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Antibacterial activity of plant essential oils and possibilities of application as biopesticides in plant production

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Abstract

Pathogenic microorganisms, primarily bacteria and fungi, cause plant diseases, which lead to a significant loss of plant yields. For a long time, efforts have been made to reduce the loss of plant yields, primarily with the use of chemical agents for plant protection, but also with the selection of strains resistant to phytopathogens and other pests. However, the intensive use of chemical agents in crop production leads to environmental pollution and threats to food safety. For the above reasons, the application of biological preparations (biopesticides) is recommended as an environmentally acceptable way of managing plant diseases and the environment. The aim of this paper is to describe the antibacterial activity of the essential oils (EOs) of plants and the possibilities of their application as natural biopesticides in crop production, by reviewing the scientific literature and research. The applicable literature was analysed in this review paper. The results of numerous *in vitro* and *in vivo* scientific studies indicate that the essential oils of plants exhibit strong antibacterial effects on phytopathogenic bacteria, the causative agents of plant diseases, as well as that they can be successfully used in plant production.

Keywords: essential oils, antibacterial activity, phytopathogenic bacteria, biological preparations, environmental pollution, food safety.

Introduction

In crop production, biopesticides can supress phytopathogenic organisms (bacteria and fungi) and plant pests without adversely affecting agroecosystems. Until the discovery of biopesticides, the control of phytopathogens and pests in plant production depended almost exclusively on chemical pesticides, which caused environmental pollution. Nevertheless, numerous scientific evidences appeared on the resistance of pests and weeds to pesticides in crops (Đukić et al., 2007; Marinković and Marinković, 2012; Golijan Pantović et al., 2023). The biological methods are based on the use of natural enemies against pests such as bacteria, fungi and nematodes. Biopesticides provide an environmentally friendly way to manage plant diseases and represent one of the most significant discoveries in biotechnology, which is used in the production of health-safe food. Also, they have significant potential to replace or reduce the use of chemical pesticides and the costs of their production. A significant number of products based on plant essential oils are available on the market, which are used in plant protection as fungicides, herbicides, and exhibit strong antibacterial activity against phytopathogenic bacteria. Phytopathogenic bacteria, the causative agents of plant diseases, are one of the most significant factors affecting the reduction of crop yields. Plant pathogenic bacteria (PPB) are important plant pathogens widely spread all over the world and it is estimated that approximately 150 species are responsible for different plant diseases (Đukić et al., 2007; Aguilar-Marcelino et al., 2020; Golijan and Sečanski, 2021; 2022; Šarčević-Todosijević et al., 2022; Golijan Pantović et al., 2023).

Essential oils are specific plant products, usually in a liquid state, that contain complex mixtures of volatile compounds - most often monoterpenes, sesquiterpenes and phenylpropane compounds. Monoterpenes and sesquiterpenes are classes of compounds from the terpene group, characterized by the number of isoprene units that make them up: monoterpenes consist of two isoprene units, while sesquiterpenes consist of three isoprene units. Both groups of compounds are widely represented in nature, especially in plants, and are known for their diverse biological activities and roles in ecosystems. Phenylpropane compounds are compounds containing a phenyl ring bonded to propene, more specifically those with an allyl group bonded to a benzene ring, having the parent structure of allylbenzene (Kovačević, 2004; Inamuddin et al., 2023).

The most common way to obtain essential oils is steam distillation, while for citrus fruits, pressing of fresh plant tissue is often used. Essential oils can be further processed to separate the individual ingredients. These oils are mainly obtained from vascular plants, especially rich aromatic plants from families such as: Asteraceae, Lamiaceae, Apiaceae, Rutaceae, Myrtaceae and Lauraceae. Aromatic plants contain volatile oils that give off pleasant scents when touched or crushed. They're used in cooking, perfumes, herbal remedies, and their scents can also act as a natural defense mechanism against herbivores. Essential oils are found in different parts of the plant: in flowers (chamomile), leaves (mint, lemon balm), tree bark (cinnamon, sandalwood, juniper), root (parsley), rhizome (iris), fruits (anise, citrus), seeds (walnut). Different parts of the same plant can contain oils that are similar in composition, but also significantly different. Most aromatic plant raw materials (drugs) contain less than 1% essential oil, but there are exceptions - for example, clove bud contains over 15% oil. Essential oils are produced in the plant secretory tissues. Plant secretory tissues, responsible for producing and releasing various substances, are broadly categorized into two main types: external (exogenous) and internal (endogenous). Sometimes these cells are organized into special structures, such as glands and glandular hairs, which are found on the surface of plants, especially in the Asteraceae and Lamiaceae families. Glandular hairs, also known as trichomes, are epidermal outgrowths in plants that secrete or absorb substances, with the two main types being peltate and capitate hairs, distinguished primarily by the morphology of their secretory head (Kovačević, 2004; Šarčević-Todosijević et al., 2019a).

The aim of this manuscript is to review the scientific literature and point to plant species as potential sources of compounds, primarily essential oils, with pronounced antimicrobial effects on phytopathogenic bacteria.

Materials and Methods

The data analysis method was applied in the manuscript. The data were collected from previous scientific studies. The research within present manuscript is theoretical and overview character and uses data and research from relevant journals, textbooks, monographs, and original and review scientific papers published in scientific journals and at scientific conferences.

Results and Discussion

Biopesticides used in the treatment of plant diseases are obtained from organisms originating from natural ecosystems, as well as products of their life activity. They include microorganisms and products of their metabolic activity, essential oils and other plant extracts, products of secondary plant metabolism. The first microbial biopesticides used were strains of *Bacillus thuringiensis*. Each strain of this bacterium produces a different mixture of proteins and specifically kills one or a few related species of insect larvae. For target insect species, a specific strain of *B. thuringiensis* produces a protein that causes the mortality of individual insects (Đukić et al., 2007; Marinković and Marinković, 2012). Biological plant protection products can also be pesticide substances produced by transgenic plants based on genetic material inserted into a given plant using genetic engineering techniques. For example, researchers have inserted a gene from the *B. thuringiensis*, which codes for a pesticide protein, into the genetic material of a plant, so that the transgenic plant produces this protein that is lethal to some insects species (Đukić et al., 2007; Šarčević-Todosijević et al., 2019a; Filipović et al., 2021).

Many authors (Džidić-Uzelac, 2014; Popović et al., 2019; Popović et al., 2021; Šarčević-Todosijević et al., 2019a) state the importance of allelopathy as a biological phenomenonin which a particular organism produces one or more metabolites that regulate ecological relationships in a given ecosystem, affecting the germination, growth, survival and reproduction of other organisms. Plants with allelopathic effects can be used as bioherbicides, growth regulators and the basis for the synthesis of new herbicidal preparations. Extracts of the plant species *Sorghum bicolor* exhibit inhibitory effects on many weed species in various crops such as wheat, cotton and sunflower (Kandhro et al., 2015; Bošković, 2021). These metabolites may have beneficial or harmful effects on target organisms and members of biocenoses. Allelochemicals are products of secondary metabolism, which are not necessary for the basic life processes of an allelopathic organism, but provide it with a competitive advantage, since they regulate ecological relationships in ecosystems. Among these compounds, alkaloids, heterosides, saponosides, terpenes or aromatic compounds (essential oils) exhibit significant biological activity. Essential oils belong to the group of secondary plant metabolites, i.e. allelopathic substances, which organic agriculture successfully uses to protect plant crops from certain phytopathogens and pests (Kovačević, 2004; Šarčević-Todosijević et al., 2019a). A protective effect is also achieved by planting aromatic plants near crops (Džidić-Uzelac, 2014; Popović et al., 2019; Popović et al., 2021; Šarčević-Todosijević et al., 2019a; Bošković, 2021; Šarčević-Todosijević et al., 2023; Filipović et al., 2023).

According to numerous studies (Đukić et al., 2007; Filipović et al., 2021, 2023; Golijan Pantović et al., 2023) phytopathogenic fungi lead to a significant decrease in crop yields. A review of the literature has shown that essential oils and compounds based on essential oils inhibit the growth of mycelium of a large number of phytopathogenic fungi. Kiniec et al. (2024) tested essential oils (EOs) from grapefruit, rosemary, pine, sage, and thyme against *Cercospora beticola*, the main sugar beet pathogen. Thyme (*Thymus vulgaris*) EO showed the strongest antifungal activity, with a minimum inhibitory concentration (MIC) of 0.313 mL/L for most fungal isolates, including multi-resistant ones. Field tests confirmed its effectiveness. The findings suggest thyme EO is a promising, eco-friendly option for managing *C. beticola*. Carta et al. (1996) reported the fungicidal effect of *Salvia officinalis* essential oil against *Botrytis cinerea*. Arras and Usai (2001) determined strong fungicidal effect of *Thymus vulgaris* on *Alternaria citri* by affecting spore germination. Lee et al. (2007) confirmed the antifungal effect of 39 essential oils on the growth of mycelium of *Botrytis cinerea*, *Colletotrichum gloeosporioides*, *Fusarium oxysporum*, *Pythium ultimum* and *Rhizoctonia solani*. In the research of Gaber et al. (2025) *Salvia officinalis* (sage) methanolic extract as a biocontrol agent was tested in laboratory (*in vitro*) and field (*in vivo*) conditions on four isolates of *Fusarium oxysporum* f. sp. *lycopersici*. It showed control of mycelial growth (up to 88.7%) and reduction of spore germination (up to 84.5%) at concentrations of 2.5–20 mg/ml, with significant reduction in disease severity on tomatoes. Molecular docking analyzes identified metabolites from the extract that target fungal enzymes such as tomatinase (Gaber et al., 2025). In addition to phytopathogenic fungi causing crop yield losses, a significant number of fungal species produce mycotoxins and affect food safety. Mycotoxins are secondary metabolites of fungi, and can cause numerous human and animal diseases, and even death. The species of the genus *Fusarium*, such as *F. verticillioides* and *F. proliferatum*, are the most important producers of the mycotoxin fumonisin B1, which is the most common contaminant of corn. *F. dlamini* and *F. anthophilum* may also be significant producers of fumonisin B1 (Nelson et al., 1992). The compound anethole isolated from the plant *Illicium verum* exhibits antifungal activity on the growth of mycelium of the fungi *Fusarium graminearum* and *Fusarium oxysporum* (Huang et al., 2010). *Foeniculum vulgare* essential oil, whose main component is also anethole, has an inhibitory effect on *Fusarium graminearum* and *Fusarium moniliforme* (Singh et al., 2006). *Rosmarinus officinalis* essential oil is used as an insecticide and broad-spectrum fungicide in plant production. Products containing essential oils of *Syzygium aromaticum* are used as herbicides, fungicides and germination inhibitors (Gorunović and Lukić, 2001; Hall and Fernandet, 2004).

The mechanism of antifungal action of essential oils is based on their effect on the fungal cell membrane, i.e. the destruction of the cell structure, which leads to cell death, as well as the inhibition of spore germination, mycelium growth and cellular respiration (Madigan et al., 1997; Harris, 2002).
About 350 bacteria, which are pathovars or subspecies belonging to the phyla Proteobacteria, Actinobacteria, and Firmicutes, are known to be phytopathogenic (Leonard et al., 2017). Studying the effects of essential oils (EOs) on morphology of bacteria improves understanding of potential mechanisms of action. Plant secondary metabolites, including essential oils, inhibit bacterial growth by various mechanisms. There are five basic mechanisms of action of the natural product on the bacterial cell, namely: disintegration of the cell wall, destabilization of the passage of protons through the cell membrane, prevention of electron flow, prevention of active transport and coagulation of cell contents (Sikkema et al., 1995; Šarčević-Todosijević et al., 2019b). Among antibacterial substances of plant origin, as emphasized, essential oils stand out, which are traditionally used as a natural alternative to chemical biocides and antibiotics (Sikkema et al., 1995; Madigan et al., 1997; Šarčević-Todosijević et al., 2019b).

The main constituents of the mastic-leaf prickly ash essential oil are linalool (28.2%), limonene (13.2%), and sabinene (12.1%). The antibacterial activity of this essential oil can be a result of the increased permeability of cell membranes, and the leakage of intracellular constituents. The susceptibility of tested Gram-positive bacteria was greater than that of Gram-negative bacteria (Diao et al., 2013).

Table 1. presents the summary of antibacterial activity of EOs extracted from different plants. In their study, authors Erkan et al. (2012) compared antibacterial activities of EO extracted from leaves of curry leaf tree (*Murraya koenigii* L., Rutaceae) against the bacterium *Listeria innocua* by two methods: solvent-free microwave extraction (SFME) and the conventional hydro-distilled oil (HD). The main constituents of EO obtained by SFME were α-copaene (44.3%), β-gurjunene (25.5%), isocaryophyllene (12.1%), β-caryophyllene (8.7%) and germacrene D (2.9%). DPPH radical scavenging activities of EOs recorded by both methods were relatively low (10-24%). Absolute inhibition of the *Listeria innocua* growth was observed with SFME EO at 400 μg/mL (minimum

inhibitory concentration) and HD EO at 600 µg/mL. Li et al. (2019) stated that EO extracted from fingered citron (*Citrus medica* L. var. *sarcodactylis*) exhibited moderate antibacterial activity against bacterial strains *Escherichia coli, Staphylococcus aureus, Bacillus subtilis* and *Micrococcus luteus* using *in vitro* antibacterial tests. The higher the concentration and exposure time of EO, the more seriously the morphology of the tested bacteria was altered and damaged. EO significantly reduced the growth rate of surviving bacteria and led to the cellular disruption. The intracellular material leaked, and consequently cells died (Li et al., 2019).

Table 1. Summary of antibacterial activity of EOs from different plants

Essential oil from plant species	**Target bacteria**	**Effect of essential oils on target bacteria**	**References**
Thymbra spicata L. var. *spicata*	*Erwinia amylovora*(-) *Erwinia carotovora* pv. *carotovora*(-) *Clavibacter michiganensis* subsp. *michiganensis*(+) *Pseudomonas syringae* pv. *syringae, tumefaciens*(-), *Xanthomonas axonopodis* pv. *vesicatoria*(-)	significant antibacterial activity	Basim et al. (2000)[a]
Origanum vulgare	*Staphylococcus aureus*(+) *Pseudomonas aeruginosa*(-)	strong antibacterial effect	Lambert et al. (2001)[a]
Rosa damascene	*Xanthomonas axonopodis* spp. *vesicatoria*(-)	significant antibacterial activity	Basim and Basim (2003)[a]
Coriandrum sativum *Foeniculum vulgare* var. *vulgare*	*Echerichia coli*(-) *Bacillus megaterium*(+)	significant antibacterial activity	Lo Cantore et al. (2004)[a]
Cuminum cyminum L. *Carum carvi* L.	*Escherichia coli*(-) *Pseudomonas syringae* pv. *phaseolicola*(-) *P. syringae* pv. *pisi*(-) *P. syringae pv. syringae*(-) *P. syringae* pv. *aptata*(-) *P. syringae pv. apii*(-) *P. syringae* pv. *atrofaciens*(-) *P. syringae pv. lachrymans*(-) *P. syringae* pv. *maculicola*(-) *P. syringae* pv. *tomato*(-) *P. syringae pv. glycinea*(-) *P. cichorii*(-) *P. viridiflava*(-) *P. corrugate*(-) *P. tolaasii*(-) *P. reactans*(-) *P. agarici*(-) *Erwinia carotovora* subsp.	significant antibacterial activity	Iacobellis et al. (2005)[a]

	carotovora(-) *E. carotovora* subsp. *atroseptica*(-) *E. herbicola*(-) *Agrobacterium tumefaciens*(-) *Burkholderia gladioli* pv. *agaricicola*(-) *Ralstonia solanacearum*(-) *Xanthomonas campestris* pv. *phaseoli*(-) *X. campestris* pv. *phaseoli var. fuscans*(-) *X. campestris* pv. *vesicatoria* *X. campestris* pv. *campestris*(-) *Bacillus megaterium*(+) *Clavibacter michiganensis* subsp. *michiganensis*(+) *C. michiganensis* subsp. *sepedonicus*(+) *Curtobacterium flaccumfaciens pv. flaccumfaciens*(+) *C. flaccumfaciens* pv. *betae*(+) *Rhodococcus fascians*(+)		
Origanum vulgare L. *Acorus calamus* L. *Achillea millefolium* L. *A. filipendulina* L. *A. cartilaginea* L. *Carum carvi* L. *Mentha x piperita* L.	*Erwinia carotovora* subsp. *carotovora 1122*(-) *Xanthomonas vesicatoria 67*(-) *Psudomonas marginalis* pv. *marginalis 1763*(-) *P. syringae* pv. *syringae 1139*(-) *P. syringae* pv. *syringae 1*(-) *P. syringae* pv. *tomato 506*(-) *Bacillus* sp. *1044*(+)	significant effectiveness in inhibiting the growth of phytopathogenic bacteria, essential oils rich in phenolic compounds (thymol and carvacrol) are particularly effective	Vasinauskiene et al. (2006)[a]
Matricaria chamommilla *Mentha piperita* *M. spicata* *Lavandula angustifolia* *Ocimum basilicum* *Thymus vulgaris* *Origanum vulgare* *Salvia officinalis* *Citrus limon* *C. aurantium*	*Pseudomonas tolaasii*(-)	the greatest and widest activity was expressed by the oregano EO, while carvacrol had the highest antifungal activity	Soković and van Griensven (2006)[a]
Daucus carota sativa	*Staphylococcus aureus*(+)	moderate to strong antimicrobial activity	Imamu et al. (2007)[a]
Components of some essential oils,	*Escherichia coli*(-) *Pseudomonas syringae* pv.	considerable antibacterial	Lo Cantore et al. (2009)[a]

terpenoids and phenylpropanoids, eugenol	*phaseolicola*(-) *P. syringae* pv. *pisi*(-) *P. syringae* pv. *syringae*(-) *P. syringae* pv. *apii*(-) *P. syringae* pv. *atrofaciens*(-) *P. syringae* pv. *lachrymans*(-) *P. syringae* pv. *maculicola*(-) *P. syringae* pv. *tomato*(-) *P. syringae* pv. *glycinea*(-) *P. cichorii*(-) *P. viridiflava*(-) *P. corrugate*(-) *P. tolaasii*(-) *P. reactans*(-) *P. agarici*(-) *Erwinia carotovora* subsp. *atroseptica*(-) *Agrobacterium tumefaciens*(-) *Burkholderia gladioli* pv. *agaricicola*(-) *Ralstonia solanacearum*(-) *Xanthomonas campestris* pv. *phaseoli*(-) *X. campestris* pv. *phaseoli* var. *fuscans*(-) *X. campestris* pv. *vesicatoria*(-) *X. campestris* pv. *campestris*(-)	activity was shown by terpenoid and phenylpropanoid derivatives containing phenol and alcohol functionalities, eugenol, a phenylpropanoid compound, demonstrated notable efficacy against *Xanthomonas campestris* pv. *phaseoli*	
Foeniculum vulgare Mill. var. *vulgare* *Anethum graveolens* L.	*Pseudomonas syringae* pv.*tomato*(-) *Erwinia carotovora* pv. *carotovora*(-) *Xanthomonas axonopodis* pv. *vesicatoria*(-) *Agrobacterium tumefaciens*(-) *Clavibacter michiganensis* subsp. *michiganensis*(+) *Listeria monocytogenes*(+) *Staphylococcus aureus*(+) *Escherichia coli*(-) *Salmonella enteritidis*(-) *Salmonella thyphimirium*(-)	significant antibacterial activity, higher concentrations caused stronger bacterial growth inhibition	Soylu et al. (2009)[a]
Cymbopogon citrates *Mentha arvensis* *Mentha piperita* *Eucalyptus globules*	*Pseudomonas fluorescens*(-)	significant bacterial growth inhibition	Tyagi and Malik (2010)[a]
Origanum vulgare L. *Thymus vulgaris* L. *Thymus serpyllum* L.	*Escherichia coli*(-) *Salmonella choleraesuis* (-) *Proteus mirabilis* *Staphylococcus aureus*(+) *Enterococcus faecalis*(+)	significant antibacterial activity, high activity against Gram-positive bacteria	Lević et al. (2011)[a]
Murraya koenigii L.	*Listeria inocua*(+)	absolute inhibition of the *Listeria innocua*	Erkan et al. (2012)[ab]

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Eugenia caryophylata *Cinnamomum zelanicum* *Datura metel*	*Erwinia carotovora* (-)	strong antibacterial activity, *Datura metel* extract showed weaker activity	Al-Ani et al. (2012)[ab]
Satureja hortensis	*Clavibacter michiganensis* (+) *Pseudomonas syringae*(-)a *Xanthomonas axanopodis*(-) *Xanthomonas campestris*(-)	strong antibacterial activity	Kotan et al. (2013)[ab]
Zanthoxylum schinifolium	*Staphylococcus aureus*(+) *Staphylococcus epidermidis*(+) *Bacillus subtilis*(+) *Salmonella typhimurium*(-) *Pseudomonas aeruginosa*(-) *Shigella dysenteriae*(-) *Escherichia coli*(-)	significant antibacterial activity, the susceptibility of tested Gram-positive bacteria was greater than that of Gram-negative bacteria	Diao et al. (2013)[a]
Eucalyptus globules	*Pseudomonas aeruginosa*(-)	significant antibacterial activity	Pereira et al. (2014)[a]
Thymus vulgaris *Origanum majorana*	*Pseudomonas aeruginosa*(-)	significant antibacterial activity, stronger than some antibiotics used in the study	El-Hosseiny et al. (2014)[a]
Teucrium polium	*Streptomyces scabies*(+) *Brenneria nigrifluens* (-) *Pantoea agglomerans*(-) *Rhizobium radiobacter*(-) *Rhizobium vitis*(-) *Xanthomonas campestris*(-) *Ralstonia solanacearum*(-)	significant antibacterial activity, higher oil concentrations resulted in stronger inhibition	Purnavab et al. (2015)[a]
Satureja hortensis *Calamintha nepeta*	*Agrobacterium tumefaciens*(-) *Bacillus pumilus*(+) *Clavibacter michiganensis* subsp. *michiganensis*(+) *Enterobacter intermedius*(-) *Erwinia caratovora* subsp. *caratovora*(-) *Erwinia chrysanthemi*(-) *Pseudomonas cichorii*(-) *Pseudomonas corrugate*(-) *Pseudomonas fluorescens*(-) *Pseudomonas syringae pv. syringae*(-) *Pseudomonas syringae pv. syringae*(-) *Pseudomonas syringae pv.*	significant antibacterial activity, greater activity of essential oils against Gram-positive bacteria	Gormez et al. (2015)[a]

	syringae(-) *Pseudomonas syringae pv. syringae*(-) *Pseudomonas syringae pv. phaseolicola*(-) *Pseudomonas syringae pv. pisi*(-) *Pseudomonas syringae pv.tabaci*(-) *Pseudomonas syringae pv. tomato*(-) *Ralstonia solanacearum*(-) *Xanthomonas axonopodis pv. campestris*(-) *Xanthomonas vesicatoria*(-)		
Allium sativum	*Rhodococcus fascians* (+) *Agrobacterium tumefaciens* (-) *Erwinia amylovora* (-)	garlic essential oils obtained by hydrodistillation and extraction with diethyl ether showed significant inhibition of bacterial growth	Soltan et al. (2016)[a]
Citrus aurantium *Citrus aurantifolia*	*Xanthomonas citri*(-)	significant antibacterial activity	Mirzaei-Najafgholi et al. (2017)[a]
Rosmarinus officinalis	*Staphylococcus aureus*(+) *Bacillus subtilis*(+) *Escherichia coli*(-) *Proteus vulgaris*(-) *Pseudomonas aeruginosa*(-) *Listeria monocytogenes*(+) *Salmonella enteritidis*(-) *Salmonella typhimurium*(-)	EOs and their components showed a higher antibacterial activity against Gram-positive bacteria than against Gram-negative bacteria	Stojiljkovic et al. (2018)[ab]
Citrus medica L. var. *sarcodactylis*	*Escherichia coli*(-) *Staphylococcus aureus*(+) *Bacillus subtilis*(+) *Micrococcus luteus*(+)	significant antibacterial activity, greater activity of essential oils against Gram-positive bacteria such as *S. aureus*	Li et al. (2019)[a]
Thymus vulgaris *Cymbopogon citratus*	*Solanum lycopersicum*(-)	significant antibacterial activity	Bagy et al. (2019)[ab]
Thymus vulgaris *Cymbopogon citrates* *Solanum torvum*	*Xanthomonas axanopodis*(-)	pronounced antibacterial effect, significant reduction of bacterial growth *in vitro*	Bagy et al. (2019)[ab]

Cynara cardunculus	*Pseudomonas syringae*(-) *Xanthomonas perforans*(-)	significant antibacterial activity	Scavo et al. (2019)[a]
Dysphania ambrosioides	*Pseudomonas syringae*(-)	significant antibacterial activity	Mohamed et al. (2019)[a]
Lantana camara	*Ralstonia solanacearum*(-)	strong biological effects, limonene showed the strongest effect	Mohamed et al. (2019)[a]
Eriocephalus africanus	*Agrobacterium tumefaciens* (-) *Dickeya solani* (-) *Erwinia amylovora* (-) *Pseudomonas cichorii*(-)	bacteriostatic or bactericidal effects, the strongest effect was observed against *D. solani*	Behiry et al. (2020)[a]
Cinnamomum verum	*Agrobacterium tumefaciens* (-)	membrane disruption and bacterial death	Lee at al. (2020)[a]
Pinus halepensis	*Agrobacterium tumefaciens* (-) *Dickeya solani* (-) *Ralstonia solanacearum*(-) *Pectobacterium atrosepticum*(-)	ferulic and tannic acids showed strong antibacterial effects, especially against *Dickeya solani*	Ashmawy et al. (2020)[a]
Dysphania ambrosioides	*Agrobacterium tumefaciens* (-) *Erwinia amylovora* (-)	strong *in vitro* antibacterial activity against *Erwina amylovora* and moderate activity against *Agrobacterium tumefaciens*	Zefzoufi et al. (2020)[a]
Citharexylum spinosum Bougainvilla spectabilis	*Dickeya solani* (-)	strong antibacterial effects	Ashmawy et al. (2020)[a]
Bougainvilla spectabilis	*Pectobacterium carotovorum*(-)	weaker antibacterial activity	Ashmawy et al. (2020)[a]
Apium graveolens Curcuma longa	*Erwinia amylovora* (-)	strong antibacterial activity	Akhlaghi et al. (2020)[ab]
Origanum vulgare	*Erwinia rhapontici*(-) *Xanthomonas campestris*(-)	strong bactericidal action	Simirgiotis et al. (2020)[a]
Cinnamomum cassia	*Klebsiella pneumoniae*(-) *Serratia marcescens*(-)*ab*	cell membrane damage	Vasconcelos et al. (2020)[a]

		(evidenced by protein leakage) in *S. marcescens*, cell lysis	
Origanum vulgare *Allium sativum* *Ocimum basilicum* *Cinnamomum zeylanicum* *Syzygium aromaticum* *Thymus vulgaris*	*Clavibacter michiganensis* (+) *Ralstonia* sp. *Ralstonia solanacearum*(-)	strong antibacterial efficacy	Orzali et al. (2020)[ab]
Corymbia citriodora	*Ralstonia solanacearum*(-)	strong bacteriostatic activity	Tu et al. (2020)[a]
Tagetes patula *Solanum torvum*	*Ralstonia solanacearum*(-)	strong efficacy	Vanti et al. (2020)[a]
Thymbra spicata *Thymus serpyllum* *Origanum syriacum*	*Rhizobium radiobacter*(-)	strong antibacterial activities	Bozkurt et al. (2020)[a]
Thymus serpyllum *Origanum syriacum*	*Pseudomonas savastanoi*(-)	strong antibacterial activities	Bozkurt et al. (2020)[a]
Tagetes patula	*Ralstonia solanacearum*(-)	strong antibacterial properties	Villada-Ramos et al. (2021)[a]

[a] *in vitro* study; [b] *in vivo* study; [ab] both *in vitro* and *in vivo* study; (+) Gram positive bacterium, (-) Gram negative bacterium

Turgis et al. (2009) observed antimicrobial activity of mustard EO against bacteria *Escherichia coli* O157: H7 and *Salmonella typhi.* Results indicated that mustard EO damaged bacterial cell membranes of *E. coli* and *S. typhi*, where the loss of cellular structures was essential for the survival of bacteria, as the treatment resulted in the reduction of both ATP concentration and intracellular pH. The membrane and cell wall disintegrated as a direct effect of the reduction in ATP production at the cell membrane. According to the study of Helander et al. (1998) regarding the activities of selected constituents of EOs (carvacrol, (+)-carvone, thymol, and trans-cinnamaldehyde) against bacteria *E. coli* O157:H7 and *S. typhimurium*, it was reported that carvacrol and thymol decreased the intracellular ATP concentration of E. coli and also increased extracellular ATP, indicating disruptive action on the cytoplasmic membrane. Oregano EO predominantly includes two main components, thymol and carvacrol, and their mixture can cause inhibition action against the two following bacteria: *Staphylococcus aureus* and *Pseudomonas aeruginosa* (Lambert at al., 2001). According to Lo Cantore et al., (2004) EOs of cilantro (*Coriandrum sativum*) and fennel (*Foeniculum vulgare* var. *vulgare*) could be used as efficient natural bactericides in protection against bacterial diseases of plants and in seed treatments, especially, in organic agriculture. These authors studied *in vitro* antibacterial activity of EOs of these two plant species against bacteria *Escherichia coli* and *Bacillus megaterium* and 27 phytopathogenic bacterial species. Basim and Basim (2003) stated that the EO extracted from Damask rose (*Rosa damascena*) petals could be a useful control agent in the management of the disease caused by the bacterium *Xanthomonas axonopodis* spp. *vesicatoria* in tomato and pepper plants. Soković and van Griensven (2006) tested EOs of chamomile (*Matricaria chamomilla*), peppermint (*Mentha piperita*), German pepperming (*M. spicata*), English lavender (*Lavandula angustifolia*), basil (*Ocimum basilicum*), thyme (*Thymus vulgari*), oregano (*Origanum vulgare*), bsage (*Salvia officinalis*), lemon (*Citrus limon*), bitter orange (*C. aurantium*) and their components: linalyl acetate, linalool, limonene, α-pinene, β-pinene, 1,8-cineole, camphor, carvacrol, thymol and menthol for the inhibitory activity against the *Agaricus bisporus, Verticillium fungicola* and *Trichoderma harzianum* and the bacterium *Pseudomonas tolaasii*. The greatest and widest activity was expressed by the oregano EO, while carvacrol had the highest antifungal activity among the assayed compounds.

Akhlaghi et al. (2020) observed effects of plant EOs on the growth and virulence factors of pathogen *Erwinia amylovora* that caused fireblight, a contagious disease affecting primarilty plant members of the family Rosaceae. EOs of celery (*Apium graveolens*) seed and turmeric (*Curcuma longa*) demonstrated the greatest decrease in the impact of *E. amylovora* virulence factors. Celery seed and turmeric EOs reduced the disease development caused by *E. amylovora* on unripe pear fruits by 41.71 and 30.17%, respectively. The corresponding percentages in pear seedling amounted to 26.9 and 16.7%, respectively. Diao et al. (2013) indicated that fennel seeds EO disrupted membrane integrity, as a consequence of electrolyte leakage and the losses of protein and sugar contents of targeted bacteria. Rosemary EO, due to its health benefits, is very important for medicinal uses. It is characterised by its powerful antibacterial, cytotoxic, anti-mutagenic, antioxidant, anti-phlogistic and chemopreventive properties. For this reason, Stojiljkovic et al. (2018) observed antibacterial effects of rosemary EO on some Gram-positive and Gram-negative bacteria: *Staphylococcus aureus, Bacillus subtilis, Escherichia coli, Proteus vulgaris, Pseudomonas aeruginosa, Listeria monocytogenes, Salmonella enteritidis, Salmonella typhimurium.* Rosemary EO mainly contained 1, 8-cineol, camphor, α-pinene, limonene, camphene and linalool. EOs and their components showed a higher antibacterial activity against Gram-positive bacteria than against Gram-negative bacteria regarding the effect on the bacteria cell wall. The cell wall of Gram-negative bacteria does not allow permeation of hydrophobic molecules as readily as the cell wall of Gram-positive bacteria. Generally, EOs are less able to affect the cell growth of the Gram-negative bacteria (Nazzaro et al., 2013).

Rosemary and clove EOs in combination exhibited significant inhibitory effect against the following Gram-positive and Gram-negative bacteria: *Staphylococcus aureus, Staphylococcus epidermidis, Bacillus subtilis, Escherichia coli, Proteus vulgaris* and *Pseudomonas aeruginosa*. The synergetic effect of this combination was observed when it was applied against the opportunic pathogenic yeast *Candida albicans*, but antagonistic effect was detected when it was applied against the fungus *Aspergillus niger* (Fu et al., 2007).

Bacteria secrete small signalling molecules to communicate with their external environment and with other bacteria of the same kind (cell-cell communication - *quorum sensing*). These chemical signal molecules are called autoinducers. The Gram negative bacteria use small molecules such as acyl homoserine lactones (HSLs), whereas the Gram positive bacteria use larger peptide-based molecules (modified oligopeptides) (Madigan et al., 1997; Parsek and Greenberg, 2000). *Quorum sensing* (QS) is involved in biofilm production, motility, swarming, stress resistance and virulence (Faleiro, 2011). The EOs of rose, geranium, lavender, rosemary and clove appear to be very effective as QS inhibitors, while orange and juniper EOs seem to have no anti-QS properties (Khan et al., 2009; Szabó et al., 2010).

The formation of a biofilm is one of the mechanisms of EO activities on bacterial cells. Bacteria in dense populations form a biofilm matrix that protects individual bacterium within the biofilm from external stressors. The formation of biofilms is one of the fundamental reasons for a failure of antimicrobial agents: 65-80% of infections are considered to be related to the formation of biofilms (Coenye and Nelis, 2010). By studying the effects of EOs extracted from several species of oregano on respiratory pathogens, Piasecki et al. (2023) found out that biofilms of bacteria *Haemophilus influenzae* and *Haemophilus parainfluenzae* showed an obvious reduction in the occurrence of bacterial clusters due to the action of marjoram EO. The clove EO showed potential anti-*quorum sensing* activity. *Quorum sensing* takes part in the formation of bacterial biofilm through the intercellular chemical signalling mechanism used for monitoring cell density. Biofilms need an adequate density to induce the QS signal accumulation that will regulate gene expression. Many QS activated genes are beneficial for the biofilm formation and secretion of proteases, siderophores, and toxins (Gerdt and Blackwell, 2014).

Volatile organic compounds, for instance the ones formed by the rhizospheric bacteria *Pseudomonas fluorescens* B-4117 and *Serratia plymuthica* IC1270, can inhibit the cell-cell communication by acyl homoserine lactones (AHLs) signalling molecules produced by different bacteria (*Agrobacterium*, *Chromobacterium*, *Pectobacterium* and *Pseudomonas*) and be involved in bacterial QS. Tyagi and Malik (2010) studied the antibacterial activity of lemon grass, common mint, peppermint and eucalyptus EOs (in liquid as well as in vapour phases) and negative air ions (NAI) against the bacterium *Pseudomonas fluorescens*. The bacterium was exposed to lemon grass oil vapour, negative air ions and their combination for four hours. Combined effect in eliminating bacterium was greater (91.8%) than the elimination rate achieved by lemon grass oil vapour alone (72%) or negative air ions alone (50.9%).

It was observed that the pH homeostasis might weakened by the action of EOs on the membrane that becomes incapable to block protons. According to Ultee et al. (1999), the exposure of the foodborne pathogen *Bacillus cereus* cells to carvacrol (0.25 mM to 0.5 mM) reduced the pH gradient, while the pH gradient was totally lost at the carvacrol concentration of 1 mM or higher.

Conclusion

Pesticides and mineral fertilizers, which are intensively used in the protection and fertilization of plants in agricultural production, cause pollution of all components of the environment and negatively affect food safety. Biopesticides and microbiological fertilizers are an alternative to chemical synthetic preparations and involve the use of plants, beneficial microorganisms, or products of their metabolism in plant protection. The most important products of plant secondary metabolism, which have been used since ancient times as biological agents in the protection of plants, are essential oils. *In vitro* and *in vivo* studies showed antimicrobial and pesticidal effects of essential oils.
The results of numerous scientific studies indicate that these compounds can be successfully used in the ecologically acceptable protection of plant crops from phytopathogens. In addition to increasing crop yields, the use of essential oils as biopesticides in crop production contributes significantly to the production of healthy food and environmental protection.

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Antibakterijska aktivnost etarskih ulja biljaka i mogućnosti primene kao biopesticida u biljnoj proizvodnji

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Izvod

Patogeni mikroorganizmi, prvenstveno bakterije i gljive, uzrokuju biljne bolesti, koje dovode do značajanog gubitka biljnih prinosa. Već dugo se čine napori da se smanje gubici biljnih prinosa, najčešće primenom hemijskih sredstava za zaštitu bilja, ali i selekcijom sojeva otpornih prema fitopatogenima i ostalim štetočinama. Međutim, intenzivna primena hemijskih sredstava u biljnoj proizvodnji dovodi do zagađenja životne sredine i ugrožavanja zdravstvene bezbednosti hrane. Iz navedenih razloga, preporučuje se primena bioloških preparata (biopesticida), kao ekološki prihvatljivog načina upravljanja biljnim bolestima i životnom sredinom. Cilj ovog rada je da se, uvidom u naučnu literaturu i istraživanja, opiše antibakterijska aktivnost etarskih ulja biljaka i mogućnosti njihove primene kao biopesticida u biljnoj proizvodnji. U ovom preglednom radu, analizirana je dostupna literatura. Rezultati brojnih sprovedenih *in vitro* i *in vivo* naučnih istraživanja ukazuju da etarska ulja biljaka ispoljavaju snažne antibakterijske efekte na fitopatogene bakterije, uzročnike biljnih bolesti, kao i da se mogu uspešno koristiti u biljnoj proizvodnji.

Ključne reči: etarska ulja, antibakterijska aktivnost, fitopatogene bakterije, bipreparati, zagađenje životne sredine, bezbednost hrane.

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