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Trends in the implementation of biopesticides in the Euro-Mediterranean region: a narrative literary review

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Abstract

This article explores the global commitment to achieving sustainable solutions for addressing hunger, emphasizing the urgent need to transform the agricultural sector in the face of escalating global population growth and threats to the food system. Despite commitments to reduce conventional pesticide use, the global market for these products is expanding. Biopesticides are a sustainable alternative with targeted action and ecological benefits. While the biopesticide market is growing, it remains a small segment within the overall expanding pesticide market. The study focuses on the Mediterranean region, specifically Spain, Tunisia, and Turkey, to investigate the structural challenges hindering the adoption of biopesticides. Technical issues, coupled with broader market dynamics involving producers, farmers, regulators, and consumers, contribute to the limited market presence of biopesticides in the region. Challenges such as knowledge gaps, market constraints, limited manufacturing plants, and registration complexities further impede biopesticide development, confining them to niche markets. Overcoming these challenges requires addressing issues of availability, affordability, and efficacy, alongside legislative barriers. The paper suggests potential roles for farmers, producers, and regulators as agents of change, acknowledging the complexity of devising concrete strategies to navigate the current impasse. The research proposes directions for facilitating change.

Keywords Biopesticides, Pesticides, Mediterranean, Agriculture, Implementation, Agricultural practices

Introduction

The 2030 Agenda adopted by the United Nations (UN) explicitly committed to a global effort to define and pursue the goal of not only eradicating hunger but doing so while respecting water quality and the viability of aquatic and terrestrial life [1]. It declared the need for sustainable food policies and practices to transform a sector responsible for 26% of greenhouse gas emissions and 70% of freshwater withdrawals [2]. This change is urgent due to recent projections of global population growth and the fragility of the global food system, which is jeopardized by political instability, climate change, and environmental degradation [3]. The change directly involves methods of food production and agricultural practices. This necessitates a reconsideration of the use of conventional pesticides, one of the pillars of contemporary industrial agriculture [4], due to their impact on human and environmental health [5, 6].

Despite the commitment of political entities such as the European Union (EU) to limit or eliminate the use of conventional pesticides by 2050 [7], the world's market for these products is expanding. Their usage increased from 2 million tonnes in 2000 to over 3.5 million tonnes in 2021, totaling a value of USD 7.809 billion [8]. Moreover, the implementation of new agricultural practices, such as precision farming and protected cultivation, is fueling this market expansion [8].

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Biopesticides are seen as a sustainable alternative or complement to conventional pesticides [9]. They are derived from natural substances like microbes, plants, and biochemicals, exhibiting crucial ecological activities in nature, acting as antifeedants, attractants, nematicides, fungicides, pest repellents, insecticides, and growth regulators [6]. They aid in controlling many destructive pests and achieving sustainable crop protection [10]. Due to their specific, targeted action, and biodegradability, unlike chemical pesticides, these products have proven beneficial in agriculture by preventing water and soil pollution, food contamination, and health issues such as cancer [11]. However, despite their benefits, there are some inconveniences associated with biopesticides, i.e., the development of resistance in pests due to their prolonged use or the less immediate effects compared to synthetic chemical pesticides. By adopting integrated pest management strategies that incorporate diverse control methods and combining biopesticides with other compatible pest control agents, it is possible to mitigate these inconveniences and optimize the efficacy of biopesticides in sustainable pest management practices [12].

Overall, biopesticides account for 2.5% of the whole pesticide market (3000 tons) [13], and their market is growing rapidly. The global biopesticides market is expected to increase from USD 6.54 billion in 2022 to USD 14.39 billion by 2030, at a compound annual growth rate (CAGR) of 10.34% [14, 15]. However, this positive trend should be viewed in the broader context of the pesticide market, which is experiencing even faster growth (from a USD 104.7 billion value in 2021 to an estimated USD 291.4 billion in 2030, with a revenue CAGR of 12.1% [16]. The slower growth of the biopesticide sector suggests the presence of impeding factors that limit the possibility of full success, going beyond the mere technical specificities of the products.

Based on current academic literature, this article aims to identify these factors, which involve legislative, economic, and cultural causes. The principal aim is to investigate the structural challenges hindering the adoption of biopesticides, identifying both drivers and limits to the green transition in pest management. Such an analysis, in fact, is crucial to understanding how to improve biopesticide usage and guide the plan of research, policy-making, and training of actors in the field accordingly.

It focuses on the Mediterranean region, the world's largest market for these products with a value in 2022 of USD 2.3 billion and a forecast for 2030 of USD 5.56 billion [14]. Three countries, specifically Spain, Tunisia, and Turkey, have been selected due to their central role in the global food system as key exporters of fruits, vegetables, and olive oil [14]. Despite this similarity, they also present substantial differences concerning climatic conditions, policies, regulatory frameworks, market maturity levels, and innovations in agricultural techniques. Thus, the commonalities among the trajectories occurring in these countries offer insight into more structural issues affecting the implementation of biopesticides.

This article first introduces the research context and methodology, then delves into the trends characterizing the Mediterranean region and the three countries, discussing the emergent issues at stake.

Materials and methods

The review was carried out in the third quarter of 2023 and examined both academic and grey literature sources that describe the status of biopesticide implementation in the Euro-Mediterranean region, specifically in Spain, Tunisia, and Turkey. The sources were identified using several reference databases, including EBSCO, Google Scholar, Scopus, and Web of Knowledge. The selection criteria encompassed the topic (the implementation of biopesticides), the geographical focus (the Mediterranean region, Spain, Tunisia, and Turkey), and the period of publication (1994–2024). While the primary focus was on English language sources, materials in national languages were also included when they addressed issues not covered by international sources.

The outcome of this research is this narrative review [17]. This method of literature synthesis is characterized by a more flexible and interpretative approach than that of a systematic review. It is well suited to smaller bibliographic corpora, offers greater flexibility in terms of source selection, and fosters a holistic understanding of the subject that is unimpeded by predetermined, strict inclusion criteria [18].

Results

The Euro-Mediterranean context

Agriculture is a key factor in the Mediterranean market, but agricultural production in the European and Mediterranean area is facing several challenges, which require more research and policy efforts. Among these challenges, there are climate change, the emergence of new pests and pathogens, and the ongoing ecological transition process [19]. These factors have created significant economic and practical opportunities for the introduction of biopesticides [15]. Commercial formulations based on Bacillus thuringiensis are the most widespread and easily accessible and they have been used to control other insect pests successfully. One example is related to its efficacy in combating Tuta absoluta, which is a major pest of tomato crops that causes high yield losses. Laboratory and greenhouse studies show that BT biopesticides are even more effective than chemical pesticides (i.e. Biolep, Abamectin, and Indoxacarb) against T. absoluta larvae [20].

Furthermore, the adoption of integrated pest management (IPM), which has been mandatory for all EU agriculture since 2014 [7], has been instrumental in facilitating the introduction of biopesticides. IPM requires a diversification of pest control practices and encourages the reduction of pesticide use in favor of more sustainable alternatives, ranging from physical and mechanical to biological methods of control [5].

Despite this conducive context for biopesticides, their market expansion faces several critical challenges involving biological, technological, economic, and regulatory factors [4].

A significant obstacle is the efficacy of current biopesticide compounds against pests that exhibit remarkable adaptability. Pests often develop resistance capabilities that substantially reduce the effectiveness of these products, as noted by Acheuk [4]. Damalas and Koutroubas [19] highlight the rapid degradation and lack of toxicity data as critical issues for mycopesticides, while Zaki et al. [21] emphasize the instability of active substances in mycopesticides, making them less competitive compared to chemical alternatives. Moreover, the susceptibility of biopesticides to various environmental factors, including UV radiation, affects their stability and persistence, further restricting their adoption [22]. The limited efficacy of biopesticides across different climatic zones has been identified as a factor that hampers their adoption [23].

One significant challenge is the high cost associated with refined commercial biopesticide products, making them less accessible to farmers [24]. Additionally, the lack of appropriate formulations and difficulties in production hinder the scalability and adoption of biopesticides [25]. The need for biopesticides to fit into existing value chains further complicates their integration into agricultural practices [26].

The general lack of awareness and information about organic farming systems, high managerial costs, and marketing challenges have been identified as barriers to the adoption of organic practices in agriculture, which could extend to biopesticide adoption as well [27], Fenibo et al. [28, 29]. The lack of standardized preparation methods, guidelines for application, and challenges in determining the appropriate dosage of active ingredients contribute to the complexities surrounding biopesticide use [30]. Moreover, concerns about the speed of action, short persistence, and the overall cost of biopesticides also act as barriers to their adoption [31].

The regulatory landscape also poses challenges. The process for the registration and authorization of new biopesticides is slow and complex, as outlined by researchers including Damalas and Koutroubas [19, 32], Balog et al. [33], and Karamaouna et al. [34]. Structural inefficiencies and excessive administrative, bureaucratic, and managerial complexity [21] exacerbate this situation, impeding the availability of biopesticides and compounded by high costs and the lack of an effective propagation strategy [35].

In the context of African countries within the Mediterranean basin, Fenibo et al. [28] highlight additional challenges, such as the absence of local production facilities and difficulties in attracting private investment, which hinder the development and distribution of biopesticides in these regions.

Such market limitations hinder their broader adoption in mainstream agriculture and the application of biopesticides is predominantly restricted to organic farming, limiting them to a niche market with a limited range of products [4, 19].

Spain

Overview

The Kingdom of Spain is a sovereign state, a member of the European Union since 1986. The country is a constitutional monarchy in which the civil law system shows regional variations based on the division into 17 autonomous communities and 2 autonomous cities. This differentiated autonomy is also reflected in the variation of regional agricultural policies [35].

Spain is in Southwestern Europe, bordering the Mediterranean Sea and the country occupies an area of 505,370 km^2, of which 498,980 km^2 is land. Land for agricultural use is 54.1%, of which 24.9% is arable land and 9.1% is occupied by permanent crops [35].

Spain is one of the largest exporters of fresh food products in Europe [36]. The main agricultural products are wheat, olives, grapes, tomatoes, maize, oranges, sugar beets [35].

The main climate challenges facing the country are pollution of the Mediterranean Sea from raw sewage and effluents from the offshore production of oil and gas and drought are negatively impacting water quality and quantity nationwide, air pollution, deforestation and desertification [35].

Real GDP is updated to $1.798 trillion in 2021 $, which ranks the country 16th in the world. Specifically, agriculture accounts for 2.6% of total GDP, which is 158th in the world rank for this GDP source sector [35].

Spain ranks first in Europe for pesticide consumption, with an annual use of 76,173.55 metric tons [37].

Forecasts predict a 16.5% growth from USD 816.35 billion in 2023 to USD 950.97 billion by 2028, at a CAGR of 3.10% [38].

In 2022, Spain exported $1.69B in pesticides, making it the 6th largest exporter of Pesticides in the world. At the same year, pesticides were the 35th most exported product in Spain.

In 2022, Spain imported $1.04B in pesticides, becoming the 8th largest importer of pesticides in the world. At the same year, pesticides were the 99th most imported product in Spain [39].

Trends in biopesticides

Currently, the biopesticide market in Spain, which accounts for 6% of the market, is a growing yet niche sector [40], fueled by the gradual regulation of chemical pesticides [15]. Its usage is increasing amidst close collaboration between the public and private sectors [41]. As of 2020, Spain had 38 authorized biological active substances in its market, comprising 45% fungi, 40% bacteria, and 15% viruses [42]. These include bioinsecticides, acaricides, biofungicides, bionematicides, biobactericides, biostimulants, phytosanitary bio-products, and other basic substances [43, 44], with approximately 66 products available [42].

However, the dissemination of these products faces substantial rigidity within the local legal and authorization system. Despite the inclusion of "bioproducts" in the national regulatory framework in 2020 [45], the registration process at both European and national levels remains complex for companies [35], with biopesticides largely confined to organic agriculture [32]. Their moderate efficacy of actual biopesticides, inconsistent results, concerns about the biological safety of certain microbial species, and the short shelf-life and stability of the substances further limit their widespread use [19, 46].

The scientific community, at both national and European levels, advocates for supportive measures for the sector [43]. They emphasize the need to facilitate and expedite the authorization procedure for low-risk pesticides [33], propose an autonomous registration process for biopesticides distinct from that for conventional pesticides, and suggest a specific category for biopesticides in the reference regulatory framework and IPM [24, 47]. Additionally, there is a call to refine formulas, reduce production costs, encourage mass production, enhance quality control processes, and improve preservation capacity [48]. Further research is also necessary on complete toxicology, field testing for botanical insecticides, and specific formulations to prevent degradation [46].

From a technical perspective, there is a need to enhance the stability of products currently on the market [21], as well as to improve the technical competencies of farmers to understand and increase the efficacy of these products, and to prevent resistance mechanisms [40, 49]. The hyper-specialization of biopesticides currently poses a disadvantage for cultivators, making training farmers essential to adapt the use of bioproducts to diverse circumstances [40].

Awareness and training programs are also needed to bridge the gap between European administrative demands and the methodologies practiced by small producers, along with public support for the dissemination and implementation of new biological control technologies [43].

Tunisia

Overview

The Republic of Tunisia has been a sovereign and independent state since March 20, 1956, administratively divided into 24 governorates. Tunisia is a member of the Arab League, the African Union, and the Organization of Islamic Cooperation. It maintains close relations with the United States, France, and the European Union, with which it entered into an association agreement in 1995, called the Barcelona Process, also known as the Euro-Mediterranean Partnership [50].

Tunisia is in Northern Africa, bordering the Mediterranean Sea, and the country occupies a total area of 163,610 km^2, of which 155,360 km^2 is land.

Land for agricultural use occupies 64.8% of the total and, of this, arable land: 18.3% and 15.4% by permanent crops. Tunisia's main agricultural products are wheat, tomatoes, barley, olives, watermelons, green chillies/peppers, potatoes, dates, green onions/shallots [50].

The main environmental challenges in the country are ineffective toxic and hazardous waste disposal, water pollution from raw sewage, limited natural freshwater resources, deforestation, overgrazing, soil erosion and desertification [50].

Real GDP is updated to 2021 in terms of $127,509, which ranks the country 83rd in the world rankings [50].

Notably, agriculture accounts for 10.1% of total GDP, which is 90th in the world rank for this GDP source sector. The food sector in general is a crucial component of Tunisia's national economy, accounting for 11.79% of the country's total exports in 2022 (% of GDP) [51].

Agricultural production in Tunisia heavily relies on chemical inputs, a trend that has intensified over the past decades [52].

Tunisia ranks 89th in the world for pesticide consumption, with an annual consumption of 3299.07 metric tons. Tunisia's pesticide consumption is projected to reach 4160 tons by 2026, marking a 2.1% yearly increase from 3640 tons in 2021 [53].

Pesticides' market has been growing annually by 3.1% since 1995.

In 2022, Tunisia exported $4.26M in pesticides, making it the 83rd largest exporter of pesticides in the world. At the same year, pesticides were the 315th most exported product in Tunisia. In 2022, Tunisia imported $53.8M in pesticides, becoming the 94th largest importer of pesticides in the world [39].

Trends in biopesticides

Agricultural landscapes in North Africa exhibit a significant persistence of traditional IPM methods [54]. While these methods contribute to biodiversity conservation, they are proving inadequate in addressing new challenges posed by the spread of novel exogenous pest species. These pests are threatening key productions for the international market, such as the tomato leaf miner (Tuta absoluta) [54–57], the carob moth (Ectomyelois ceratoniae) [58–61], the Mediterranean fruit fly (Ceratitis capitata) [62], and the olive moth (Prays oleae) [63, 64]. In response to these challenges, farmers have often intensified the use of non-selective conventional techniques [58], which present substantial sustainability limitations [54] and significant health and environmental impacts [65, 66].

To improve quality, new tools and agronomic strategies are being adopted in both greenhouse cultivation and open fields [57]. These efforts aim to refine IPM by reducing the use of chemical pesticides and incorporating reduced-risk options, including biopesticides [54, 55].

Plant-based biopesticides, although still a niche in Tunisia's pesticide market, are emerging as viable alternatives to synthetic products [59, 60, 62, 63, 65, 67–71]. This trend is supported by legislative measures limiting conventional agricultural practices, such as fumigation with methyl bromide [65]. Additionally, the use of homemade plant-based pesticides is common among farmers [66]. This indicates that producers have a positive attitude towards biopesticides and underscores the potential effectiveness of new capacity-building actions and the transmission of advanced scientific and technical knowledge related to these products [55, 57].

Turkey

Overview

The Republic of Turkey is a state located between Southeastern Europe and Southwestern Asia, bordering the Mediterranean Sea and administratively divided into 81 provinces.

The European Union is Turkey's first trading partner, with which it is linked by the Customs Union in force since 1995. Trade in agricultural products, are subject to the 1998 Decision on the trade regime for agricultural products [50].

The country occupies an area of 783.562 km^2, of which 769.632 km^2 is land. Land in agricultural use is 49.7%, occupied 26.7% by arable land and 4% by permanent crops.

Turkey's main agricultural products are wheat, sugar beets, tomatoes, barley, maize, potatoes, apples and grapes [50].

The main climate challenges facing the country are water pollution from dumping of chemicals and detergents, air pollution, particularly in urban areas, deforestation, land degradation, concern for oil spills from increasing Bosporus ship traffic, and the threats which jeopardize conservation of biodiversity [50].

Real GDP updated to 2022 is $2.817 trillion, fueled 6.8% by the agricultural sector.

Food production in Turkey, constituting approximately 11.58% of the national exports in 2022, is largely oriented towards export and heavily relies on chemical inputs [52].

The country represents a significant market for pesticides. Turkey's pesticide use is 52,963 metric tons per year, ranking the country 12th in the world, with projections indicating it will reach a turnover of USD 0.8 billion by 2027 [72].

In 2022, Turkey exported $189M in pesticides, making it the 33rd largest exporter of pesticides in the world.

In 2022, Turkey imported $549M in pesticides, becoming the 26th largest importer of pesticides in the world [39].

Trends in biopesticides

International corporations are investing in the construction of pesticide production sites within Turkey to meet both national and regional demands [72, 73]. The growth in row crop production and the expansion of the horticulture sector are fueling the demand for pesticides [3], with demand for specific crops like cotton witnessing annual peaks of +34.5% growth in the past five years [72].

Over the past two decades, the implementation of pesticides in Turkey has faced significant challenges, including a fragmented legislative framework, a complex authorization process, and a general lack of product knowledge among operators [74, 75]. Recently, the Turkish government has implemented several regulations on pesticides, creating opportunities for the biopesticide market's expansion [76]. For example, the 2017 Plant Protection Products and Maximum Residue Limits of Pesticides Regulations enhanced licensing and releasing policies for plant protection products [77]. Additionally, in January 2022, the Ministry of Agriculture and Forestry banned the use of two pesticides, chlorpropham and oxadiazon.

While these regulatory actions provide a favorable framework for the diffusion of biopesticides, their use is still limited, particularly in provinces like Ardahan, Bayburt, and Tunceli, where the use of chemical products is restricted [78]. Furthermore, Turkish agriculture is predominantly based on small-scale enterprises [79], which face structural poverty, a lack of services, and limited access to modern agricultural knowledge [80]. These conditions pose significant barriers to accessing new products such as biopesticides. Therefore, further actions are necessary to raise awareness of biopesticides' properties and support their implementation [79, 81].

The emerging picture

Table 1 represents a functional synoptic chart to capture the similarities and differences of the three main countries analyzed. The purpose is to provide a clarity tool for analytical comparison against the main themes considered in this article.

Discussion

There are several evidence supporting the expansion trend of the global biopesticide market. Studies predict that biopesticides are poised to equal synthetic pesticides in market size by the late 2040s or early 2050s, indicating a significant growth trajectory for biopesticides [82]. The emergence of entrepreneurial start-up companies, along with support from regulatory bodies and funding programs, provides incentives for the development of biopesticides, highlighting a conducive environment for market expansion [83]. While biopesticide use is increasing globally, there is a recognition that further market growth is essential for biopesticides to substitute chemical pesticides effectively and reduce over-reliance on them [32]. The economic growth of the biopesticides market, with a compound annual growth rate outpacing that of synthetic pesticides, indicates a positive outlook for the biopesticide industry [33]. Additionally, the advantages of biopesticides over chemical counterparts and the expected increase in market share underscore the potential for biopesticides to capture a significant portion of the market in the future [84]. Furthermore, the expansion of biopesticides globally, with the market size expected to double by 2025, particularly in segments like bioinsecticides, signifies a growing demand and acceptance of bio-based pest control solutions [4]. The development of novel active ingredients and the continuous release of new biopesticide products are crucial for further market expansion, especially in commercialization models that leverage patent protection [85].

This type of research effort is crucial to realize the predictions related to the increase in the spread of biopesticides, especially in areas such as the Mediterranean region, where biopesticides currently play a marginal role in the market [19]. Technical issues related to efficacy [4] and stability [19, 21] are partly responsible. However, our research underscores the significance of structural market issues.

The development of the agricultural market involves various actors: producers (pesticide manufacturers), users (farmers), regulators (national and international legislators), and consumers (food buyers). Our research indicates that consumers play a limited role. Despite growing attitudes towards sustainable foods [86] and increasing awareness of the health implications of food production [36], there is no corresponding surge in knowledge about biopesticides. Consequently, consumers do not significantly influence farmers' choices or those of other stakeholders. Therefore, limitations arise from interactions among legislators, producers, and users, creating a vicious circle.

Farmers across the region tend to avoid biopesticides due to a lack of knowledge and limited market availability [29]. Production is constrained by the small number of manufacturing plants, difficulties in attracting private investment [28], and administrative complexities in the registration process [19, 21]. These factors also limit new research, which could lead to more affordable and reliable products [15]. Consequently, due to their limited market presence, low legislative attention, and minimal producer pressure due to scarce investment, biopesticides are not a priority for regulators, which is delaying legislative reform and discussion [28, 29]. As a result, biopesticides remain confined to organic farming and niche markets [4, 32].

This trend is a general characteristic of the international market, as confirmed by similarities in the three case studies. To break this cycle, we examined the Italian wine market's response to the 1986 Methanol crisis. Barbera and Audifredi [87] demonstrated the crucial role of aligning producers' and legislators' agendas towards a more transparent and convincing certification system. Importantly, they highlighted consumers' changed attitudes towards Italian wine as a driving force for this transformation. However, biopesticides lack the same level of consumer awareness and are subject to technophobia [88], which complicates the situation.

Farmers, producers, and regulators can be agents of change, but the research does not suggest straightforward strategies for overcoming the current impasse. Availability, affordability, and efficacy are key factors limiting farmers' adoption of biopesticides, as are legislative barriers to introducing new products for producers. Regulators are in a position to support change through new research, investment, and market liberalization. However, the research shows that this process is in its infancy and mostly confined to the EU, raising questions about how to facilitate it further [7, 89, 90].

Conclusion and recommendations

A comparative analysis of three geographical contexts reveals a shared narrative of challenges and opportunities for growth in the biopesticide sector. Our review shows that while biopesticides are emerging as an alternative to conventional prevention and intervention methods, they face biological, economic, and regulatory hurdles. Their proliferation is predominantly limited to organic farming, representing a niche in the broader pesticide market. Specifically, in North Africa, and particularly in Tunisia, the issues involve IPM. In Spain, the complexities of European regulations are paramount,

Table 1 The table presents the similarities and differences of the three main countries analyzed

Topic	Spain	Tunisia	Turkey
Agricultural Land	- Land for agricultural use: 54.1% - Arable land: 24.9% - Permanent crops: 9.1%	- Land for agricultural use: 64.8% - Arable land: 18.3% - Permanent crops: 15.4%	- Land for agricultural use: 49.7%, - Arable land: 26.7% - Permanent crops: 4%.
Real GDP and Agricultural sector	- Real GDP: $1.798 - World ranking: 16th - From agricultural sector: 2.6% - World ranking: 158th	- Real GDP: $127,509, - World ranking: 83rd - From agricultural sector: 10.1% - World ranking: 90th	- Real GDP: $2.817 trillion - World ranking: 11th - From agricultural sector: 6.8% - World ranking: 111th
Food Production and Exports	- Main agricultural products: wheat, olives, grapes, tomatoes, maize, oranges, sugar beets. - Food sector accounts for 17.2% of total exports.	- Main agricultural products: wheat, tomatoes, barley, olives, watermelons, green chillies/peppers, potatoes, dates, green onions/shallots. - Food sector accounts for 11.79% of total exports.	- Main agricultural products: wheat, sugar beets, tomatoes, barley, maize, potatoes, apples, grapes. - Food sector accounts for 11.58% of total exports
Pesticide Usage	- Annual use: 76,173.55 metric tons. - World ranking: 10	- Annual use: 3299.07 metric tons. - World ranking: 89th	- Annual use: 52,963 metric tons. - World ranking: 12th
Pesticide Export/Import (annual)	- Exported $1.69B in pesticides - Imported $1.04B in pesticides	- Exported $4.26M in pesticides - Imported $53.8M in pesticides	- Exported $189M in pesticides - Imported $549M in pesticides
IPM	- National Action Plan 2023–2024 aims to promote IPM - No direct support from the Common Agricultural Policy (CAP)	- Traditional IPM methods persist but proving inadequate - Efforts to refine IPM	- Efforts to refine IPM
Market	- Growing yet niche sector (6% of the pesticide market) - Gradual regulation of chemical pesticides - 38 authorized biological active substances	- Growing yet niche sector in pesticide market	- Growing yet niche sector in pesticide market - Growth in the food market
Drivers to the Adoption of Biopesticides	- Collaboration between public and private sectors. - Regulatory pressures on chemical pesticides. - Inclusion of "bioproducts" in the national regulatory framework - Advocacy from scientific community - Potential for organic agriculture market	- Challenges from novel pest species. - Legislative measures limiting conventional agricultural practices - Trend towards plant-based biopesticides. - Common use of homemade plant-based pesticides - Producers have a positive attitude towards biopesticides. - Potential for reduced-risk options in IPM.	- International investment in pesticide production in Turkey - Demand from growing agricultural sectors. - Several regulations on chemical pesticides - Enhanced licensing and releasing policies for plant protection products - Ban on chlorpropham and oxadiazon - Regional specific restriction on chemicals
Limits to Adoption of Biopesticides	- Regulatory complexities - Confined to organic agriculture. - Concerns over efficacy, safety and stability	- Farmers have often intensified the use of non-selective conventional techniques - Limited knowledge and access to biopesticides among farmers. - Structural barriers in small-scale agriculture.	- Fragmented legislative framework and complex authorization process. - Limited awareness and access among small-scale enterprises. - Structural barriers in small-scale agriculture.
How to improve biopesticide usage	- Supportive measures for the sector - Facilitate the authorization procedure - Autonomous registration process for biopesticides - Specific category for biopesticides - Refine formulas - Reduce production costs - Encourage mass production - Enhance quality control processes - Improve preservation capacity - Complete toxicology, testing	- Improve quality - Incorporating reduced-risk options, including biopesticides in IPM - Legislative measures supporting biopesticides - Capacity-building actions among farmes - Transmission of advanced scientific and technical knowledge to farmers	- Raise awareness of biopesticides' properties - Support biopesticides' implementation - Support small-scale enterprises

Table 1 (continued)

Topic	Spain	Tunisia	Turkey
	- Specific formulations to prevent degradation, to enhance the stability - Improve the technical competencies of farmers		

while in Turkey, the legislative landscape for biopesticides poses significant challenges, including the lack of a specific definition for biopesticides.

The research suggests a complex yet promising future for biopesticides, although the market structure currently limits their full potential in the Mediterranean region. A vicious circle involving regulators, producers, and users is hindering progress, although EU legislation and initiatives provide a more favourable context for biopesticide implementation, as evidenced in Spain. All the case studies highlight the necessity for additional economic, social, and cultural interventions. In this regard, the research suggests specific directions:

- Invest in research and development for biopesticides: allocate resources to in-depth research focusing on formula improvements, cost reductions, and enhanced quality control processes. Encourage mass production and explore technologies to improve stability and longevity, addressing concerns about short conservation periods.
- Legislative reforms for biopesticide registration: advocate for legislative changes at national and European levels to simplify the registration and authorization process. Establish a specific category within the regulatory framework and implement an autonomous registration process recognizing the unique characteristics of biopesticides.
- Facilitate local production in African countries: address the challenges of establishing local biopesticide production facilities in African countries. Foster public-private partnerships and attract private investment, supporting the development of local production structures and overcoming barriers to private sector engagement.
- Promote collaboration for technological development: encourage public-private sector collaboration to drive technological advancements in biopesticides. Establish knowledge-sharing platforms and create incentives for companies to invest in sustainable agricultural technologies.
- Invest in social and cultural research: deepen studies in the field of agricultural and productive traditions in different Mediterranean basin contexts. Traditional cultivation methods are linked to cultural conceptions about relationships with the environment and are passed down through generations. These can represent strengths for the introduction of sustainable biopesticides and for developing effective information and awareness campaigns.
- Implement training and awareness programmes: develop training programmes to enhance farmers' technical competencies in using biopesticides effectively. Conduct awareness-raising activities to align regulatory demands with the practices of small-scale producers and promote the benefits of biopesticides for sustainable agriculture.
- Advance biotechnologies for cost reduction: invest in biotechnologies to reduce biopesticide production costs and explore innovative technologies that simplify biocontrol application methods.
- Strengthen collaboration among stakeholders: facilitate collaboration among scientists, farmers, and policymakers for knowledge exchange and cooperation. Encourage farmer involvement in research partnerships to tailor solutions to diverse agricultural circumstances.

Thus, the research indicates a path forward for this emerging and more sustainable product category. It also calls for structural changes and new actions to raise awareness among producers, users, and the general public, thereby better integrating biopesticides into current farming practices. This direction aligns with the UN 2030 Agenda and warrants further exploration.

Abbreviations

CAGR Compound annual growth rate
GDP Gross domestic product
EU European Union
IPM Integrated pest management
UN United Nations
USD United States of America Dollar

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Declarations

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The authors declare no competing interests.

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