Romanian Journal for Plant Protection, Vol. XVIII, 2025
ISSN 2248 – 129X; ISSN-L 2248 – 129X

BIOLOGICAL CONTROL AGENTS IN SUSTAINABLE AGRICULTURE: FROM EUROPEAN REGULATION TO FARMERS' ADOPTION

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Doi: http://www.doi.org/10.54574/RJPP.18.07

Abstract: The increasing emphasis on sustainability and reduced chemical dependency in agriculture has brought renewed attention to biological control as a viable alternative for crop protection. This review outlines the historical evolution of biological control, tracing the shift from early empirical practices to modern approaches informed by scientific research, the development of biopesticides, and the growing understanding of their ecological roles in sustainable agriculture. Furthermore, the paper examines the European regulatory framework, global market trends, and farmers' perceptions regarding the adoption of bio-based products. Despite significant progress in research, innovation and policy support, the adoption of biological control agents remains uneven across regions, limited by economic constraints, regulatory complexity and insufficient awareness. Strengthening farmer education, harmonizing regulations and promoting applied innovation are key steps toward broader implementation and a more sustainable agricultural future.

Keywords: *biological control, biopesticides, EU regulations, farmer.*

INTRODUCTION

Modern agriculture faces a dual challenge: ensuring sufficient production to meet the needs of a growing global population while reducing the negative impact on the environment and human health. The intensive use of synthetic plant protection products, although effective in pest control, is widely recognized for its adverse environmental and health impacts. In this context, the development of sustainable alternatives that reduce dependence on conventional pesticides and contribute to safe, ecological, and durable agricultural systems becomes imperative.

Biological control, through the use of entomopathogenic microorganisms-bacteria, fungi, viruses, or nematodes-represents one of the most promising solutions for the management of specific pests, offering the advantages of selectivity, safety for non-target organisms, and easy integration into modern agricultural technologies (Deka et al., 2021, Wyckhuys et al., 2024).

Current scientific research is called upon to support this approach by identifying efficient microbial strains, characterized morphologically, ecologically, biochemically, and genetically, that are adapted to specific pedoclimatic conditions and compatible with local agricultural practices. It is also necessary that these microorganisms be rigorously evaluated in

terms of their spectrum of action, stability under various environmental conditions, and efficacy in controlling agriculturally relevant pests.

MATERIALS AND METHODS

This paper is a narrative literature review based on scientific articles published between 2010 and 2025, retrieved from databases such as Scopus, FAO, and ScienceDirect, focusing on biological control agents, regulatory frameworks and farmers' adoption.

1. The emerging role of bioproducts in modern plant protection

The current global context highlights an increasingly evident trend of placing plants at the center of contemporary human interest. The diversity of control methods applied in agriculture has, over time, led to phenomena that have diminished consumer confidence.

Traditionally, pest, disease and weed control in agriculture has relied heavily on chemical pesticides, which have long represented the key component of integrated pest management (Hernández-Rosas et al., 2020; Nchu, 2024). However, the continuous and often excessive use of these compounds has generated well documented risks including the development of pest resistance (Pu & Chung, 2024), pest resurgence (Gill & Garg, 2014), accumulation of residues throughout the food chain (Akter et al., 2024; Beyuo et al., 2024), environmental contamination (European Environment Agency, 2023; Tang et al., 2021), indirect loss of beneficial fauna (Pathak et al., 2022; Mata et al., 2024), and negative effects on human health (Tudi et al., 2022; Akter et al., 2024). These issues have collectively emphasized the urgent need to develop alternative, sustainable pest management strategies (Kidanu et al., 2020).

In this context, biological control has regained its position as one of the most promising approaches for sustainable agriculture. At the beginning of the 21st century, both the opportunities and necessity for effective biocontrol have become increasingly evident particularly given the persistent public skepticism surrounding genetically modified pest-resistant crops, which are often perceived as environmentally or ethically questionable (Medani et al., 2024; Tanda et al., 2024).

Although early projections estimated a 5.3% global growth of the combined synthetic and biological pesticide market by 2022 (Chen, 2018), several factors including the COVID-19 pandemic, recurrent production bottlenecks in biopesticide manufacturing, and trade slowdowns have affected these expectations. In reality, the European chemical pesticide market declined by 5% compared to 1990 and by 7% in more recent years, while global pesticide use increased by 4% in 2022 relative to 2021, effectively doubling since 1990 (FAO, 2024). This trend underscores that chemical pesticides remain the dominant pest control tool worldwide. Furthermore, the pesticide market exceeded USD 60 billion in 2022, while the illegal trade in plant protection products accounted for an estimated USD 6-10 billion (OECD, 2022).

Considering the rising environmental and economic costs of pesticide dependence, the transition toward more resilient and sustainable solutions is not only desirable but essential (Karabörklü et al., 2017; Baker et al., 2020). Encouragingly, the biopesticide market is projected to grow at a compound annual growth rate (CAGR) of 15.1% through 2027, with bioinsecticides alone increasing at 5% CAGR (Mordor Intelligence, 2022a and b). These developments align with the European Union's Farm to Fork Strategy, which aims to reduce chemical pesticide use by 50% by 2030 (European Commission, 2020) and to expand organic farming to 25% of the EU's agricultural land (European Commission, 2021).

The evolution of biocontrol reflects a continuous adaptation of scientific knowledge to the needs of modern agriculture. While in the past the use of beneficial microorganisms relied on empirical observations, today the development of bioproducts is supported by rigorous research on microbial genomics, physiology, and plant-microorganism interactions. This evolution has been reinforced by a significant increase in research and development investments, as well as a progressively clearer legislative framework.

2. Evolution of bioproduct use in agriculture: from traditional practices to modern approaches

Although biological control was practiced long before the invention of synthetic pesticides, its origins date back to around 300 BC in China, where the weaver ant (*Oecophylla smaragdina*) was used to control pests in citrus orchards. The concept has since undergone remarkable development, passing through several major historical milestones. By 1200 AD, the effectiveness of lady beetles in aphid control was already well recognized (Kwenti, 2017), marking an important stage in the natural use of biological predators against agricultural pests.

Plant extracts, used since the 17th century against various plant pests, represent some of the earliest known biocontrol methods in agriculture (BPIA, 2017). The scientific study of biological control in agriculture began in 1835, when Agostino Bassi demonstrated that the fungus *Beauveria bassiana* could cause a specific disease in silkworms, laying the foundation for the future use of biological pest control (Fowler, 1981). Around the same time, by the late 19th century, experiments involving the use of oils (e.g., petroleum-based oils) for crop protection were also reported (Riley, 1892). The accelerated development of agricultural research at the beginning of the 20th century led to a significant increase in studies addressing biological pest management, highlighting the growing scientific and practical interest in such approaches.

A major turning point in large scale biocontrol use was the discovery and application of the bacterium *Bacillus thuringiensis* (Bt). In 1901, Japanese biologist Shigetane Ishiwata isolated Bt from an infected silkworm, marking a key milestone in the development of microbial bioproducts (Isiwata, 1901). Ten years later, in 1911, Ernst Berliner from Germany, rediscovered Bt in the larvae of the flour moth, confirming its potential for biological pest control (Smith, 2023). The practical application of Bt began in France in the early 1920s, and the first commercial product, Sporeine, was launched in 1938 (Ibrahim, 2010). In the United States, biocontrol gained momentum in the 1950s following extensive studies on the bacterium's insecticidal efficacy.

In 1953, Hannay Fitz-James and Angus demonstrated that Bt's insecticidal activity was due to its parasporal crystal proteins, contributing significantly to the understanding of its mode of action (Khachatourians, 2009). However, during the second half of the 20th century, research and development in bioproducts slowed considerably as synthetic chemical insecticides, though more toxic, became more widely adopted due to their lower economic cost. During this period, bioproducts were confined to niche markets, primarily in cases where chemical pesticides were unregistered, ineffective, or economically unfeasible.

Another landmark achievement in the history of biological control occurred in 1888 with the introduction of the ladybird *Rodolia cardinalis* for controlling the cottony cushion scale, *Icerya purchasi*. This was a notable success that demonstrated the effectiveness of natural predators in pest management (Clausen, 1978).

Today, Bt-based products remain the most widely used microbial insecticides in the world (Ibrahim et al., 2010; Dinu et al., 2013), accounting for nearly 90% of the bioinsecticide

market (Chattopadhyay et al., 2004), with a high success rate in pest control for both agricultural and environmental applications (Jouzani et al., 2017). Bt is considered one of the most promising microbial biopesticide sources due to its valuable biological characteristics (Ongena & Jacques, 2008).

Over time, Bt's cytotoxic activity has been demonstrated against various groups of pests, including insects (Gonzalez-Vazquez et al., 2021), nematodes (Baghaee & Mahdikhani, 2015; Huang et al., 2018), mites (Erban et al., 2009; Dunstand-Guzmán et al., 2015), gastropods (Abd El-Ghany & Abd El-Ghany, 2017), flatworms and protozoa (Feitelson, 1993). Laboratory studies have further suggested that Bt toxins may have broader applications, not only in agriculture and environmental pest management but even as potential cytocidal agents against human cancer cells (Palma et al., 2014a). Nonetheless, Bt's principal mode of action remains its highly specific insecticidal activity, targeting particular pest species with minimal non-target effects (Bravo et al., 2011).

This high host specificity enables Bt proteins to be used in environmentally friendly pest control technologies. Consequently, Bt-based insecticides provide efficient pest management while preserving biodiversity, minimizing environmental risks, and avoiding harm to vertebrates and beneficial insects (Jurat-Fuentes & Crickmore, 2017).

With the emergence of the Integrated Pest Management (IPM) concept in the 1960s, biological control became one of its fundamental pillars, highlighting its essential role in sustainable pest management (van den Bosch, 1982). Today, biological control has evolved substantially, leading to the development and commercialization of a diverse range of biological products for sustainable pest population management offering a viable and eco-friendly alternative to conventional control methods.

In recent definitions, biological control is described as the use of one organism to reduce the population density of another (Bale et al., 2008; Tariq et al., 2020). Also referred to as *biocontrol*, the term is widely used across biological disciplines, including entomology (e.g., use of predatory insects to manage pest species) and plant pathology (e.g. use of fungi or bacteria antagonistic to plant diseases). In all such cases, the organism responsible for suppressing a crop pest or pathogen is known as a biological control agent (BCA) (Pal & Gardener, 2006).

Biological control agents interact with the plant, the target pathogen and the resident microflora. Past studies on these interactions were limited by the lack of advanced methodologies; however, the advent of metagenomic tools has enabled a detailed understanding of microbiome composition and function. This has allowed a more holistic comprehension of interactions between BCAs and the resident microbiota, which in turn supports more efficient timing, formulation, and application of bioproducts.

Microorganism based bioproducts offer several advantages over synthetic pesticides, including competitive costs, lower toxicity, and higher selectivity for target pests, while being safer for human health (Wend et al., 2024; Cai & Dimopoulos, 2024). This is particularly important for export crops, which must comply with international maximum residue limits (MRLs). Moreover, bioproducts provide growers with effective pest management solutions that do not negatively impact the environment. They are generally characterized by very low toxicity to birds, fish, and pollinators (Chavana & Joshi, 2024; Mawcha et al., 2024), degrade rapidly in the environment, and contribute to reducing the number of chemical applications when integrated into pest management programs (Hajnal et al., 2020).

The concept of biological control has evolved over time, supported by various international institutions that have played key roles in promoting and implementing it within integrated crop protection programs. Among these are the Commonwealth Institute for

Biological Control (CIBC), established in 1947 (initially as the Imperial Parasite Service) and currently based in Trinidad, and the International Organization for Biological Control (IOBC), founded in 1955, which continues to promote biological control within integrated pest management frameworks and to influence international policy in this domain (Polanczyk & Pratissoli, 2009).

2.1. Classification and application of biopesticides in modern agriculture

Biopesticides are a key subset of pest control products, derived from microorganisms, natural substances, or living organisms, that manage pests through diverse, eco-friendly mechanisms (Kachhawa, 2017; Kumar et al., 2021; Vermelho et al., 2024). They are typically grouped into three main categories, each with distinct modes of action and agricultural applications (Hegde & Vijaykumar, 2022).

Microbial biopesticides include bacteria, fungi, viruses, or algae that control pests via infection or antimicrobial compound production, providing targeted pest suppression while minimizing environmental impact (Ayilara et al., 2023; Wend et al., 2024; Sawangproh et al., 2025). Biochemical biopesticides are derived from natural compounds, such as pheromones, plant extracts, essential oils, or insect growth regulators that influence pest behavior, development, or reproduction through repellent, attractant, or disruptive effects, remaining non-toxic to humans and beneficial organisms (Abdollahdoknt et al., 2022). Genetically modified organisms (GMOs), including crops expressing specific genes like Cry proteins from *Bacillus thuringiensis*, offer additional pest protection with high specificity and compatibility with integrated pest management strategies (Parker & Sander, 2017; Moshi & Matoju, 2017). Together, these biopesticides provide sustainable alternatives to conventional chemical pesticides, aligning with modern agricultural practices, EU regulations on pesticide reduction, and increasing demand for environmentally responsible crop protection solutions.

3. EU regulations on biopesticides: legal framework and approval requirements

The harmonization of pesticide registration procedures in the EU was initially governed by Directive 91/414/EEC, which distinguished between two categories: Part A, referring to chemical pesticides, and Part B, dedicated to ecotoxicological studies for microorganisms and viruses. This directive was later replaced by Regulation (EC) No. 1107/2009, introducing specific data requirements for the evaluation of these substances (544/2011 and 545/2011). These requirements were slightly revised in 2013 through Regulations (EU) No. 283/2013 and 284/2013, concerning active substances and plant protection products (PPPs), respectively. This update represented an important advancement, allowing the approval of microbial consortia and acknowledging the need to adapt regulations to integrate advances in microorganism containing formulations.

The most recent changes were implemented in 2022 (EU Regulations 2022/1439 and 2022/1440), entering into force in November of the same year. These updates focused on evaluating the active properties of microorganisms, strengthening approval criteria, and differentiating them from chemical pesticides. On 1 September 2022, the EU published four regulations modifying its approach to the approval of microorganisms used in PPPs. These regulations established more appropriate criteria for evaluating microorganisms, changed the information required for the approval of active substances and PPPs, and modified the principles of assessment and authorization of PPPs by Member States. The EU's objective is to simplify the risk assessment of microorganisms and bring biopesticides to the EU market more quickly.

Additionally, PPPs containing microorganisms (hereafter referred to as mPPPs) are evaluated and authorized according to the Uniform Principles established in Part B of Annex of Regulation (EU) No. 546/2011, recently amended by Regulation (EU) 2022/1441. According to EU regulations, the approval process for microbial active substances begins with an evaluation conducted by a Rapporteur Member State (RMS), which may receive support from another Member State (co-RMS). Upon completion of the initial evaluation, the dossier is forwarded to the European Food Safety Authority (EFSA) and other Member States for further comments. However, the EU regulatory framework was primarily designed for chemical pesticides and does not fully reflect the characteristics and mechanisms of action of innovative biotechnologies. For instance, RNAi- and peptide based products, although biomolecules, are subjected to the same registration requirements as conventional chemical pesticides despite fundamental differences in their modes of action.

At the European level, there is increasing openness toward simplifying procedures for new plant protection technologies while maintaining high safety standards. An example of such an initiative is the EU-funded project "Risk Assessment Innovation for low-risk pesticides" (RATION), with a completion date in 2026, aiming to develop schemes and tools for assessing the risks of innovative pesticides.

4. Global overview of farmers' perceptions and adoption of biopesticides

Biopesticides are promoted as a sustainable alternative to conventional pesticides, but farmers' attitudes toward them vary significantly depending on region, education, economic accessibility, and perception of the risks associated with chemical pesticide use.

The adoption of biopesticides across Europe displays a heterogeneous pattern, reflecting substantial differences among countries in terms of market maturity, adoption rates, and growth dynamics. France stands out as one of the most advanced European markets, where biopesticide products account for nearly 10% of the total crop protection market, with particularly strong penetration in the biofungicide (approximately 16% of the fungicide market) and bioinsecticide segments (around 17% of the insecticide market), relative to conventional products (Kynetec, 2023). In Spain, biopesticides currently represent about 6% of the market and are considered a growing yet still niche sector, shaped by agronomic conditions and the gradual uptake of sustainable agricultural practices (Fusar & Fontefrancesco, 2024). In contrast, other major European markets such as Italy, Germany, and the United Kingdom are characterized by steady but moderate growth trajectories, with projected market values by 2030 of approximately USD 55.0 million in Italy, USD 42.5 million in Germany, and USD 13.9 million in the United Kingdom, supported by compound annual growth rates ranging from 5.3 to 6%. Collectively, these trends underscore the increasing relevance of biopesticides within European crop protection strategies, driven by regulatory pressure, sustainability objectives, and policy frameworks aimed at reducing reliance on conventional chemical pesticides (Grandviewresearch, 2022).

Globally, in countries such as China, India, Ethiopia, and Thailand, usage of biopesticides remains relatively low. For instance, only 68.63% of Chinese farmers would consider using biopesticides, but only if these yield results similar to chemical pesticides (Liu et al., 2016). In India, the gap between the declared willingness to use biopesticides and actual usage is influenced by factors such as price, education, and awareness of the negative effects of chemical pesticides (Pithiya et al., 2024). In Ethiopia, although the concept of biological products is widely known, only 60% of farmers use biofertilizers, and biopesticides for plant protection are largely absent (Mulugeta et al., 2024). In Thailand, while 65% of farmers

reported using biopesticides, widespread adoption is constrained by high registration costs, even within an accelerated approval system, with most farmers continuing to rely on conventional pesticides (Praneetvatakul et al., 2024). These data suggest that farmers in these regions are more influenced by practical factors, such as efficacy and cost, than by health or environmental concerns.

When analyzing the use of biopesticides across Europe, it becomes evident that reporting and monitoring data remain relatively limited. Even so, Fusar Poli et al., (2024) provide valuable insights into the situation in Spain and Turkey, noting that in Spain, the biopesticide market represents about 6% of the total crop protection market, with 38 authorized biological active substances, while in Turkey, the predominance of small-scale farms, limited access to services, and insufficient agricultural knowledge continue to hinder the adoption of such bio-based products.

Studies in Romania reveal a concerning perception among farmers regarding the use of conventional pesticides and biopesticides. Approximately 70% of farmers do not recognize the negative impact of chemical pesticides on health and the environment (Petrescu-Mag et al., 2019). Adoption of biopesticides is primarily driven by perceptions of reduced efficacy of conventional pesticides and their negative health effects. However, most Romanian farmers are not motivated by ecological concerns, outlining a consumer profile less oriented toward sustainability.

Changing farmers' attitudes to increase the adoption and use of biological control methods remains a challenge, particularly among smallholders, who continue to be influenced by the immediate efficacy and economic accessibility of chemical pesticides. By accessing a diverse range of biological products, organic farms primarily use biopesticides, biofertilizers, and predatory insects for crop protection (McGrath et al., 2010; Benbrook et al., 2021). This sustainable approach reduces environmental impact and promotes biodiversity in agricultural ecosystems.

Globally, organic farmland reached 74.9 million hectares in 2020, with the European Union accounting for 19.7% of this global area, demonstrating the region's commitment to ecological agricultural practices. Romania has seen significant growth in organic farmland, reaching 469,000 hectares in 2020, 41% of which were under conversion. Support through the Common Agricultural Policy (CAP) has been essential for this expansion, with approximately 82% of certified farmland receiving financial support that year. Romanian authorities recognize the potential of organic agriculture, developing national plans that include subsidies for conversion and maintenance of organic lands, promotion of organic product consumption, and integration into school programs (European Commission, 2023). In 2023, in Romania, 14,044 operators were certified in organic agriculture, reflecting growing interest in this sector (MADR, 2023).

4.1. Recent developments and technological advances in biological control

Increasing the efficiency and success of biological control globally requires rigorous evaluation of the entire application process, including planning, implementation, and subsequent monitoring. These interventions are particularly important for conservation biological control, which involves adapting the agricultural ecosystem to support both the establishment and efficiency of biological control agents or bioproducts used.

A positive outlook on biological control is emerging worldwide, reflected in growing understanding of its mechanisms and benefits. For example, supplementing orchards with nectar and pollen producing flower species, strategically placed at orchard edges, significantly

stimulates and optimizes biological control by increasing populations of predatory insects (McKerchar et al., 2020). This has been shown to reduce populations of pests such as *Cydia pomonella* (codling moth) and *Dysaphis platanginea* (rosy apple aphid) through the use of parasitic wasps recognized as natural predators of these key apple pests (Laffon et al., 2024).

Beyond these positive aspects, the integration of artificial intelligence (AI) offers promising directions for sustainable agricultural solutions. With its capacity to rapidly analyze large datasets, AI facilitates the identification of efficient and ecological biological agents. A relevant example is an AI-based model used to identify optimal release zones for the parasitoid *Cotesia icipe* in controlling *Spodoptera frugiperda* (fall armyworm) in maize crops, leading to increased efficiency of this biological agent (Agboka et al., 2024).

Additionally, AI is utilized to discover micropeptides, short amino acid sequences that regulate plant phenotypes or target pests very specifically. Innovative platforms, such as those developed by Micropep, integrate machine learning and deep learning techniques to generate micropeptide libraries and predict their interactions with target proteins, accelerating discovery. These advances contribute to diversifying bioproducts and developing innovative agricultural solutions, reducing reliance on chemical pesticides and minimizing environmental impact (Micropep, 2024).

In conclusion, while regions such as Europe have seen legislative support and expansion of organic farming encourage biopesticide adoption, other areas remain limited by a preference for conventional chemical methods. Nevertheless, global trends indicate growing interest in biological solutions due to sustainability requirements and concerns about human health and environmental impact. Emerging technologies, such as AI, provide new opportunities for efficient biopesticide development and implementation, facilitating a transition to more environmentally friendly agriculture. Supporting farmer education and subsidy policies remains key to increasing biopesticide adoption globally.

5. Global trends and market outlook for biological products

The agrochemical industry remains focused on developing and launching new plant-protection solutions to meet growing food demand. Increasing agricultural production needs drive greater use of these products, particularly in developing regions where yields must be constantly improved. As pressures on agriculture rise due to climate change and global population growth, farmers are increasingly inclined to adopt innovative solutions to protect crops and optimize yields. Consequently, many countries implement policies to reduce the use of chemical products. National legislative changes, new policies, and management structures for reducing chemical control represent opportunities for biological control agents. As alternative biological technologies become increasingly available, chemical usage will face more restrictions and bans (Fluekiger, 2021).

In this context, bioproducts, including biopesticides, biofertilizers and biological agents, play a crucial role in promoting sustainable and ecological agriculture. Growing demand for environmentally friendly solutions, coupled with stricter regulations on conventional pesticides, has led to the rapid expansion of the global biological products market. These global trends also influence national markets, and Romania is beginning to adopt these solutions, particularly in the context of organic agriculture.

The global biocontrol product market started from a relatively small size in the 1990s to become a multi-billion-dollar industry, growing faster than conventional crop protection. Biopesticides represented the largest market share due to farmers' and growers' demand for pest resistant products that increase both yield quantity and quality. The growing interest of

stakeholders in agriculture in changing pest management perspectives, along with the adoption of safer pest population management strategies, drives the growth of the biopesticide market.

The global biopesticide market is rapidly expanding, estimated to grow from USD 7.35 billion in 2024 to USD 8.75 billion in 2025, reaching USD 17.21 billion by 2029 (Research and Markets, 2025), with Europe projected at USD 1.6 billion (IBMA, 2024). Although biopesticides are expected to surpass chemical pesticides in market share, the exact timing of this transition remains uncertain (Dunham, 2019).

Biopesticide usage, as an alternative to chemical insecticides, varies significantly across regions, reflecting distinct priorities and agricultural practices. In Oceania, the median share of insecticidal biopesticides is highest at 44%, due to efforts to protect marine ecosystems. In other regions, usage is lower: 2% on average in the Americas (data from 14 countries), and only 1% in Africa and Asia (data from 7 countries). Saudi Arabia is a notable exception in Asia, with 44% insecticidal biopesticide usage in 2020, while in Europe, data from 21 countries indicate a very low share of 0.7%. These regional differences highlight the diversity of challenges and opportunities in adopting biopesticides, emphasizing the need for strategies tailored to each region (FAO, 2024). These global trends also influence Romania's market, which is increasingly adopting these solutions, especially in the context of organic agriculture, reflected in the reduction of pesticide consumption from 8,700 tons in 2020 to 7,957 tons in 2022 (FAOSTAT, 2024). Although this represents notable progress, Romania faces multiple challenges, including EU-imposed bans on established plant protection products and active substances such as tebuconazole, thiophanate-methyl, or chlorothalonil, limiting farmers' access to effective and viable solutions.

Biopesticides occupy an increasingly important share of the plant protection market due to growing demand from farmers and growers seeking higher crop yields, both quantitatively and qualitatively. They also allow integration of alternative products into pest management schemes. The increasing interest of stakeholders in agriculture in changing pest management paradigms, alongside the adoption of safer and more sustainable strategies, are key factors driving biopesticide market growth. Producers, growers, and consumers all recognize clear benefits in adopting and using biocontrol, further fueling this growth. Producers appreciate the significantly lower costs associated with developing a bioproduct, which can be achieved with a budget of approximately USD 10 million in just 4 years, compared to USD 301 million and approximately 12 years needed for a chemical pesticide to reach the market (Olson, 2015; Crop Life International, 2024).

Growers adopt alternative methods to benefit from worker safety and application flexibility (Rijal et al., 2018). In crops with successive harvests throughout the year, growers consider the short waiting period between applications an advantage, while also recognizing that using these methods helps prevent pest resistance development. Consumers, although not specifically requesting biocontrol methods in crops, are increasingly concerned about the environmental and health impacts of chemical products, leading to greater interest in safer and more sustainable management approaches (Lahlali et al., 2022).

CONCLUSIONS

Biological control and biopesticides are increasingly recognized as essential tools for sustainable agriculture, offering effective pest management with minimal environmental impact. Advances in microbial research and plant–microorganism interactions have enabled the development of targeted, low-toxicity bioproducts compatible with integrated pest management strategies. European regulatory frameworks and global policies promoting organic farming

further support the adoption of these solutions, although regional differences in farmer awareness and economic factors influence uptake. Emerging technologies, including artificial intelligence and precision application tools, provide new opportunities to optimize biocontrol efficacy and expand its use.

Overall, biopesticides contribute to enhanced biodiversity, reduced chemical inputs, and safer food production. The global trend toward biological solutions highlights a shift in agriculture: achieving productivity while safeguarding ecosystems and human health. Continued research, education, and supportive policies remain key to fully realizing the potential of biocontrol worldwide.

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