slow development of new herbicide modes of action. The high cost of developing new herbicides, often exceeding $300 million, has greatly limited the introduction of new modes of action, with only one new herbicide mode of action released in the past 40 years (Duke, 2012). Meanwhile, herbicide resistance has spread rapidly over the years, causing yield losses worldwide due to weed control failures (Beckie, 2020). Over the past decade, natural herbicides, commonly referred to as bioherbicides, have gained increasing attention and have become commercially available, providing additional options for weed control (Brankov et al., 2025a). Bioherbicides are weed control agents derived from phytopathogenic microorganisms, plant- or synthetic-derived compounds (discussed later in this review), or their natural metabolites (Hoagland et al., 2007). They are typically applied at high rates to suppress target weeds and, alike conventional herbicides, require repeated applications each cropping season. Bioherbicides are directly linked with specific agroecological principles by Snapp (2017) and Brankov et al. (2025b): i) enhancing biodiversity and ecosystem health, ii) by minimizing or reducing synthetic chemical inputs; iii) enhancing ecological resilience; iv) supporting sustainable soil management; and v) integrated or agroecological weed management. Furthermore, there is a disproportionate economic burden between organic and conventional production systems due to the unequal distribution of costs and risks. While organic farming may often be more profitable due to price premiums, it carries greater financial burdens in areas where conventional systems are highly optimized for efficiency (Riar et al., 2025). Therefore, by using bioherbicides as natural-based agents to complement crop diversification and improve soil health, they may serve as a foundational component of agroecological cropping systems, driving a transition toward reduced external inputs and strengthening essential ecosystem services for long-term sustainability.

2 Bioherbicides: definition, types, and efficacy

Bioherbicides are biologically active agents used for weed control that are delivered from natural sources (microorganisms (fungi, bacteria or viruses), essential oils and allelochemicals, and natural products, or insects) (Parven et al., 2025). The classification of bioherbicides is presented in Table 1.

Bioherbicides commonly lack a clearly defined mode of action and induce rapid contact-type tissue necrosis shortly after application. They are non-selective and do not translocate within the plant (Zhang et al., 2025), thereby posing many challenges for their integration into weed management programs. Some of the challenges are listed below and will be discussed in this review (Figure 1). Bioherbicides do not translocate in weeds and, consequently, weeds might regrow (Figure 2).

Currently, the use of bioherbicides often requires greater management investment than conventional synthetic herbicides (Duke, 2024), as they are typically labeled for application at high rates (up to 15% v v^{-1} or greater) (Peng and Wolf, 2008). Some bioherbicides have been available on the market for almost a decade (e.g., pelargonic acid) (Loddo et al., 2023), whereas others are entirely new, and data on their efficacy are limited. Furthermore, guidance on product labels regarding application technology, including the selection of suitable operational parameters such as nozzle type and spray additives, remains limited, highlighting the need for further research.

Currently, most of the research (Table 2) on weed control using bioherbicides is conducted under controlled conditions (greenhouse experiments), while research under real-field conditions is limited because of the limitations on the use of bioherbicides (non-selective nature) (Radhakrishnan et al., 2018). Literature reported various results using bioherbicides on several weed species, mostly pelargonic acid (Loddo et al., 2023). According to their results, complete and consistent weed control with pelargonic acid is rarely achieved with a single application of herbicide. As reported, higher efficacy was achieved against broadleaved weeds than against grassy weeds. The restricted application window of bioherbicides limits their use to pre-plant, pre-emergence, or post-harvest. In those situations, most weeds will not be affected by the application (Cordeau et al., 2016). As the MOA of bioherbicides is complex and largely unknown, most studies to date have not attempted to elucidate their mechanism of action.

TABLE 1 **Bioherbicide classification, examples, and mode of action (MOA) (adapted from Zhang et al., 2025).**

Group	Examples	MOA
Microbial: fungi	*Colletotrichum gloeosporioides*, *Phytophthora palmivora*, *Phoma macrostoma*	Induces disease (stem/leaf blight, root rot); produces phytotoxins that cause photobleaching and root inhibition.
Microbial: bacteria	*Xanthomonas campestris*, *Pseudomonas fluorescens*, *Streptomyces acidiscabies*	Produces secondary metabolites (thaxtomin A) that inhibit cell wall synthesis or root growth; induces systemic infection in wounded tissues.
Microbial: viruses	Tobacco Mild Green Mosaic Virus, Araujia Mosaic Virus	Systemic infection that stunts growth or leads to plant death; primarily used for specific invasive species.
Essential oils	Clove oil, Cinnamon oil, Citrus oil, Eucalyptus oil	Rapidly disrupts cell membrane integrity (burn-through); inhibits respiration and reduces chlorophyll content.
Allelochemicals	Juglone (Black Walnut), Sorgoleone (Sorghum), Citric Acid	Interferes with photosynthesis (PS II inhibition), mitochondrial respiration, and electron transport; can act as auxin mimics.
Natural products	Corn Gluten Meal, Mustard Seed Meal	Inhabits seed germination and seedling emergence; often works by releasing allelopathic compounds during degradation.
Fatty acid-based	Pelargonic acid, caprylic acid, ammonium nonanoate	Disturbing cell membranes

Several plant-derived and fatty acid–based bioherbicides have been evaluated for weed-control efficacy, with studies consistently showing rapid, contact-only activity. Ammonium nonanoate has demonstrated superior post-emergence efficacy, with field studies reporting 88 to 98% weed suppression, indicating strong burndown potential when applied to young weeds (Parkash et al., 2022). Similarly, formulations containing caprylic and capric acids have shown substantial, rapid efficacy, reducing weed cover by up to 98% within 72 hours of application in perennial systems (Appleby et al., 2025). Likewise, D-limonene–based herbicides have demonstrated substantial weed injury and reductions in vegetative cover in field and greenhouse trials, although their performance is often

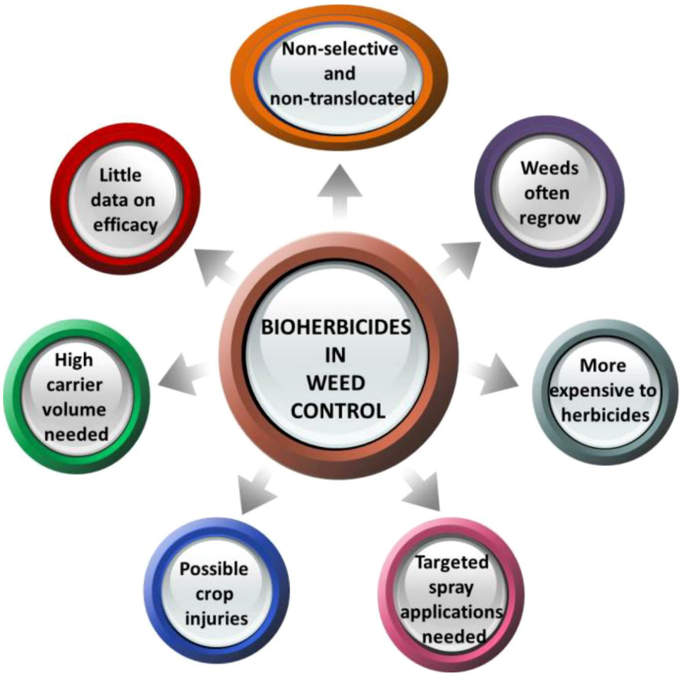

FIGURE 1
Challenges in bioherbicide applications.

somewhat lower or more variable than that of fatty-acid herbicides. Bioherbicides derived from microorganisms have been also evaluated for weed control. A bioherbicide derived from *Phoma macrostoma* Mont. achieved 80–100% control of *Taraxacum officinale* F.H. Wigg. and *Cirsium arvense* (L.) Scop (Bailey, 2014; Zhou et al., 2004). Furthermore, a product containing *Fusarium oxysporum* demonstrated 71–95% efficacy against *Striga hermonthica* (Delile) Benth (Wolde Assena et al., 2025). Overall, the literature indicates that these bioherbicide actives can provide rapid, high initial weed control, particularly on small, emerged weeds, but efficacy can decline with larger plants or perennial species due to their primarily contact-mode of action.

3 Regulatory framework

Bioherbicides can be used in either conventional or organic production systems, while for the organic, they have to be approved by the organic certified institutions (Organic Material Review

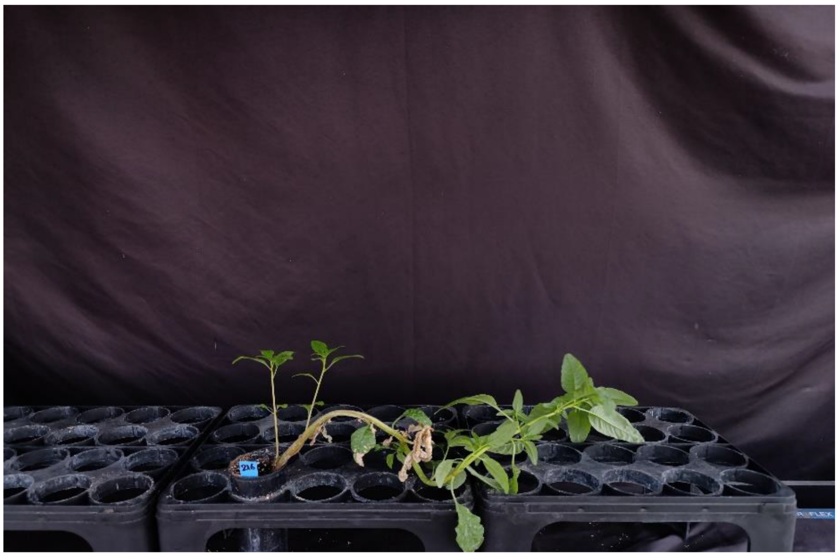

FIGURE 2
Common waterhemp (*Amaranthus tuberculatus* [Moq.] J.D. Sauer) regrowth after pelargonic acid application on 21 DAT (Org. photo).

TABLE 2 Summarized efficacy reports on bioherbicides.

Bioherbicide (ingredient)	Weed evaluated	Reported efficacy	Reference
Pelargonic acid	*Gallium aparine, Conyza canadensis, Echinochloa cruss-galli*	90-100%	Travlos et al., 2020 Loddo et al., 2023 Pannacci et al., 2022
Pelargonic acid	*Lolium multiflorum Cirsium arvense,*	30-43%	Ganji and Andert, 2024
Ammonium nonanoate	*Amaranthus spinosus, A. albus, Mollugo verticilata, Palmer amaranth*	88-98%	Parkash et al., 2022 Webber et al., 2010
Cinnamon oil	*Amaranthus retroflexus*	92-100%	Campiglia et al., 2007
Manuka oil	*Lolium rigidum, Avena sterilis, Digitaria sanguinalis*	50-90%	Travlos et al., 2020
Lemongrass oil	*Gallium aparine*	67-70%	Travlos et al., 2020
Fusarium oxisporum	*Striga hermontica, Cannabis sativa,*	70-95%	Wolde Assena et al., 2025 Hasan et al., 2021
Trichoderma	*Amaranthus retroflexus, Echinochloa cruss-galli*	50-83%	Guzmán-Guzmán et al., 2023 Ganji and Andert, 2024
Phoma macrostoma	*Taraxacum officinale, Sinapis arvensis, Stellaria media, Cirsium arvense*	75-100%	Bailey, 2014 Hubbard et al., 2015

Institute (OMRI, https://www.omri.org/) in the USA, while in the EU, bioherbicides must be approved centrally at the EU level and then authorized at the national level. Bioherbicides are not automatically allowed for applications in organic production. In the US, the Environmental Protection Agency (EPA) regulates all pesticides for safety, while the OMRI provides an independent review to verify that products are compliant with U.S. National Organic Program (NOP) standards. Some natural substances have herbicidal activity and might be used in organic farming, and were previously approved by the OMRI. It usually takes up to three months for a substance to be approved by the OMRI, while the substance:

Must not be on the National List of Prohibited Substances;

Manufacturing process does not include prohibited methods (genetic engineering, ionizing radiation, etc.);

All ingredients are compliant with organic standards and do not have any prohibited contaminants (contamination of crops, soil, and water with heavy metals or other toxins).

In the European Union, bioherbicides are regulated under the same stringent legal framework as their synthetic chemical counterparts (Regulation (EC) No 1107/2009) concerning the placing of plant protection products (PPPs) on the market. Hence, there is no separate regulatory category specifically for bioherbicides (nor biopesticides as a broader category). Furthermore, the regulatory process involves the following approach: 1) Approval of the active substance at the EU level and 2) Authorization of the product at the member state level. The first step implies that the active substance in the bioherbicide must be approved by the EC following a thorough risk assessment and peer review coordinated by the European Food Safety Authority. For that, the manufacturer submits a comprehensive dossier to a designated Member State, which conducts the initial evaluation. In the second step, once the active substance is approved, companies can apply to individual EU member states for authorization to place the specific *product* on their national markets. The product must be effective and safe under the specific regional agricultural and environmental conditions.

As it was previously mentioned, some bioherbicides have been commercially available for more than 60 years. In the EU, they are evaluated and registered using the same model as for registration of conventional herbicides, while laws and policies regulating their use vary from country to country (Teicher, 2018). Based on current knowledge and regulations, there are major disparities between EU and US regulations on bioherbicides. The primary differences in the EU and the USA are in registration pathways. In the EU, the precautionary approach is used [Regulation EC (No 1107/2009)], whereas the risk-based approach is used in the US. Consequently, the EU registration process for bioherbicides is longer, more costly, and more barrier-to-entry, particularly for new biological herbicides, compared to the US. The timeline and costs for bioherbicide registration are 1.5–2 years and $300-400k in the US and the EU, and are often longer than 4 years and €3.5-5.5m (the process is slow and complex) (Lane, 2025). Furthermore, fewer bioherbicides, including all biopesticides, are approved for use in the EU compared to the US, South America, India, or China. It could be projected that, based on the EU Green Deal and Farm to Fork strategy, the need to reduce risks and overall chemical pesticide use could accelerate the registration process and reduce existing barriers to bioherbicide use in the EU. Increasing consumption of organic and sustainable products, coupled with the growing market for these products, could play a crucial role in overcoming regulatory gaps and in the acceptance of bioherbicides, particularly substances of natural origin, in EU organic and sustainable agricultural production.

4 Application technology challenges

Contact herbicides, including bioherbicides, require greater carrier volume to achieve higher efficacy. Furthermore, the activity of bioherbicides is to a high degree influenced by the carrier volume, and much larger amounts are needed, up to 1200 L ha^{-1} (Hewitt et al., 2024), which would increase overall application costs. Additionally, the variability in control may be associated with insufficient spray coverage and the plant growth stage at the time of application (Hewitt et al., 2024). Larger plants with greater leaf area can reduce spray deposition on critical tissues, potentially limiting herbicide efficacy. In addition, the rapid activity of contact-type products can cause initial tissue injury while allowing surviving meristematic tissues to recover, resulting in the regrowth of treated plants. This is particularly relevant for bioherbicides, which generally do not translocate within weeds and may allow regrowth after initial injury (Figure 2).

As mentioned before, bioherbicides are mostly non-selective; there is a need to evaluate any potential crop damage they may cause. Any crop injury from bioherbicides might directly lead to yield losses. To date, the literature reports little data on crop damage caused by bioherbicides. Parkash et al. (2022) suggested ammonium nonanoate for pumpkin farming, using a directed spray hood to prevent drift onto pumpkins, with no reports of crop injury. Due to their non-selective nature, bioherbicides may injure crops and lead to yield losses; therefore, specific applications or adjustments should be made prior to applications. Sprayers with shields or hooded sprayers significantly reduce drift incidents, including those from bioherbicides. Although this technology is not new, having been reported in the 1950s, adding external barriers around the nozzles helps reduce crosswind interference with droplets in the treated area (Vieira et al., 2022). Hooded sprayers may be effective because they prevent off-target droplet movement by physically containing the spray.

The existing use of bioherbicides is limited; they are commonly used for weed control at crop edges, between rows, or in alleys to avoid crop injuries (Raza et al., 2025). Integrating bioherbicides in either row or specialty crop would require targeted spray application, which sprays only weeds, while not the crop (Avent et al., 2024; Spaeth et al., 2024). Therefore, targeted spray application enables targeted post-emergence spraying only on weeds in-crop areas (Ugljic et al., 2026), reducing the possibility of crops being affected by bioherbicides (Bajwa et al., 2015).

5 Integration of bioherbicides into agroecological weed management

Bioherbicides have significant potential for inclusion in weed management strategies; however, without targeted applications, they are often integrated with other non-chemical measures to enhance weed-control efficacy. The combinations of false or stale seedbed and bioherbicides can be highly effective. These techniques involve preparing the seedbed to trigger weed germination, followed by destroying the seedlings before sowing the crop, which can reduce weed biomass by up to 81%. A stale seedbed would involve the use of non-selective herbicides or bioherbicides for weed control (Kanatas et al., 2025). Furthermore, mechanical weed control with bioherbicides could be used together with intra-row banded bioherbicide application, while weeds within the inter-row will be controlled mechanically (Gagliardi et al., 2026). For these applications, more precise or targeted applications will be needed.

6 Conclusion

Based on the presented, integrating bioherbicides as an effective and ecologically acceptable solution into weed management programs will be challenging, but it could be beneficial. A combination of targeted spray techniques will be needed to apply only to weeds and avoid potential crop injury. The same technique will reduce overall use of bioherbicides, directly lowering their price per treated area. This will require more research and projects focusing on bioherbicide safety and effectiveness, and on integrating more natural substances with herbicidal attributes. It is important to note that other weed management strategies will also need to be integrated to achieve efficient weed control. Increasing the use of bioherbicides as ecologically friendly agrochemicals worldwide, and especially in Europe's arable areas, would be crucial as one of several tools for improved weed management and crop production.

Based on current challenges and opportunities, specific research priorities should be pursued: formulation improvements, multi-site trials, mode-of-action studies, and economic analyses to demonstrate their safety and effectiveness. This should be integrated into a EU policy, establishing a fast-track registration process for bioherbicides, similar to the US system, to expedite registration and enable their wider acceptance in weed management strategies as a safe alternative to chemical pesticides.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

Author contributions

MZ: Writing – review & editing, Writing – original draft, Conceptualization. VD: Writing – review & editing, Writing – original draft, Validation, Methodology. MS: Writing – review & editing. NP: Writing – review & editing. MB: Writing – original draft, Supervision, Writing – review & editing.

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Conflict of interest

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