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Review

Propolis: Harnessing Nature's Hidden Treasure for Sustainable Agriculture

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Abstract: Recently, the search for sustainable and environmentally friendly agrochemicals from natural origin is steadily growing. Propolis, a resinous substance collected by honeybees, well known for its diverse biological activities, has attracted the attention of scientists and farmers with its agrochemical potential in the last years. This review article aims to delve into the fascinating world of propolis and its utilization in agriculture. Here, we provide a brief overview of propolis: its chemical composition and the bioactive substances responsible for its biological properties. The effectiveness of propolis in controlling common pests and diseases that affect crops, suppressing postharvest illnesses of fruits and vegetables, stimulating plant defenses and increasing stress resistance, is reviewed. Discussion of the challenges and future perspectives related to the integration of propolis in agriculture is also one of our objectives, including chemical variability, standardization and regulatory considerations. We also focused on the latest research trends and technological advances that promise to unlock the full potential of propolis as a sustainable agricultural tool.

Keywords: propolis; pesticides; herbicides; fungicides; bactericides; postharvest disease control

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1. Introduction

Recent years have seen a significant global drive towards sustainable and ecological agricultural practices. This change is due to growing concerns about the harmful effects of synthetic pesticides and chemical fertilizers on ecosystems and human health [1]. Researchers and farmers are exploring alternative methods to increase crop productivity and ensure the long-term viability of agricultural systems. One such natural solution that is gaining more and more attention is propolis.

Propolis, also known as "bee glue", is a resinous substance collected by honeybees from various plant sources. For centuries, propolis has been valued for its medicinal properties, primarily in human health applications [2]. However, its potential as a tool for sustainable agriculture has only recently begun to emerge as an area of study and research [3].

This review article aims to delve into the fascinating world of propolis and its use in agriculture. By exploring the existing body of knowledge and recent scientific advances, we aim to shed light on the multifaceted benefits that propolis offers for pest control, crop cultivation and overall agricultural sustainability. To date, only one review article has been published in 2021 on the application of propolis in agriculture (Accepted: 24 November 2020) [3]. This is more of a mini review, with only three pages of text. However, the significant number of publications on the subject in the last three years warrants a review of the current literature on the use of propolis as an agrochemical and a discussion of progress and perspectives in this field.

In this review, we present a brief overview of propolis, including its composition in terms of chemical constituents such as flavonoids, phenolic compounds, terpenoids and other bioactive substances responsible for its biological activity. We also survey the process by which honeybees collect propolis. The effectiveness of propolis in combating common pests and diseases that affect crop plants, as well as its ability to control postharvest diseases of fruits and vegetables, stimulate plant defenses and increase resistance to stress, are being investigated. We highlight the potential of propolis as a natural pesticide, growth promoter and plant immunity enhancer. Furthermore, we discuss the challenges and future prospects related to its integration into agriculture, including standardization and regulatory considerations. We also focus on new research trends and technological advances that promise to unlock the full potential of propolis as a sustainable agricultural tool.

2. Propolis Chemical Composition, Origin and Biological Activity

Honeybees, *Apis mellifera* L., collect resinous materials from plants, such as exudates on buds and leaves, gums, resins, latices, etc., and mix them with wax to produce propolis. Bees use propolis as a building material to fill in holes and cracks in the hive, repair combs and strengthen the thin borders of the combs. Propolis also plays a crucial role in the so-called "social immunity" of the bee colony due to its ability to effectively suppress bacteria, fungi and viruses [4]. It serves as the "chemical weapon" of the bees.

For this reason, bee glue has been used for millennia, by ancient Greek and Roman physicians as an antiseptic and cicatrizing agent. Modern scientific research has confirmed propolis' antimicrobial potential against fungi, bacteria and viruses, along with a variety of other beneficial pharmacological and health-promoting activities, including antioxidant, anti-inflammatory, hepatoprotective, immunomodulatory, antiallergic, antitumor and antidiabetic properties [2,5,6]. Nowadays, propolis is globally popular as a remedy and is readily available in its pure form or as an ingredient in over-the-counter preparations, cosmetics and health food supplements when combined with other natural products.

The antimicrobial properties of propolis are attributed to its chemical constituents, which are derived from plant resinous material. The most important bioactive propolis constituents, especially in terms of their antimicrobial and antioxidant properties, are considered to be phenolic compounds: flavonoid aglycones, phenolic acids and their esters and prenylated benzophenones [7]. Terpenoids also play an important role in the pharmacological properties of some propolis types [8].

The release of antimicrobial substances is a common phenomenon in the plant kingdom, with numerous plant species producing potent antimicrobial resins to protect their young leaves, vegetative tips and injured tissues [9]. Thus, the very origin of propolis from plant defense materials suggests its potential as a natural substance that can be used in agriculture to protect crop plants from different pests. Scientific research in this field started at the beginning of the 21st century, and interest in the use of propolis as an agrochemical has steadily increased in recent years [2].

An important feature of propolis is that its chemical composition varies greatly depending on the source plant(s). There are different types of propolis, each characterized by specific bioactive plant metabolites. As a result, the number of substances identified as propolis constituents now exceeds 800, but only a fraction of them can be found in a particular propolis sample. Based on their chemistry and plant origin, the most widespread and well-studied types of propolis are briefly listed, together with their most important bioactive marker constituents:

Poplar type (European) propolis:

- Found in Europe, North America and non-tropical regions of Asia;
- Plant source: *Populus* spp. bud exudates;
- Main biologically active compounds: flavonoids (pinocembrin, chrysin, galangin, pinobanksin 3-O-acetate), phenolic acids (coumaric, ferulic, caffeic) and phenolic acid esters (CAPE, prenyl caffeates) [10,11].

Green Brazilian propolis:

- Found in Brazil;
- Plant source: *Bacharis dracunculifolia* leaves;

- Main biologically active compounds: p-coumaric acid derivatives (artepillin C, baccharin, drupanin) and flavonoids [12,13].

Red Brazilian propolis:

- Found in the states of northeastern Brazil;
- Plant sources: *Dalbergia ecastaphyllum* resin and *Clusia* spp. flower resin;
- Main biologically active compounds: isoflavonoid derivatives (medicarpin, isosativan), prenylated benzophenones. [14,15].

Mediterranean propolis:

- Found in southern Greece, Mediterranean islands and North Africa;
- Plant source: *Cupressus sempervirens* resin;
- Main biologically active compounds: diterpenoids (isocupressic acid, communic acid, pimaric acid, totarol) [8].

Pacific propolis:

- Found in the Pacific islands (Okinawa, Taiwan, Hawaii);
- Plant source: *Macaranga tanarius* fruit resin;
- Main biologically active compounds: prenylated flavonoids [16].

Many propolis types contain flavonoids. Plant flavonoids are not only antimicrobial and antioxidant but also have protective properties against some biotic and abiotic stress situations. The polyphenolic structure of flavonoids allows for various modes of action, promoting plant survival in various challenging environments [17].

It is essential to note that different propolis types have varying chemical compositions and may differ in their biological activity. Therefore, researchers should be aware of this variability and work with chemically well-characterized propolis samples.

3. Propolis as Fungicide and Bactericide

Despite the chemical variability of propolis from different parts of the globe, its antimicrobial activity remains consistent. Propolis is collected by bees from materials secreted by plants, which are well known for their important role in plant self-defense. These secretions help preserve vegetative apices, young leaves, injured tissues and many plant species exude highly antibacterial resins [9] This, combined with the well-documented effectiveness of propolis against human pathogens [18], has attracted the attention of scientists searching for natural ("green") fungicides and bactericides for application in sustainable agriculture [9].

Plant pathogenic fungi are widespread and are among the most dangerous pathogens of important agricultural crops, causing significant losses in quality and yield. It was thus natural for scientists to investigate the effects of propolis on fungal phytopathogens. Reports about these effects are the most numerous among the data on propolis as an agrochemical. Research in this area covers the microorganisms that cause the most significant damage to agricultural production. The potential of propolis to suppress phytopathogenic bacteria has also been demonstrated. Many of the studies have been performed in vivo. The data are presented in Table 1.

Table 1. Activity of propolis against phytopathogenic microorganisms.

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Microorganisms	Type of Experiment	Reference
Antifungal activity					
Brazil	Green Brazilian	Not identified Not measured	*Penicillium* spp.	In vitro (20% of solution of propolis extract of the commercial product Propomax®) In vivo: cauliflower seeds	[19]
Iran	Unknown	Not identified Not measured	*Rhizoctonai solani*	In vitro (6% of ethanol propolis extract) In vivo: broad bean (6% of ethanol propolis extract)	[20]
Italy	Unknown	Not identified Not measured	*Botrytis cinerea*	In vitro In vivo: strowberry (4000 ppm propolis solution)	[21]
Venezuela	Unknown	Flavonoids (UV) Not measured	*Colletotrichum gloeosporioides*	In vitro (10% of ethanol propolis extract)	[22]
Brazil	Unknown	Not identified Not measured	*Colletotrichum gloeosporioides*	In vitro (32 mL/L of propolis extract)	[23]
Iran	Unknown	Not identified Not measured	*Fusarium* spp.	In vitro (propolis ethanol extract of 1000 μg/L)	[24]
Argentina	Unknown	Not identified Not measured	*Sclerotinia sclerotiorum*	In vitro (5 μL/mL propolis ethanol extract) In vivo: lima bean seeds (20% propolis ethanol extract + 6% oregano essential oil + 74% sterile distilled water)	[25]
Turkey (Northeast)	Unknown	Not identified Not measured	*Phytophthora infestans*, *P. capsica*, *P. parasitica*	In vitro (propolis methanol extract at 10, 7, 5 and 3 μg/mL)	[26]
Turkey	Poplar type	Flavonoids, phenolic acids	*Verticillium dahliae*	In vitro (1 ppm 80% ethanol propolis extarct/mL in sterilized PDA medium) In vivo: cotton (1 ppm 80% ethanol propolis extarct/mL in sterilized PDA medium)	[27]
Brazil	Unknown	Not measured	*Pythium aphanidermatum*	In vitro (1 μg/mL of ethanolic propolis extract)	[28]
Brazil	Green Brazilian	Phenolic acids, flavonoids	*Fusarium proliferatum*	In vitro (2% of 70% ethanol propolis extract)	[29]
Egypt	Unknown	Not identified Not measured	*Fusarium solani*, *Phythium ultimum*, *Sclerotinia sclerotiorum*	In vitro (5 g/L propolis ethanol extract) In vivo: cucumber (5 g/L propolis ethanol extract)	[30]

Table 1. *Cont.*

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Microorganisms	Type of Experiment	Reference
Brazil	Unknown *	Not identified Not measured	*Sclerotinia sclerotiorum*, *Colletotrichum gloeosporioides*, *C. acutatum*	In vitro: *S. sclerotiorum* (400–500 µL/mL propolis etanol extract) *C. gloeosporioides and C. acutatum* (200 µL/mL propolis etanol extract)	[31]
Turkey	Unknown	Not identified Not measured	*Fusarium solani*	In vitro (5% of 70% ethanol propolis extract)	[32]
Turkey	Unknown	Not identified Not measured	*Verticillium dahliae*, *Fulvia fulva*, *Penicillium digitatum*	In vitro (1 ppm of 70% propolis ethanol extract)	[33]
Slovenia	Poplar	Quercetin, apigenin, pinobanksin, chrysin, pinocembrin, galangin	*Alternaria solani*, *Phytophthora infestans*	In vivo: potatoes plants (5 mL propolis glycolic extract/L H_2O)	[34]
Brazil	Unknown	Not identified Not measured	*Botrytis cinerea*	In vitro	[35]
Brazil	Unknown	Not identified Not measured	*Podosphaera fuliginea*	In vivo: cucumber (8% of 70% ethanol propolis extract in distilled water)	[36]
Argentina	Poplar type	Not identified Not measured	*Didymella bryoniae*, *Rhizotocnia solani*	In vitro (1.5 mL of ethanol propolis extract/ Petri dish)	[37]
Colombia	Unknown	Not identified Not measured	*Aspergillus niger*, *Penicillium* sp., *Rhizopus oryzae* *Botrytis cinerea*	In vitro: *A. niger*—propolis ethanol extract 0.09% *w*/*v*, *Penicillium* sp.—0.42% *w*/*v*, *R. oryzae*—0.53% *w*/*v*, *B. cinerea*—1.09% *w*/*v*.	[38]
Thailand	Unknown	Not identified Not measured	*Pestalotiopsis* sp	In vitro (50 mL of natural bio-extract composed of 80–85% wood vinegar, 5–10% propolis, 1–5% tar, and 0.5–1% zinc oxide) In vivo: *Hevea braziliensis* (50 mL of the natural bio-extract)	[39]
Argentina	Unknown	Pinocembrin, galangin	*Aspergillus niger*, *Fusarium* sp., *Macrophomina* sp., *Penicillium notatum*, *Phomopsis* sp., *Thichoderma* spp.	In vitro (MIC pinocembrin: 20–50 µg/mL; MIC galangin: 14–40 µg/mL)	[40]

Table 1. *Cont.*

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Microorganisms	Type of Experiment	Reference
Argentina	Unknown	Apigenin, chrysin, pinocembrin, galangin	*Penicillium allii*	In vitro [MIC and MFC 12.5 µL/mL (8.6 mg/mL of 70% dry propolis) and 50 µL/mL (34.4 mg/mL of dry propolis), respectively]	[41]
Brazil	Unknown	Not identified Not measured	*Alternaria brassicicola*	In vivo: kale seeds germination and vigor (1.0% of propolis, commercial product Apis Flora)	[42]
Chile	Unknown	Pinocembrin, galangin, caffeic acid phenethyl ester (CAPE)	*Alternaria alternata*, *Fusarium* sp., *Ulocladium* sp., *Botrytis cinerea*, *Penicillium expansum*, *Trichoderma reesei*	In vitro [5% (*v*/*v*) of commercial ethanolic extracts in 70% ethanol]	[43]
Brazil	Green Brazilian	Artepillin C	*Pythium aphanidermatum*	In vitro, mechanism (70% ethanol propolis extract 750 µg/mL)	[44]
Antibacterial Activity					
Brazil	Green Brazilian, Red Brazilian, Brown Brazilian	Total phenolics, total flavonoids	*Xanthomonas fragariae*	In vitro (green propolis—1 mg/mL 70% ethanol propolis extract in distilled water) In vivo: strawberry (all propolis types—5 mg/mL 70% ethanol propolis extract in distilled water)	[45]
Brazil	Unknown	3,4-Dihydroxybenzoic acid, kaempferol, gallic acid	*Xanthomonas axonopodis* pv. *passiflorae*	In vitro (0.5% of 80% ethanol propolis extract)	[46]
Brazil	Unknown	Caffeic acid, quercetin, apigenin, pinobanksin, chrysin, pinocembrin, galangin	*Clavibacter michiganensis* subsp. *michiganensis*, *Xanthomonas gardneri*, *X. vesicatoria*, *Pseudomonas corrugata*, *P. mediterranea*	In vitro (15.0 mg/mL of geopropolis ** and 78.7 mg/mL of 70% propolis dry extract)	[47]
Brazil	Unknown	Not identified Not measured	Bacterial growth	In vivo: Mango explants (0.5 and 1% propolis extract *v*/*v*)	[48]
Saudi Arabia	Unknown	Not identified Not measured	*Pectobacterium carotovorum*, *Agrobacterium tumefaciens*	In vitro (4000 µg/mL methanol propolis extract)	[49]

Table 1. *Cont.*

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Microorganisms	Type of Experiment	Reference
Turkey	Unknown	Not identified Not measured	*Pseudomonas syringae* pv. *tomato*	In vitro (0.1, 1, and 2% of water-based propolis extracts, with 14.4 and 90% concentrations)	[50]
Brazil	Green Brazilian	Not identified Not measured	*Xanthomonas axonopodis* pv. *phaseoli* *Pseudomonas syringae* pv. *tabaci*	In vitro [2.5% and 5.0% of ethanol propolis extract, containing 11% dry extract (*w*/*v*)] In vivo: common bean [5% of ethanol propolis extract, containing 11% dry extract (*w*/*v*)]	[51]
Argentina	Unknown	2′,4′-Dihydroxychalcone, 2′,4′-dihydroxy-3′-methoxychalcone, galangin, pinocembrin	*Erwinia carotovora*	In vitro In vivo: Potato tubers (500 mL of ethanol propolis extract, containing 87.5 µg GAE/mL)	[52]
Egypt	Green Brazilian	Not identified Not measured	*Ralstonia solanacearum*	In vitro [water extract of propolis (1, 10 and 100 mg/mL water)] In vivo: tomato [water extract of propolis (1, 10 and 100 mg/mL water)]	[53]
Turkey	Unknown	Not identified Not measured	*Agrobacterium tumefaciens*, *A. vitis*, *Clavibacter michiganensis* subsp. *michiganensis*, *Erwinia amylovora*, *E. carotovora* pv. *carotovora*, *Pseudomonas corrugata*, *P. savastanoi* pv. *savastanoi*, *P. syringae* pv. *phaseolicola*, *P. syringae* pv. *syringae*, *P. syringae* pv. *tomato*, *Ralstonia solanacearum*, *Xanthomonas campestris* pv. *Campestris*, *X. axonopodis* pv. *vesicatoria*	In vitro (1/10 concentration of methanol propolis extract)	[54]

* Of stingless bees Tetragonisca angustula; ** Of stingless bees Scaptotrigona jujuyensis.

In these studies, propolis was applied as a solution, using mostly ethanolic extracts with varying concentrations. In some cases, aqueous extracts [19,52] and extracts obtained with supercritical fluids [32] were used in the experiments. It is important to note that the use of different solvents, even with the same propolis, will result in different chemical compositions of the solutions.

The mechanism of action of propolis against some phytopathogens has been studied. Pazin et al. [28] investigated the effect of propolis extract on model membranes made of zwitterionic and anionic unilamellar vesicles and found that it significantly interacted with nano-organized amphiphilic structures, modifying their physicochemical and structural properties. In a later study, the same research group demonstrated that artepillin C in Brazilian green propolis increased the permeability of membranes with relatively high fluidity in their lateral structure [44]. The number of such studies is limited; further research on the mechanism of action of propolis on microbial plant pathogens is necessary.

In addition to its action against phytopathogens, propolis can activate the defense mechanisms of plants. Guginski-Piva et al. [36] demonstrated that propolis application resulted in the induction of phytoalexins in soybean (*Glycine max*) cotyledons, potentially helping to control the powdery mildew. Recently, propolis extracts were also tested for their capacity as plant defense activators of the defense response genes WRKY70 and CaBP22 in *Arabidopsis thaliana*; propolis induced the expression of these genes [50].

The antimicrobial properties of propolis have been used not only for plant protection but also in postharvest preservation of the quality of economically important fruits and vegetables [55]. Postharvest losses of fruits and vegetables range from an estimated 5% to more than 20%, and postharvest fungicides have traditionally been the main for controlling these losses. However, due to the harmful effects of synthetic fungicides on human health, as well as the development of pathogen resistance to many of the important preparations, the use of postharvest fungicides is progressively decreasing [55,56]. Data about the successful replacement of synthetic agricultural fungicides with propolis are summarized in Table 2.

Postharvest use of propolis for protection against pests is one of the most promising applications of propolis as an agrochemical. Immersing the fruits or vegetables in a propolis solution or spraying them with such solutions has been found to offer effective protection and significantly improve their preservation.

Table 2. Propolis' application as postharvest fungicide.

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Microorganisms	Type of Experiment	Reference
Brazil	Unknown	Not identified Not measured	*Colletotrichum* spp.	In vitro (2 mL/L)	[57]
China	Unknown	Not identified Not measured	*Penicillium digitatum*, *Penicillium italicum*	In vitro: *Penicillium digitatum* (200 mg/L), *Penicillium italicum* (150 mg/L) On fruits: mandarins	[58]
China	Unknown	Pinobanksin, pinocembrin, chrysin, galangin	*Penicillium italicum*	In vitro (EC_{50} 144.8 mg/L)	[59]
Iraq	Unknown	Not identified Not measured	*Penicillium* spp.	On fruits: apples (1% propolis in water)	[60]
Egypt	Unknown	Not identified Not measured	*Penicillium digitatum*	In vitro (3% ethanolic extract) On fruits: lemons	[61]
Turkey	Unknown	Not identified Not measured	Not indicated	On fruits: grapefruit (5% ethanolic extract)	[62]

Table 2. *Cont.*

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Microorganisms	Type of Experiment	Reference
Portugal	Unknown	Chrysin, tectochrysin, pinocembrin, chrysophanol [9.8 g/L phenolic compounds (GAE)]	*Penicillium expansum*	On fruits: "Rocha" pear (propolis extract 1:20)	[63]
India	Unknown	Not identified Not measured	*Escherichia coli*, *Aspergillus* spp.	On fruits: tomatoes (40 µL 1:1 *w*/*v* EtOH extract per fruit)	[64]
Egypt	Unknown	Not identified Not measured	Not indicated	On fruits: Balady Oranges (5% ethanol extract)	[65]
Brazil	Green Brazilian Other Brazilian	Not identified Not measured	Not indicated	On fruits: Papaya (2.5% (*w*/*v*))	[66]
Thailand	Unknown	Not identified Not measured	Causative agents of Crown Rot Disease	On fruits: Banana (50% propolis, 100% paraffin and 50% propolis)	[67]
Bulgaria	Poplar type	Not identified Not measured	Unidentified yeasts and/or fungi	On fruits: * Blueberries (1% propolis in edible coating)	[68]
Brazil	Green Brazilian	Flavonoids, artepillin-C, ρ-coumaric acid (ethanolic extract, 30% dried matter with 50% total soluble solids; flavonoids 20 mg/L; artepillin-C: 10.5 mg/L; ρ-coumaric acid 2.5 mg/L)	*Colletotrichum gloeosporioides*	In vitro On fruits: 'Kent' mango (2.5% propolis)	[69]
Brazil	Green Brazilian, Red Brazilian, Other Brazilian	Not identified Not measured	Not indicated	On fruits: banana 'Prata' [2.5% (*w*/*v*) propolis extract]	[70]
Chile	Unknown	Rutin, myricetin, querecetin, kaempferol, galangin, CAPE, pinocembrin	*Phlyctema vagabunda*	On fruits: apples (0.05 and 0.1% propolis extract)	[71]
China	Unknown	Not identified Not measured	Not indicated	On fruits: dragon fruit (1% ethanol extract)	[72]
Colombia	Unknown	Pentacyclic triterpenes, cycloartane-type triterpenes, aromatic acids and esters	*Colletotrichum gloeosporioides*	In vitro On fruits: papaya (coating of chitosan, 1%; containing propolis ethanolic extract, 5%)	[73]
Mexico	Unknown	Not identified Not measured	*Aspergillus flavus*	In vitro (nanoparticles of chitosan and 40% propolis)	[74]

* Propolis as constituent of edible coating.

4. Propolis as Herbicide

Weeds are among the most significant causes of severe damage to crops, alongside plant pests and diseases. A large number of pesticides are used to control weeds, most of them being chemically synthesized. Often these herbicides pose risks to people, pollinators and other non-target creatures [75]. Due to this reliance on pesticides, several issues arise, including resistance and secondary pest outbreaks, as well as environmental and health risks. Growing concerns have invigorated the search for new environmentally compatible herbicides of natural origin [76,77].

Given the diverse reported bioactivities of propolis, it has been a subject of research in this context. Reports dating back to the 1960s mention the phytoinhibitory and phytotoxic activities of propolis extracts [78] (and references cited therein). It is worth noting that there are publications describing the prevention or delayed germination of seeds from cultivated plants by propolis extracts [79,80]. Sorkun et al. [79] found that Turkish propolis could inhibit the division of plant cells, while King-Diaz et al. [77] demonstrated that individual flavonoids found in Mexican propolis inhibit photophosphorylation in freshly lysed chloroplasts. Recently published studies dedicated to the application of propolis as an herbicide, along with data on its phytoinhibitory effects on certain crop plants, are presented in Table 3.

Table 3. Propolis' application as herbicide.

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Affected Plant	Type of Activity	Reference
Iran	Unknown	Not identified Not measured	Broadleaf (*Silybum marianum*) and narrow-leaf (*Hordeum spontaneum*, *Avena sativa*) weeds	Prevention or postponement of weed seed germination (1:2 propolis ethanol extract/water)	[75]
Mexico	Unknown	Acacetin, chrysin, 4′,7-dimethylnarangenin	*Lolium perenne*, *Echinochloa crus-galli* and *Physalis ixocarpa*	Growth of the plants (300 µM of every individual compound)	[77]
Romania	Brown European	Total phenolics and total flavonoids	*Triticum aestivum*, *Zea mays*, *Avena sativa and Hordeum vulgare* L.	Phyto-inhibitory activity (10% aqueous propolis extract)	[80]
Brazil	Geopropolis *	Not identified Not measured	Pasture weeds *Mimosa pudica* and *Senna obtusifolia* (1% *w*/*v* alcohol extract)	Inhibition of seed germination, radicle elongation and hypocotyl growth (1% *w*/*v* alcohol extract)	[81]
Brazil	Not determined	Gallic acid, 3,4-dihydroxybenzoic acid, catechin and kaempferol.	Pasture weeds *Mimosa pudica* and *Senna obtusifolia*	Inhibition of seed germination, radicle elongation and hypocotyl growth (0.75% and 1.0%)	[82]
Brazil	Green Brazilian propolis	Volatile fraction (3-prenylcinnamic acid allyl ester, spathulenol, 7-phenyl-5-oxo-heptanol)	Lettuce	Inhibition of seed germination and the growth of its seedlings (1% solution of volatile fraction)	[83]

* Of stingless bees *Melipona subnitida*.

5. Propolis as Insecticide

Honeybees use propolis to defend their colonies against microbial pathogens and it can also protect them against other pests. Invaders and parasites, such as insects and arthropods, must be stopped and neutralized within the hive. It has been demonstrated that propolis can have a negative impact on the reproduction of their major ectoparasite, the arthropod *Varroa destructor* [84], and that it is toxic to the larvae of another dangerous pest, the lesser wax moth, *Achroia grisella* [85]. These effects suggest that propolis could be useful in protecting crops from arthropod and insect pests. The data from the literature on this subject are relatively limited; they are presented in Table 4.

Table 4. Propolis' application as insecticide.

Propolis Geographic Origin	Propolis Type	Major Active Compounds	Affected Organism	Type of Activity	Reference
Egypt	Unknown	Total phenolics, total flavonoids	Two-spotted spider mite *Tetranychus urticae*	High mortality in all stages (egg, larva, nymph and adult) (2000 ppm concentration of extract)	[86]
Nigeria	Unknown	Not identified Not measured	Larger grain borer *Prostephanus truncatus*	Low effect on mortality (5 mg propolis powder for 250 mL maiz grains)	[87]
Italy	Unknown	Total flavonoids	Olive fly *Bactrocera oleae* and its endosymbiont *Candidatus Erwinia dacicola*	Interruption of symbiosis (solution 20 mg/mL flavonoids, applied as 200–250 mL/100 L)	[88]
Nigeria	Unknown	Not identified Not measured	*Sitophilus zeamais*	Minimizing weight loss in infected maize grains (15% propolis extract added to the grains)	[89]
Iraq	Unknown	Not identified Not measured	Fig moth larvae *Cadra cautella*	Repellant effect (2.5% extract)	[90]
China, Egypt	Unknown	Phenolic acid and flavonoids identified by HPLC with standard compounds	Pink bollworm *Pectinophora gossypiella*; cotton leafworm *Spodoptera littoralis* and cowpea aphid *Aphis craccivora*	Toxicity to larvae (LC_{50} and LC_{90}—0.282 and 5.987%)	[91]
Egypt	Unknown	Chlorogenic acid, acacetin	Tomato leafminer *Liriomyza sativae*	Toxicity to larvae (LC_{50} of 4628.002 ppm water extract)	[92]
Egypt	Unknown	Phenolic acid and flavonoids identified by HPLC with standard compounds	*Tetranychus urticae* and *Tetranychus cinnabarinus*	Moderate toxicity (LC_{50} 13,579 ppm water extract; LC_{50} 15,881 ppm ethanol extract)	[93]

Ethanol extracts of propolis were used in most experiments, although aqueous extracts also showed activity [92]. However, not all experiments demonstrated a high potential for propolis. For example, in the case of the larger grain borer *Prostephanus truncatus*, propolis extract had only a week effect on mortality [87]. The lack of studies on the mechanism of action of propolis and/or its constituents against arthropods and insects is evident; future studies should aim to clarify this.

6. Other Applications of Propolis as an Agrochemical

Propolis has also been tested for its potential against other plant pests, such as nematodes and viruses. Egyptian propolis showed a good nematocidal effect against the second-stage larvae of the root-knot nematode *Meloidogyne* spp. in eggplant roots under greenhouse conditions [94] and had an effect against the citrus nematode *Tylenchulus semipenetrans* [95]. In a recent study, field experiments demonstrated a considerable reduction in the population of the pest snail *Monacha cartusiana* using propolis [96].

Propolis from Serbia exhibited a positive effect on reducing *Zucchini yellow mosaic virus* infection in oilseed pumpkins, despite the fact that the plants were challenged with higher levels of the virus than naturally occurs [97].

A few experiments have shown the positive effects of propolis solutions on the growth of crop plants. A formulation of Cuban propolis was evaluated for its effect on in vitro micropropagation of potato plants (*Solanum tuberosum* L.) [98]. Foliar application of propolis from Egypt has been shown to improve the growth parameters and pigment content in tomatoes, as well as to have a significant impact on enhancing the concentration of antioxidant enzymes [99]. The use of Egyptian propolis extract as a foliar application ingredient resulted in improved growth, yield and chemical composition of spinach plants, even under adverse saline conditions [100]. These results were even better when propolis was applied as both seed soaking and foliar spray simultaneously [101]. The foliar application of a water-diluted ethanol extract of propolis from the Paraná Coast of Brazil led to enhanced bean productivity [102]; propolis extract also stimulated the growth and productivity of sweet pepper plants [103].

7. Conclusions and Perspectives

The rising demand for agricultural products necessitates a continuous search for pesticides and food preservatives that are cost effective, environmentally safe and readily available. Most agrochemicals used for crop protection and postharvest preservation of fruits and vegetables are synthetic compounds [104]. However, the excessive use of synthetic agrochemicals creates environmental hazards and health problems. Natural products of plant origin have been used by humans for managing plant diseases since ancient times. Therefore, the development of natural alternatives to agrochemicals is a key focus in sustainable farming. In recent decades, several alternatives based on natural products have emerged as more environmentally friendly options compared to synthetic pesticides and other agrochemicals [104]. A well-known example of such insecticides are pyrethroids, synthetic products inspired by plant compounds with wide applications in crop protection [105]. In recent years, successful applications of plant-based pesticides, such as neem (*Azadirachta indica*), garlic (*Allium sativum*), eucalyptus (*Eucalyptus globulus*), turmeric (*Curcuma longa*) and tobacco (*Nicotiana tabacum*) for managing various plant diseases, have been reported [106].

One of the tested products is propolis. Although propolis is not as effective as pyrethroids, it shows promising effects compared to other tested plant materials. For instance, parallel tests of propolis extract and shiitake polysaccharide fraction against angular leaf spot on strawberries in vivo demonstrated better results for propolis [45]. Propolis extract showed comparable effectiveness to neem (*Azadirachta indica*) and Mexican sunflower (*Tithonia diversifolia*) in population management of the Larger Grain Borer *Prostephanus truncatus* on maize grains [87]. However, the leaves of *Theobroma cacao* and *Chromolaena odorata* gave better results. Propolis extract and garlic powder showed similar effectiveness against the maize weevil *Sitophilus zeamais* [89].

Clearly, there is much work to be performed before propolis can be applied on a commercial scale [107]. For propolis to be widely accepted, larger field experiments are needed to confirm its effectiveness against various pests. In addition, there is still not enough information about the mechanism of action of propolis in all presented applications. While a few studies have revealed the mechanism of its antimicrobial action [28,44], future studies should also investigate the herbicidal and insecticidal mechanisms of propolis, as well as its potential to activate plant defense mechanisms.

A promising route for propolis application as an agrochemical is the development of nanoformulations. Nanotechnologies are profoundly influencing various aspects of human activities, including agriculture. As a result, specific nanomaterials have the potential to update the development of natural pesticides, enhancing their efficiency and environmental friendliness. Nanoformulations can improve efficacy, reduce required doses and enhance precision in delivering treatments to the intended pest targets [108]. Thus, the development of propolis nanoformulations is an important opportunity to enhance the effectiveness of propolis as an agrochemical [109].

Undoubtedly, propolis has great potential for efficient and sustainable use in agriculture. However, there is a general criticism that can be directed at many of the experimental studies presented in this review. These studies have been performed with propolis, which has not been chemically characterized. Because of the variability in the chemical composition of propolis, for such experiments to be scientifically sound, they should use chemically characterized, and if possible, chemically standardized propolis. If tests are conducted with "propolis from..." without further chemical characteristics, they are difficult to reproduce. This, among other problems, was one of the reasons why the European Food Safety Authority (EFSA) did not issue an official permission for the basic substance application of propolis extract for use in plant protection as a fungicide and bactericide [110]. However, in recent years, there has been an understanding that specific standards can be created for particular chemical types of propolis, based on their botanical origin [111]. Even if a standardization approach based on the chemical type of propolis is adopted, the complex composition of each specific propolis chemical type presents an additional challenge to analytical efforts. Thus, standardization is an important focus of future research on propolis.

In conclusion, we hope that with this review we provide an informed perspective on the current state of knowledge regarding propolis in agriculture and offer insights that will inspire further exploration, innovation and implementation of this natural resource.

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