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Microbial biopesticides: A one health perspective on benefits and risks

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ABSTRACT

Controlling insect pests that destroy crop and spread diseases will become increasingly crucial for addressing the food demands of a growing global population and the expansion of vector-borne diseases. A key challenge is the development of a balanced approach for sustainable food production and disease control in 2050 and beyond. Microbial biopesticides, derived from bacteria, viruses, fungi, protozoa, or nematodes, offer potentially significant benefits for promoting One Health and contributing to several United Nations Sustainable Development Goals (SDGs). This narrative review examines the benefits and risks of microbial biopesticides from a One Health perspective, focusing on the Americas and Europe, and aligned with respective SDGs.

The value of biopesticides in sustainable agriculture and integrated pest management (IPM) approaches for food security, particularly SDG 2 (Zero Hunger) and SDG 1 (No Poverty) has been widely recognized, with relatively fewer adverse effects to people and the environment than synthetic pesticides. With increased demand and usage, microbial biopesticides can be expected to contribute further to additional SDGs such as SDG 12 (responsible consumption and production) through waste recycling for biopesticide production and remediation of polluted ecosystems, and by reducing vector-borne disease burdens such as malaria and dengue. Nevertheless, the prudent and judicious application of microbial biopesticides is crucial to ensuring their effectiveness and maximizing their One Health benefits while minimizing pest resistance and unintended impacts. From a One Health perspective, this goal involves incorporating microbial biopesticides into a comprehensive biological control strategy within an IPM framework for sustainable agriculture and for controlling vector-borne diseases.

1. Introduction

Biopesticides are naturally occurring compounds or agents obtained from animals, plants, certain minerals, or microorganisms such as bacteria, viruses, fungi, protozoa, microalgae, and nematodes [1,2]. Biopesticides have been reported to effectively control specific pests and plant pathogens while minimizing adverse effects on crops, the environment, and human health. Therefore, they offer potentially significant benefits for promoting One Health and contributing to several United Nations Sustainable Development Goals (SDGs). Worldwide, plant diseases and pests are responsible for annual yield reductions of 20 % to 40 % in major food and cash crops, mostly pre-harvest, with losses exceeding $470 billion [3–6]. Crop losses due to these diseases have been devastating, leading to severe famines throughout human history, such as the Irish Potato Famine of 1845, caused by late blight [3]. Plant pathogens are now estimated to cause the annual loss of at least 47 million metric tons of durable crops and 60 million metric tons of perishable crops [7].

With an estimated 67,000 pest species posing threats to crops, of which 9000 are insects and mites, significant pest management efforts are crucial for protecting crop yields [4,8]. At the same time, two-thirds of the world's population are at risk of at least one vector-borne disease, with malaria and dengue being the most widespread. While the extensive use of pesticides and other agrochemicals increases crop yields and controls disease vectors, their use has occurred against a backdrop of human activities that have negatively affected the environment and ecosystems, leading to water pollution and scarcity, soil contamination and degradation, erosion, a loss of agricultural land, and exacerbation of climate change [9]. The United Nations (UN) estimates that with the global population increasing exponentially and rapidly aging, there will be almost 10 billion people by 2050, with the number of those aged 80 or over tripling to 425 million [10]. As the average life expectancy continues to increase, pest control will become increasingly critical for meeting the food demands of a growing global population and for vector

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control to control disease [11]. A major challenge is the development of a balanced approach for sustainable food production and vector control in 2050 and beyond. Biopesticides, as naturally occurring compounds or agents that can control agricultural pests and pathogens, may offer a potential solution (Fig. 1) [1,12,13].

This paper examines the impact of microbial biopesticides (the largest sub-group of biopesticides currently used in the field) through a One Health lens, assessing effects on plant, human, animal and environmental health [14]. It focuses on the Americas and Europe as the largest user groups, aligning benefits and risks described in the literature with relevant UN SDGs (Fig. 2) [15,16].

2. Method

A literature review was conducted to assess the benefits and risks of microbial biopesticides. Scopus and PubMed databases were searched for relevant keywords from 1981 to March 26, 2024, yielding 1065 records. After removing duplicates and further screening of titles, abstracts, and analyzing full articles, 46 relevant peer-reviewed articles, book chapters, and conference proceedings describing microbial biopesticides and their impact on One Health were used for this narrative review. The literature search process is illustrated in Fig. 3.

3. Benefits

3.1. Eliminate plant pests, increase crop yield [SDGs 1,2,15]

The key benefit reported for microbial biopesticides was the elimination of pests without affecting crops [17]. For example, a commercial *Cydia pomonella* granulovirus (CpGV) product effective against the codling moth larvae, a major pest of apple and pear trees, was widely integrated into pest management programs by apple growers in central Europe [15,16,18,19]. Conventional fruit growers also adopted it because of challenges associated with insecticide resistance, stricter regulations, and residue concerns for exported fruit [18]. Microbial pesticides were utilized on 13 % of the apple crop in Washington State,

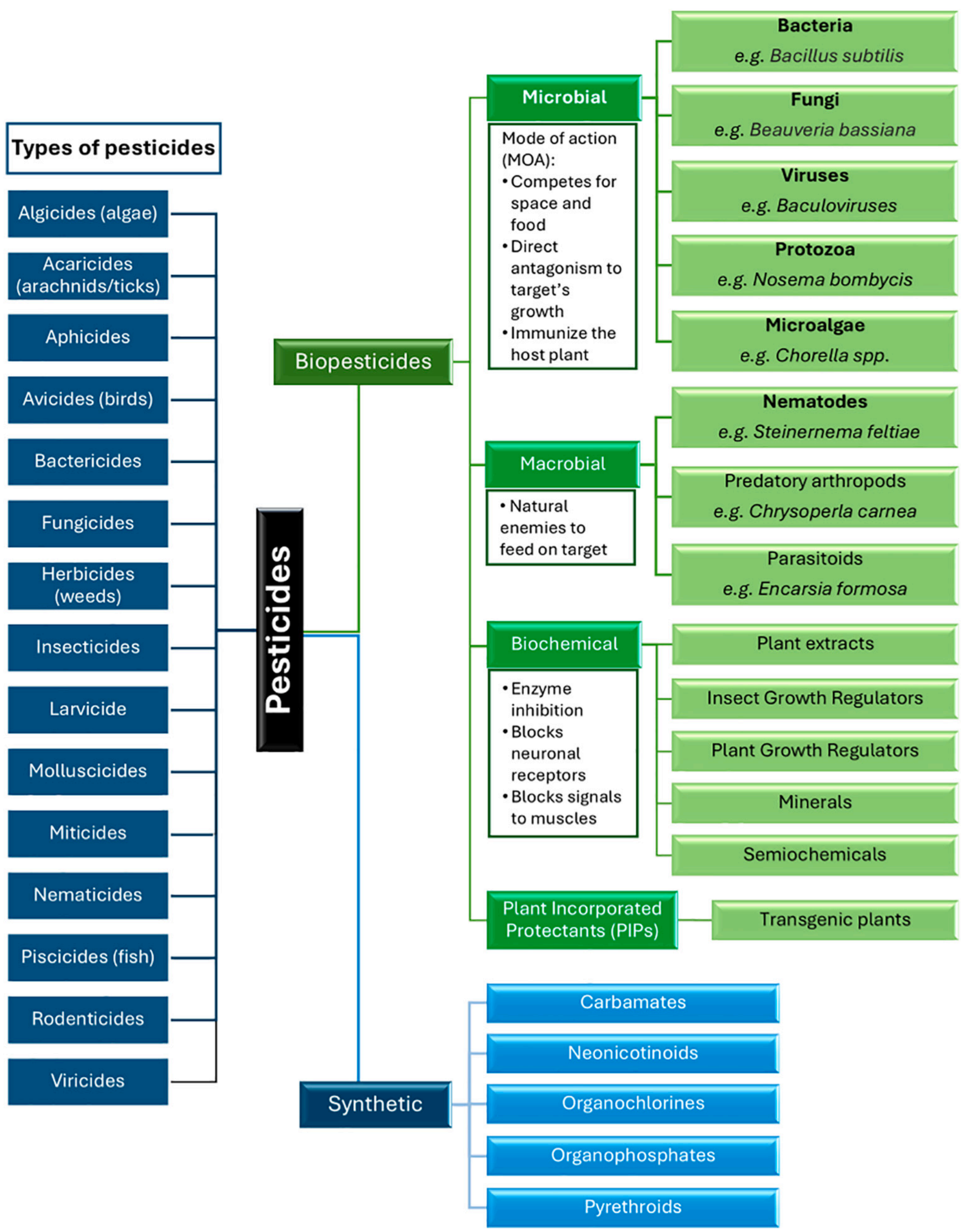

Fig. 1. Overview of distinct types of pesticides - synthetic and biopesticides (adapted from [9,14,15,22,28,35,49,51–53]).

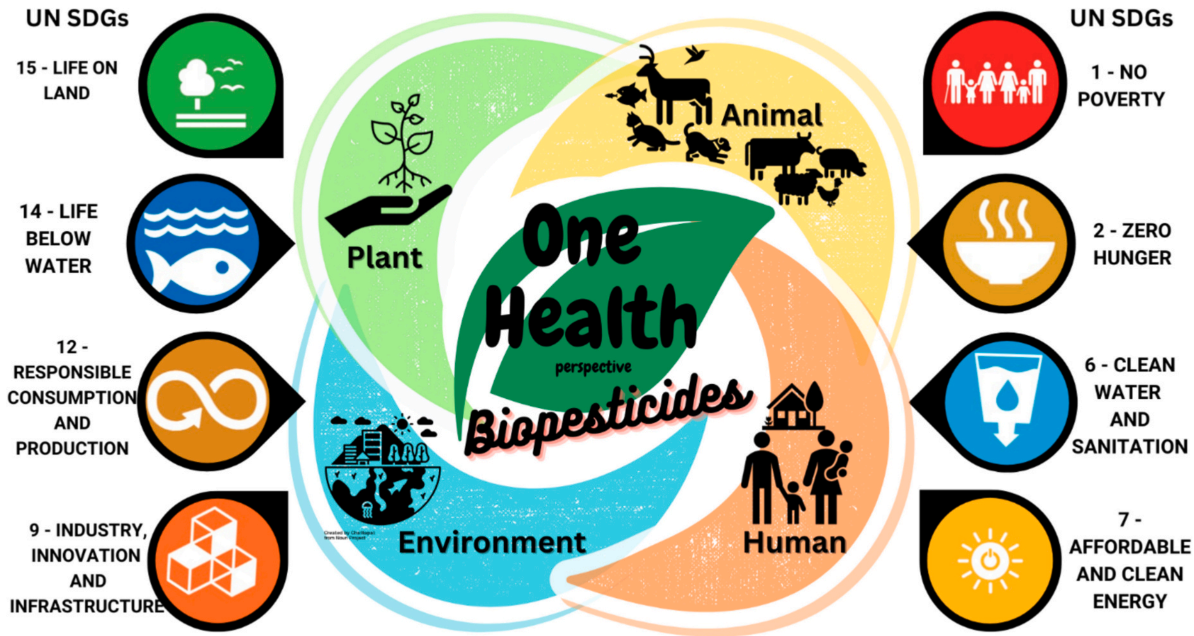

Fig. 2. Biopesticides – benefits and risks through a One Health lens*, aligned with 8 UN Sustainable Development Goals.*

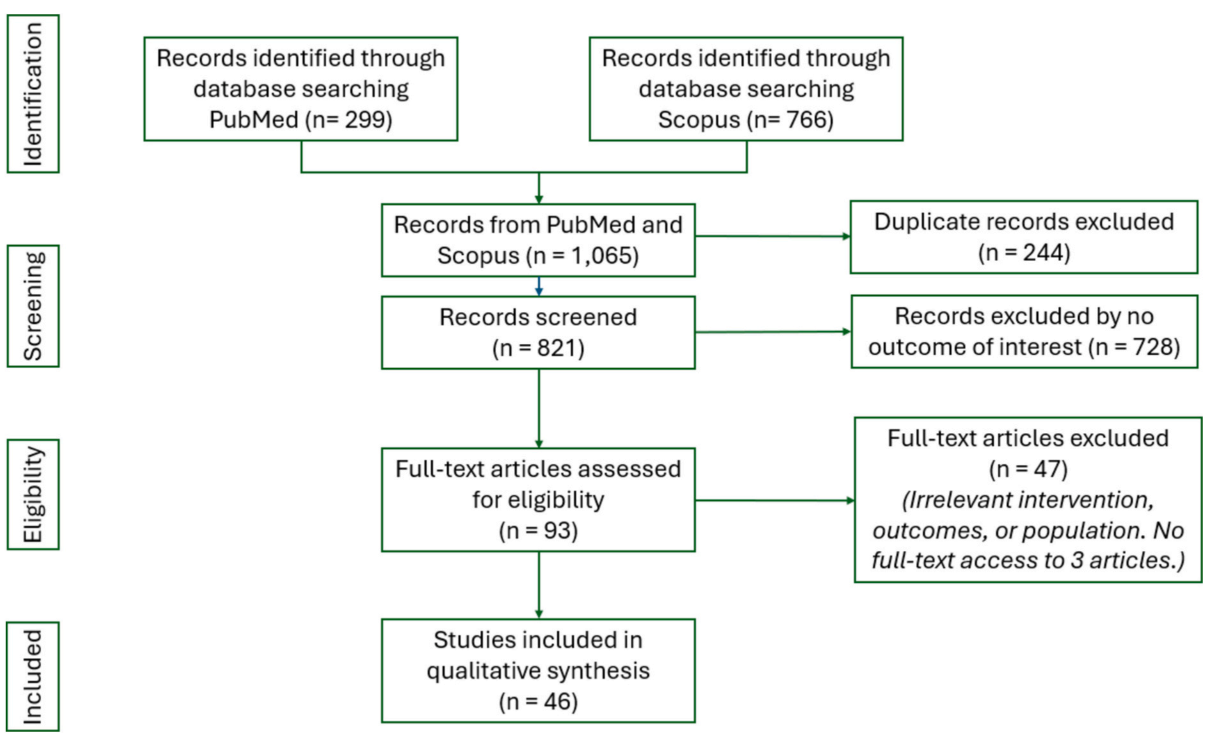

Fig. 3. PRISMA Flow Diagram for this literature review.

the largest apple producer in the US [20]. During the mid-1990s in Brazil, AgMNPV (*Autographa californica* multiple nucleopolyhedrovirus) was sprayed on approximately 4 million hectares (around 35 %) of soybean crops to control the soybean caterpillar *Anticarsia gemmatalis* [19,20]. Also in Brazil, the largest user of the entomopathogenic fungal biopesticides, *Metarhizium anisopliae* was applied annually to combat spittlebugs across approximately 750,000 ha of sugarcane and 250,000 ha of grassland [6,7,20]. Baculovirus biopesticides were widely used in Latin America, such as the granulovirus ErelGV in central and southern Brazil, where it proved effective for pest control in the field [19]. The same virus was also used in Colombia to control the sphingid moth (*Erinnyis ello)* on rubber trees [19]. In 6000 ha of poplar plantations affected by the defoliating pest Brazilian poplar moth (*Condylorrhiza vestigialis*), use of the CoveNPV virus was preferred over chemical insecticides because the forested areas were floodplains [19].

3.2. The importance of biopesticides for integrated pest management (IPM) and sustainable agriculture [SDGs 1,2,15]

Several articles reiterated that biopesticides worked best when integrated into agricultural programs with other crop protection tools, such as IPM and organic farming practices, and not as standalones [2,5,6,21–23]. Some microbial biopesticides offered multiple benefits beyond pest control. For example, bio-fungicides formulated with plant growth-promoting rhizobacteria (PGPR) such as *Bacillus* spp. and *Pseudomonas* spp. promoted plant growth directly in healthy plants or indirectly by controlling phytopathogens in various crops [2,3]. *Pseudomonas chlororaphis* PcO6 bacteria were shown to act as a biopesticide and biofertilizer, protecting plants from microbial diseases, insects, and nematodes while stimulating plant growth [2]. PcO6 also formed a biofilm around roots, shielding them and improving water retention in the soil [2]. The non-pathogenic fungal strain *Fusarium oxysporum* Fo47, commercialized in Europe, exhibited a dual mode of action against plant pathogens [24]: It could outcompete pathogens for nutrients in the soil and rhizosphere environments, as well as compete for colonization of the root tissues [24]. Fo47 also induced systemic resistance responses within the plant itself, bolstering the plant's innate defense mechanisms [24].

Biopesticides have also been shown in many instances to be highly cost-effective. A killed bacterial biopesticide (*Burkholderia rinojensis A396)* boosted control of the navel orangeworm (*Amyelois transitella*) from around 50 % with chemicals alone to over 90 % when added to farmers' usual program involving mating disruption pheromones in 2018 and 2019 [21]. That approach led to an impressive 20-fold estimated return on investment for almond growers in the US [21]. The study led by the US Department of Agriculture in 2010 also demonstrated the cost-effectiveness of using biopesticides in US organic corn production [25]. Although conventional yields were 31 % higher, the organic farms achieved 81 % higher net returns per hectare ($1371 vs $759). This increased return was driven by substantially lower input costs: Organic farms spent 39 % less on seeds, fertilizers, and pesticides ($331/ha vs $544/ha conventional) [25]. Crucially, the organic corn realized a 72 % higher price ($21.17 vs $12.29 conventional), resulting in a gross production value of $2233 per hectare compared to $1702 for conventional culturing [25].

3.3. Increased food security with higher yields and reduced pesticide toxicity risks [SDGs 6,7,12]

Organic farms were found to apply pesticides far less intensively than did conventional farms, resulting in lower levels of pesticide residues in food [26]. Organic farms under the US National Organic Program (NOP) used integrated pest management practices like planting cover crops, buffer strips, crop rotation, and beneficial insect habitats [26]. Less than a dozen pesticides, primarily biopesticides like Bt and Spinosad, were approved for organic farms and used only when other practices were deemed ineffective [26]. Importantly, dietary risk assessments consistently showed lower residues and chronic toxicity in organic food when compared to conventional food [26]. The study concluded that transitioning just 1.2 % of the 1.6 million hectares of US cropland to organic farming could nearly eliminate all pesticide dietary exposure and risk [26].

3.4. Potential efficacy against ticks, prevention of vector-borne diseases in people and animals [SDGs 1,15]

The literature review results did not explicitly cover any commercial microbial biopesticides used to improve animal health with regard to disease prevention or control. Limited potential for controlling invasive ticks and mites in poultry production was reported, however. Spraying soil surfaces with suspensions containing spores of highly virulent strains of the fungus *Metarhizium anisopliae* after the release of Asian longhorned ticks *(Haemaphysalis longicornis)* resulted in 60–90 % mortality of the ticks within 30 days [6]. The results suggested that treating areas with the fungal biopesticide could potentially control populations of the invasive tick species and thereby decrease the probability of tick-borne disease transmission to pets, livestock, wildlife, and humans [6]. The three strains of the fungus *Metarhizium* spp. tested against the poultry red mite (*Dermanyssus gallinae*) achieved 85–92 % efficacy in killing the mites under optimal conditions, but that high efficacy dropped to 30–40 % under actual poultry house conditions [6].

The use of biopesticides for mosquito control to prevent and control vector-borne diseases such as malaria and dengue fever has been predicted to significantly increase, especially in areas where the disease burden was already expected to rise because of climate change [27]. As part of an integrated vector management (IVM) approach, biological control, i.e., the use of the bacterial biopesticides Bti and Bs, has proven to be an effective approach to reduce mosquito populations, larvae, and bites [27]. These biopesticides demonstrated efficacy against some *Aedes* spp., *Anopheles* spp., and *Culex* spp. mosquito vectors, with increased effectiveness when used together [27]. The IVM approach also involves situation analysis, monitoring, surveillance, and capacity building to monitor strategy effectiveness and address potential insecticide resistance driven by insect evolutionary rates [27].

3.5. Restore polluted ecosystems, degrade pesticides [SDGs 6,7,14,15]

Certain commercial biopesticides were able to degrade synthetic pesticides ranging in number from 1 to 28 compounds, at maximum degradation percentages of 49 % to 100 % [28]. They were able to degrade these pesticides through (i) enzymatic reactions, (ii) non-enzymatic reactions or (iii) co-metabolism, whereby organisms independently cooperated in modifying substrates through oxidation and/or reduction, without using the product as a carbon and energy source, potentially detoxifying substances like DDT [28]. *Bacillus* spp. and *Trichoderma* spp. biopesticides were highlighted as having the most impact, given their effectiveness in pesticide degradation and the large number of commercial products containing these microorganisms [28]. The remediation effects of these biopesticides involved the breakdown of persistent organic pollutants into non-toxic compounds, reductions in soil and water contamination from pesticide residues, and preservation of biodiversity by minimizing harmful effects on non-target organisms [28,29].

3.6. Promote circular economy, recycle solid waste [SDGs 7,9,12]

Microbial biopesticides can be produced from solid waste, providing a cost-effective method of solid waste disposal and thereby promoting a circular economy [30]. Nearly $20 billion could be saved from utilizing solid waste to produce compost, biofertilizers, and biopesticides, which would otherwise be spent on chemical fertilizers and pesticides for crop cultivation [30]. Furthermore, recycling solid waste could substantially reduce greenhouse gas emissions emanating from landfills by 30 % to 50 % [30]. Furthermore, using biopesticides instead of chemical pesticides would avoid chemical pesticides' detrimental effects on the environment as well as human and animal health [1,30,31]. Examples of microbial biopesticides cited as being produced with solid waste as substrate included:

1. Bacterial: Production of *Bacillus thuringiensis* (Bt), a widely used bioinsecticide, was attempted using municipal solid waste (MSW) and spent mushroom substrate as raw materials [30]. The results showed similar or higher levels of entomotoxicity (e.g. 6×10^7 to 2.40×10^8 cfu/mL from MSW) when compared to the production of Bt by culturing on synthetic media [30]. Bt was also produced using wastewater from the starch industry, at an estimated unit production cost for the biopesticide of $2.54/L [17].

   The enormous waste from dairy industries, such as clarified butter sediment waste (CBSW), has been found to be capable of being repurposed as a nutrient source for growing *Bacillus thuringiensis* var. *israelensis* (Bti) bacteria, which produce mosquito-killing toxins [30]. The addition of *Bacillus sphaericus* (Bs) served the dual purposed of providing a useful larvicidal compound and simultaneously breaking down and consuming the difficult-to-dispose dairy waste [18].

2. Fungal: Entomopathogenic fungi such as *Beauveria bassiana and Paecilomyces fumosoroseus*, have been produced using various solid wastes, including grains, vegetable wastes, and rice husks [30]. *B. bassiana* exhibited optimal growth and achieved its highest spore production when cultivated on a wheat substrate [30]. Solid vegetable wastes like carrot, jackfruit seeds, and okra supported superior growth and sporulation of all three fungal strains when compared to cereal substrates [30].

3. Viral: A *Carpocapsa* larva infestation that crippled apple production in the US and Canada was effectively controlled using viral biopesticides (*Cydia pomonella granulosus virus*; CpGV) [30]. The biopesticides could be produced from solid wastes such as starch industry wastewater (SIW), apple pomace sludge (APS), and brewery wastewater (BWW) [30].

4. Risks

Overall, in the literature, commercial microbial pesticides were generally regarded as safe for human health, with rare adverse health effects reported [1,31]. However, people can be exposed to biopesticides through the air, food, and water.

4.1. Possible spread of infectious pathogens to immunocompromised individuals if not appropriate strain [SDGs 9,12]

Several bacterial and fungal biocontrol agents were reported to effectively combat plant pathogens and insect pests but pose potential health risks to humans, particularly immunocompromised individuals [22]. Some *Burkholderia* strains initially registered for antifungal activity were withdrawn from the market because of their links to human diseases. For example, *Burkholderia cepacia* caused outbreaks among cystic fibrosis patients, and highly transmissible strains spread across North America and the United Kingdom in the 1980s [22,32]. While *B. cepacia* showed great potential as a biopesticide and bioremediation agent, it was found to be resistant to multiple antibiotics, and "safe" strains could not be easily identified; moreover, its complex genome structure and propensity for rapid mutation and adaptation raised concerns about its widespread agricultural use [32].

Several bacterial genera with plant growth-promoting (PGP) traits, such as *Burkholderia* spp*., Enterobacter* spp*., Ochrobactrum* spp*., Pseudomonas* spp*., Serratia* spp*., Klebsiella* spp*., and Ralstonia* spp., were shown to be closely related to pathogenic or opportunistic human pathogens [33], and this relationship raised concerns about the potential risk of nosocomial infections and diseases in immunocompromised patients from exposure to some of these PGP bacteria [33]. *Pseudomonas aeruginosa* showed biocontrol potential against gray leaf spot of turfgrasses but was also found to be a virulent opportunistic pathogen that could infect wounds and severe burns [3]. Entomopathogenic fungi employed for insect biocontrol, such as *Metarhizium* spp., *Conidiobolus coronatus*, and certain *Cladosporium* species, despite their bioinsecticidal properties were also shown to have adverse impacts of human health [22]. Appropriate safety measures to prevent potential human exposure and infections will be crucial when developing and applying these biocontrol agents [34]. Two older studies reported that injured (and probably immunosuppressed) human patients had wounds infected by Bt [25]. Conversely, a recent study highlighted the low likelihood of negative health effects from microbial pesticides because an alkaline environment, present in insect guts but absent in mammals, was necessary for Bt to become toxic [35]. While Bt had been found in human bodily fluid cultures (in the US) and skin infections, often as a contaminant, it was rarely the cause of clinical illness [35].

4.2. Rare cases of allergies from occupational exposure to biopesticides [SDGs 9,12]

Bt-based insecticides were generally regarded as safe for human health, but health risks from occupational exposure through immune responses induced by Bt were observed in forestry and farm workers, though none of them developed any related disease [36,37]. An older study mentioned that a farmer developed a corneal ulcer after being splashed in the eye by Bt solution; fortunately, the ulcer resolved after gentamicin treatment [38]. Spores of entomopathogenic fungi such as *Trichoderma* spp., *Metarhizium anisopliae*, and *Beauveria bassiana* have been reported to cause allergies in farmworkers [8,36]. Eleven clinical cases of documented human *M. Anisopliae* infections were related to allergies and no other pathologies [37]. Six were ocular infections, primarily associated with contact lens use, two were instances of rhinitis, and three were other infections, one of which occurred in an immunocompromised individual [37]. Notably, none of these reported infections were directly linked to the application of *M. anisopliae* as a biopesticide [37]. Two greenhouse workers showed Type 1 allergic sensitization to the nematode biopesticide *Steinernema feltiae* [39]. They had been compared with seven control subjects, and their allergy was confirmed by positive skin prick tests to *S. feltiae* samples and negative results with the carrier medium [39]. They experienced work-related respiratory symptoms such as rhinitis, conjunctivitis, wheezing, and shortness of breath that resolved on weekends/holidays [39].

Colony formation assays conducted in a laboratory study sparked potential genotoxicity concerns when they demonstrated that higher Spinosad concentrations inhibited A549 cell proliferation, pointing to a potential risk of lung damage from inhalation exposure [40].

4.3. Implicated biopesticides in rare cases of foodborne illness [SDGs 1,2,12]

Implication of Bt in rare gastroenteritis outbreaks has been reported [25]. A recent study to investigate Bt residues in the food chain detected a higher prevalence and higher levels in fresh and frozen spinach treated with this type of biopesticide as compared to untreated samples [41]. Six of 11 Bt isolates were confirmed to originate from applied biopesticides and carried enterotoxin genes [41]. Whole genome sequencing identified Bt biopesticide strains, including four biofilm-formers with the potential to cause persistent contamination in food facilities [41]. While most samples had Bt counts below 105 CFU/g, which is considered the limit for safety, one fresh spinach sample exceeded this threshold just 2 days before harvest [41]. The study recommended establishing longer pre-harvest intervals after treatment to reduce excessive Bt residues, highlighting the importance of food labeling and monitoring Bt residues from biopesticide use [41].

4.4. Potential secondary pest/ vectors outbreaks from resistance/ selection [SDGs 1,2,15]

Several articles concluded that the risk of pest resistance was lower for biopesticides than for synthetic insecticides [11,20,21,30,34,42]. They pointed out that biopesticides typically had novel, complex, and multiple modes of action; hence, pests and pathogens causing plant diseases were less likely to evolve resistance to them [21]. Instances of resistance have only rarely been reported over the last 60 years of commercial use [21]. Nevertheless, the unintended selection of resistance to the active ingredient of biopesticides in non-target species was considered theoretically possible [36]. Such an event could release secondary pest species from natural controls, leading to pest outbreaks affecting plant health and crop production [36,37]. Exposure to these compounds might also induce detoxification enzymes in non-target pests [36]. Another possibility would be a shift in ecological dominance, where a secondary pest species became more prevalent at the expense of the primary target, as seen with mosquitoes and grain beetles exposed to synthetic insecticides [36]. For biopesticides targeting disease vectors, such a situation could lead to a resurgence of vector-borne diseases affecting public health.

4.5. Impact on pollinators that affect plant reproduction [SDGs 2,12,15]

While some impact on pollinators has been reported, there was an overall lack of studies investigating potential adverse effects on post-pollination events in plant reproduction [43]. Most safety studies focused on adult honeybees, indicating that microbial biopesticides were mostly safe at normal crop protection concentrations, with mixed results at high doses that could affect bee longevity and brood reproduction [4,43]. Potential effects on honeybee larvae and pupae and sublethal effects were not extensively tested [43].

4.6. Lower risk of field/soil/air persistence due to rapid degradation [SDGs 6,14,15]

Several articles highlighted the lower field persistence of microbial biopesticides as compared to chemical insecticides, limiting efficacy but lowering the environmental health risk [9,11,42,44]. Because of their biological nature, exposure to air, moisture, high temperatures, and sunlight (ultraviolet rays) facilitate the breakdown of biopesticides, enabling their rapid degradation and preventing environmental accumulation or pollution in water and soil [11,20,42,44].

A study using DNA markers demonstrated that a reintroduced soil microorganism was likely to survive, but not proliferate excessively, and become part of the native populations of the same species [24]. Baculoviruses were not found below 14 cm in soil after 9 months and were not present in the air after spraying because their occlusion bodies degraded rapidly in sunlight [37]. In aquatic systems, they quickly precipitated like soil particles, with a low risk of reaching groundwater [37]. Bt bacteria were not well-adapted to soil, with low growth potential for spores, and Cry toxin concentrations were too low to affect nematodes, bacteria, or fungi, thereby limiting risks for potential resistance development [37]. Entomopathogenic fungi, naturally present in soil and insects, persisted for 0.5 to 1.5 years in the case of *B. bassiana* to over 10 years for *M. anisopliae*, with longevity being influenced by spore production, formulation, and environmental conditions such as UV, temperature, soil factors, and agricultural practices [37]. Although microbial biopesticides were considered low-risk from a regulatory point of view, their safety assessment required thorough checks for potential interactions with other environmental organisms and any negative effects from produced metabolites [16,45]. Concerns were also expressed regarding insufficiently researched interspecific gene transfer and expression issues, as pointed out in the EU assessment of *Bacillus thuringiensis* subsp. *tenebrionis* strain NB-176 [45].

4.7. Low risk of ecotoxicity to non-target species [SDGs 14,15]

Various toxicological and ecotoxicological tests have been conducted to evaluate the human and environmental safety of end-use products for commercial use [46]. These studies on aquatic and terrestrial organisms determined the presence of any hazardous toxins in the strains of microorganisms and estimated the effects of these strains and their toxins on non-target species [46]. Many articles highlighted the fact that biopesticides act on specific pests and hence pose a low overall risk to non-target species, typically lower than that of synthetic pesticides [1,31,46]. Nevertheless, comparison across ecotoxicity studies was found to be challenging because of differences in concentration units, causing confusion and generating doubts during the process of regulatory or registration decisions [46].

For example, baculoviruses were established as being safe, since they could not infect vertebrates (including humans and higher animals) and no adverse effects were reported from short-term toxicities after repeated exposure of different species of mice, dogs and rhesus monkeys [16,37]. The risk to aquatic invertebrates was low in terms of infectivity and pathogenicity [37,46]. Bti had no lethal or sublethal effects on most non-target benthic ("bottom dwelling" small aquatic animals and the aquatic larval stages of insects such as dragonfly larvae, snails, worms, and beetles) insects, except at very high dosages [4,47]. Bti and Bs did also not have significant adverse environmental effects at concentrations used for mosquito control [48]. In contrast, Spinosad exposure could was able to cause several ecotoxic effects in exposed small mammals (mice, rats, rabbits), fish, and crustaceans, affecting their mobility, appetite, and reproduction [49]. Notably, Spinosad was detected by chromatographic and mass spectrometry analyses at concentrations of 0.54 and 1.2 μg/L in water samples collected from various rivers near agricultural activity in Spain [49]. Such concentrations could potentially affect non-target organisms, leading to ecosystem damage [49].

Two older large-scale field studies found no adverse effects on non-target animals. *Bacillus thuringiensis* var. *kurstaki* (Btk) was sprayed aerially over a 12,803-ha area in 1999 to control the invasive European gypsy moth, and no spraying was done in 2000 [50]. Point-count surveys of over 40 bird species revealed no consistent adverse effects of spraying on the relative abundance of most songbird species, except for the spotted towhee, with significantly lower numbers in sprayed plots in 1999, but its relative abundance was similar in the sprayed and reference plots in 2000 [50]. Intensive searches for songbird broods also showed no differences in the numbers of broods between the sprayed and unsprayed areas for any examined species [50]. Btk was also sprayed over 100,000 –to 225,000-Ha forests in New Brunswick, Canada, annually from 1986 to 1989 [38]. There were no adverse effects reported from the application, as compared to the other two synthetic pesticides in the same study. Bt biopesticides could be applied by agricultural-type aircraft, up to a distance of 155 m (500 ft) from habitation, because of its relative non-toxicity, as compared to double the distance for other synthetic or oil-based pesticides [38].

Fig. 4 illustrates the benefits versus risks of using microbial biopesticides, through a One Health lens aligned with respective UN SDGs.

5. Conclusions

The benefits of using biopesticides currently outweigh the risks, provided proper mitigation measures are taken. These measures include wearing personal protective clothing during application, thorough washing of produce before consumption, and adhering to recommended application dosages and durations for target species. Where pesticide use is necessary, biopesticides are preferable, but we must adapt to the corresponding increases in associated risks. Biopesticides, including microbial biopesticides, have the potential to contribute significantly to several United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 1 (No Poverty). Findings from the literature reviewed highlight the valuable role biopesticides can play in sustainable agriculture and IPM approaches, which aim to maintain crop yields, soil health, and minimize adverse environmental impacts.

This is a rapidly evolving field, with extensive ongoing research anticipated to lead to more novel microbial pesticides. Though biopesticides currently occupy only 5 % of the total crop protection market, demand for them has been increasing significantly, with a predicted global market value of USD 7.38 billion in 2023 and a CAGR of 17.02 % [11,15]. Widespread demand may enhance the impact of certain benefits, such as waste recycling for biopesticide production and remediation of polluted ecosystems, supporting SDG 12 (responsible consumption and production) and others.

However, as with the responsible use of antimicrobials, the prudent and judicious application of biopesticides is crucial to ensure their effectiveness and maximize their One Health benefits while minimizing pest resistance and unintended consequences. From a One Health perspective, this involves incorporating biopesticides as part of a comprehensive biological control strategy within an IPM framework for sustainable agriculture and an integrated vector management approach

Fig. 4. Infographic depicting the benefits and risks of using biopesticides in an urban environment through a One Health lens aligned with UN SDG.

for controlling vector-borne diseases with high disease burdens.

Many of the studies discussed here focused on laboratory or research-based investigations into the biological properties, efficacy, or additional modes of action of established and prototype biopesticides, and there is a lack of information on the long-term chronic toxicity, health consequences, and quantified benefits and cost-effectiveness of using biopesticides in terms of plant health, crop protection, environmental health, and public health. Modeling studies demonstrating the benefits of using biopesticides versus synthetic pesticides or no pesticides could encourage wider adoption and implementation.

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CRediT authorship contribution statement

Panqin Cai: Writing – original draft. **George Dimopoulos:** Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

These materials include

1) Search strategy and keywords used to generate results for this narrative review
2) A bibliometric analysis (VOSviewer illustration) of keywords from the literature review articles
3) An original illustration of the 4H paradigm of One Health – interconnectedness between human, animal, plant, and environmental health
4) Infographic depicting the benefits of using microbial biopesticides through a One Health lens aligned with UN SDGs
5) Infographic depicting the risks of using microbial biopesticides through a One Health lens aligned with UN SDGs
6) A non-exhaustive tabulation of examples of microbial biopesticides and their uses
7) A tabulation of aquatic and terrestrial ecotoxicities from literature review articles

Supplementary data to this article can be found online at [https://doi.org/10.1016/j.onehlt.2024.100962].

Data availability

All data has been shared in references, figures, tables and supplementary materials in this review article.

References

[1] M.S. Ayilara, B.S. Adeleke, S.A. Akinola, C.A. Fayose, U.T. Adeyemi, L. A. Gbadegesin, R.K. Omole, R.M. Johnson, Q.O. Uthman, O.O. Babalola, Biopesticides as a promising alternative to synthetic pesticides: a case for microbial

pesticides, phytopesticides, and nanobiopesticides, Front. Microbiol. 14 (2023) 1040901, https://doi.org/10.3389/fmicb.2023.1040901.

[2] R. Lahlali, S. Ezrari, N. Radouane, J. Kenfaoui, Q. Esmaeel, H.E. Hamss, Z. Belabess, E.A. Barka, Biological control of plant pathogens: a global perspective, Microorganisms 10 (3) (2022) 596, https://doi.org/10.3390/microorganisms10030596.

[3] C. Rettinassababady, C. Jeyalakshmi, Bio-fungicides: The best alternative for sustainable food security and ecosystem, in: N.K. Dubey, R.S. Upadhyay, R. Raghuwanshi, R.N. Kharwar (Eds.), Microbial Diversity and Biotechnology in Food Security, Springer eBooks, 2014, pp. 401–411, https://doi.org/10.1007/978-81-322-1801-2_35.

[4] S.B. Gaudana, T. Bagchi, Environmental impact from the use of Bt toxin, in: T. Satyanarayana, B.N. Johri (Eds.), Microorganisms in Environmental Management: Microbes and Environment, Springer, Netherlands, 2011, pp. 431–450, https://doi.org/10.1007/978-94-007-2229-3_20.

[5] A. Vlaiculescu, C. Varrone, Sustainable and eco-friendly alternatives to reduce the use of pesticides, in: Pesticides in the Natural Environment: Sources, Health Risks, and Remediation, Elsevier eBooks, 2022, pp. 329–364, https://doi.org/10.1016/B978-0-323-90489-6.00014-86.

[6] J. Jampílek, K. Kráľová, Biopesticides for management of arthropod pests and weeds, in: Biopesticides: Volume 2: Advances in Bio-Inoculants, Elsevier eBooks, 2021, pp. 133–158, https://doi.org/10.1016/B978-0-12-823355-9.00009-2.

[7] N. Sharma, Biologicals: Green alternatives for plant disease management, in: Biological Controls for Preventing Food Deterioration: Strategies for Pre- and Postharvest Management, Wiley, 2014, pp. 1–25, https://doi.org/10.1002/9781118533024.ch1.

[8] P. Sharma, N. Gaur, Microbial biopesticides use in insect-pest management: An overview, in: M. Kaushal, R. Prasad (Eds.), Microbial Biotechnology in Crop Protection, Springer, 2021, pp. 123–145, https://doi.org/10.1007/978-981-16-0049-4_5.

[9] J. Kumar, A. Ramlal, D. Mallick, V. Mishra, An overview of some biopesticides and their importance in plant protection for commercial acceptance, Plants (Basel) 10 (6) (2021) 1185, https://doi.org/10.3390/plants1006118510.

[10] United Nations, World Population Projected to Reach 9.8 Billion in 2050, and 11.2 Billion in 2100. https://www.un.org/en/desa/world-population-projected-reach-98-billion-2050-and-112-billion-2100 (accessed 18 March 2024).

[11] D. Duarte, C. Gaspar, C. Galhano, P. Castro, Biopesticides and sustainability in a land use context, in: A.F.F. Setti, U.M. Azeiteiro, W.L. Filho, U.M. Azeiteiro (Eds.), Sustainability in Natural Resources Management and Land Planning, Springer, 2021, pp. 111–133, https://doi.org/10.1007/978-3-030-76624-5_8.

[12] D. Abdollahdokht, Y. Gao, S. Faramarz, A. Poustforoosh, M. Abbasi, G. Asadikaram, M.H. Nematollahi, Conventional agrochemicals towards nano-biopesticides: an overview on recent advances, Chem. Biol. Technol. Agric. 9 (1) (2022) 1–19, https://doi.org/10.1186/s40538-021-00281-0.

[13] United States Environment Protection Agency, What are Biopesticides?. https://www.epa.gov/ingredients-used-pesticide-products/what-are-biopesticides, 2024 (accessed 18 March 2024).

[14] I. Kumari, R. Hussain, S. Sharma, M. Ahmed, Microbial biopesticides for sustainable agricultural practices, in: Biopesticides: Volume 2: Advances in Bio-Inoculants, Elsevier eBooks, 2021, pp. 301–317, https://doi.org/10.1016/B978-0-12-823355-9.00024-9.

[15] P. Singh, P. Mazumdar, Microbial pesticides: Trends, scope and adoption for plant and soil improvement, in: Biopesticides: Volume 2: Advances in Bio-Inoculants, Elsevier eBooks, 2021, pp. 37–71, https://doi.org/10.1016/B978-0-12-823355-9.00023-7.

[16] F. Karamaouna, L.P. Economou, M. Lykogianni, S. Mantzoukas, P.A. Eliopoulos, Biopesticides in the EU: State of play and perspectives after the Green Deal for agriculture, in: Development and Commercialization of Biopesticides: Costs and Benefits, Elsevier eBooks, 2023, pp. 213–239, https://doi.org/10.1016/B978-0-323-95290-3.00004-2.

[17] A.E.D. Mahmoud, M. Fawzy, M. Hosny, Feasibility and challenges of biopesticides application, in: A. Vaishnav, H.B. Singh (Eds.), New and Future Developments in Microbial Biotechnology and Bioengineering, Elsevier eBooks, 2022, pp. 83–97, https://doi.org/10.1016/B978-0-323-85581-5.00023-9.

[18] P. Hunter, Fight fire with fire: can biopesticides fill the void left by banning chemical pesticides and herbicides? EMBO Rep. 10 (5) (2009) 433–436, https://doi.org/10.1038/embor.2009.77.

[19] D.R. Sosa-Gómez, F.S. Morgado, R.F.T. Corrêa, L.A. Silva, D.M.P. Ardisson-Araújo, B.M.P. Rodrigues, E.E. Oliveira, R.W.S. Aguiar, B.M. Ribeiro, Entomopathogenic viruses in the neotropics: current status and recently discovered species, Neotrop. Entomol. 49 (3) (2020) 315–331, https://doi.org/10.1007/s13744-020-00770-1.

[20] E. Hassan, A. Gökçe, Production and consumption of biopesticides, in: D. Singh (Ed.), Advances in Plant Biopesticides, Springer, New Delhi, 2014, pp. 361–379, https://doi.org/10.1007/978-81-322-2006-0_18.

[21] P.G. Marrone, Status and potential of bioprotection products for crop protection, in: Recent Highlights in the Discovery and Optimization of Crop Protection Products, Elsevier eBooks, 2021, pp. 25–38, https://doi.org/10.1016/B978-0-12-821035-2.00002-4.

[22] A. Ratnadass, P. Deberdt, T. Martin, M. Sester, J.P. Deguine, Impacts of crop protection practices on human infectious diseases: Agroecology as the preferred strategy to integrate crop plant health within the extended "One Health" framework, in: M. Vithanage, M.N.V. Prasad (Eds.), One Health: Human, Animal, and Environment Triad, Wiley, 2023, pp. 287–308, https://doi.org/10.1002/9781119867333.ch21.

[23] E.O. Fenibo, G.N. Ijoma, T. Matambo, Biopesticides in sustainable agriculture: a critical sustainable development driver governed by green chemistry principles, Front. Sustain. Food Syst. 5 (2021) 619058, https://doi.org/10.3389/fsufs.2021.619058.

[24] C. Alabouvette, C. Cordier, Risks of microbial biocontrol agents and regulation: Are they in balance?, in: Regulation of Biological Control Agents Springer eBooks, 2011, pp. 157–173, https://doi.org/10.1007/978-90-481-3664-3_7.

[25] F. Magkos, F. Arvaniti, A. Zampelas, Organic food: buying more safety or just peace of mind? A critical review of the literature, Crit. Rev. Food Sci. Nutr. 46 (1) (2006) 23–56, https://doi.org/10.1080/10408690490911846.

[26] C. Benbrook, S. Kegley, B. Baker, Organic farming lessens reliance on pesticides and promotes public health by lowering dietary risks, Agronomy 11 (7) (2021) 1266, https://doi.org/10.3390/agronomy11071266.

[27] T. Ahmed, M.Z. Hyder, I. Liaqat, M. Scholz, Climatic conditions: conventional and nanotechnology-based methods for the control of mosquito vectors causing human health issues, Int. J. Environ. Res. Public Health 16 (17) (2019) 3165, https://doi.org/10.3390/ijerph16173165.

[28] P. Książek-Trela, E. Szpyrka, The effect of natural and biological pesticides on the degradation of synthetic pesticides, Plant Prot. Sci. 58 (4) (2022) 273–291, https://doi.org/10.17221/152/2021-pps.

[29] R.A. Bhat, B.A. Beigh, S.A. Mir, S.A. Dar, A.D. Moonisa, A. Rashid, R. Lone, Biopesticide techniques to remediate pesticides in polluted ecosystems, in: Research Anthology on Emerging Techniques in Environmental Remediation, IGI Global eBooks, 2021, pp. 336–356, https://doi.org/10.4018/978-1-6684-3714-8.ch017.

[30] S. Balasubramanian, R.D. Tyagi, Biopesticide production from solid wastes, in: Current Developments in Biotechnology and Bioengineering: Solid Waste Management, Elsevier eBooks, 2017, pp. 43–58, https://doi.org/10.1016/b978-0-444-63664-5.00003-4.

[31] C. Swapan, B. Mainak, B. Deewa, M. Tanmoy, Natural pesticides for pest control in agricultural crops: an alternative and eco-friendly method, Plant Sci. Today 11 (1) (2024) 433–450, https://doi.org/10.14719/pst.2547.

[32] A. Holmes, J. Govan, R. Goldstein, Agricultural use of *Burkholderia* (*Pseudomonas*) *cepacia*: a threat to human health? Emerg. Infect. Dis. 4 (2) (1998) 221–227, https://doi.org/10.3201/eid0402.980209.

[33] P. Martínez-Hidalgo, M. Maymon, F. Pule-Meulenberg, A.M. Hirsch, Engineering root microbiomes for healthier crops and soils using beneficial, environmentally safe bacteria, Can. J. Microbiol. 65 (2) (2019) 91–104, https://doi.org/10.1139/cjm-2018-0315.

[34] M.D.T. Islam, Current status and future prospects of Cladosporium sp., a biocontrol agent for sustainable plant protection, Biocontrol Sci. 27 (4) (2022) 185–191, https://doi.org/10.4265/bio.27.185.

[35] N. Chakraborty, R. Mitra, S. Pal, R. Ganguly, K. Acharya, T. Minkina, A. Sarkar, C. Keswani, Biopesticide consumption in India: insights into the current trends, Agriculture 13 (3) (2023) 557, https://doi.org/10.3390/agriculture13030557.

[36] K. Haddi, L.M. Turchen, L.O. Viteri Jumbo, R.N.C. Guedes, E.J.G. Pereira, R.W. S. Aguiar, E.E. Oliveira, Rethinking biorational insecticides for the pest management: unintended effects and consequences, Pest Manag. Sci. 76 (7) (2020) 2286–2293, https://doi.org/10.1002/ps.5837.

[37] C. Deshayes, M. Siegwart, D. Pauron, J.-A. Froger, B. Lapied, V. Apaire-Marchais, Microbial pest control agents: are they a specific and safe tool for insect pest management? Curr. Med. Chem. 24 (27) (2017) https://doi.org/10.2174/0929867324666170314144311.

[38] D.J. Ecobichon, Chemical management of forest pest epidemics: a case study, Biomed. Environ. Sci. 3 (2) (1990) 217–239.

[39] T. Thilsing, D. Sherson, A.M. Madsen, J. Baelum, Type 1 sensitisation against a Steinernema feltiae product, BMJ Case Rep. (2012), https://doi.org/10.1136/bcr-2012-006279 bcr2012006279.

[40] Y. Zhang, H. Chen, Y. Fan, Y. Yang, J. Gao, W. Xu, Z. Xu, Z. Li, L. Tao, Cytotoxic effects of bio-pesticide spinosad on human lung A549 cells, Chemosphere 230 (2019) 82–189, https://doi.org/10.1016/j.chemosphere.2019.05.042.

[41] X. Zhao, A. Zervas, M. Hendriks, A. Rajkovic, L. van Overbeek, N.B. Hendriksen, M. Uyttendaele, Identification and characterization of *Bacillus thuringiensis* and other *Bacillus cereus* group isolates from spinach by whole genome sequencing, Front. Microbiol. 13 (2022) 1030921, https://doi.org/10.3389/fmicb.2022.1030921.

[42] S.A. Lone, A. Malik, J.C. Padaria, Applications of Bacillus thuringiensis for prevention of environmental deterioration, in: Environmental Deterioration and Human Health: Natural and Anthropogenic Determinants, Springer eBooks, 2013, pp. 73–95, https://doi.org/10.1007/978-94-007-7890-0_5.

[43] P.G. Kevan, L. Shipp, G. Smagghe, Ecological intensification: Managing biocomplexity and biodiversity in agriculture through pollinators, pollination and deploying biocontrol agents against crop and pollinator diseases, pests and parasites, in: G. Smagghe, O. Boecking, B. Maccagnani, M. Mänd, P. Kevan (Eds.), Entomovectoring for Precision Biocontrol and Enhanced Pollination of Crops, Springer International Publishing AG, 2020, pp. 19–51, https://doi.org/10.1007/978-3-030-18917-4_2.

[44] J.A. Essiedu, F.O. Adepoju, M.N. Ivantsova, Benefits and limitations in using biopesticides: a review, AIP Conf. Proc. 2313 (2020) 080002, https://doi.org/10.1063/5.0032223.

[45] K. Czaja, K. Góralczyk, P. Struciński, A. Hernik, W. Korcz, M. Minorczyk, M. Łyczewska, J.K. Ludwicki, Biopesticides - towards increased consumer safety in the European Union, Pest Manag. Sci. 71 (1) (2014) 3–6, https://doi.org/10.1002/ps.3829.

[46] E.C. Oliveira-Filho, C.K. Grisolia, The ecotoxicology of microbial insecticides and their toxins in genetically modified crops: an overview, Int. J. Environ. Res. Public Health 19 (24) (2022) 16495, https://doi.org/10.3390/ijerph192416495.

[47] US EPA, Indicators: Benthic Macroinvertebrates. https://www.epa.gov/national-aquatic-resource-surveys/indicators-benthic-macroinvertebrates, 2019 (accessed 6 April 2024).
[48] S. Lawler, Environmental safety review of methoprene and bacterially-derived pesticides commonly used for sustained mosquito control, Ecotoxicol. Environ. Saf. 139 (2017) 335–343, https://doi.org/10.1016/j.ecoenv.2016.12.038.
[49] V.S.V. Santos, B.B. Pereira, Properties, toxicity and current applications of the biolarvicide spinosad, J. Toxicol. Environ. Health Part B 23 (1) (2019) 13–26, https://doi.org/10.1080/10937404.2019.1689878.
[50] L. Sopuck, K. Ovaska, B. Whittington, Responses of songbirds to aerial spraying of the microbial insecticide *Bacillus thuringiensis var. kurstaki*(Foray 48B®) on Vancouver Island, British Columbia, Canada, Environ. Toxicol. Chem. 21 (8) (2002) 1664–1672, https://doi.org/10.1002/etc.5620210818.
[51] G.M. Daraban, R.-M. Hlihor, D. Suteu, Pesticides vs. biopesticides: from pest management to toxicity and impacts on the environment and human health, Toxics 11 (12) (2023) 983, https://doi.org/10.3390/toxics11120983.
[52] I. Ansari, M.M. El-Kady, C. Arora, M. Sundararajan, D. Maiti, A. Khan, A review on the fatal impact of pesticide toxicity on environment and human health, in: Global Climate Change, Elsevier, 2021, pp. 361–391, https://doi.org/10.1016/b978-0-12-822928-6.00017-4.
[53] E.O. Fenibo, G.N. Ijoma, T. Matambo, Biopesticides in sustainable agriculture: Current status and future prospects, in: S.D. Mandal, G. Ramkumar, S. Karthi, F. Jin (Eds.), New and Future Development in Biopesticide Research: Biotechnological Exploration, Springer, 2022, pp. 1–53, https://doi.org/10.1007/978-981-16-3989-0_1.