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REVIEW PAPER

Genus *Abies* Mill. (Pinaceae) as the source of plant antimicrobials: A Review

Rod *Abies* Mill. (Pinaceae) kao izvor biljnih antimikrobnih supstanci: Pregled

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ABSTRACT

Antimicrobial resistance is one of the major global health problems and it's related to the enormous number of human deaths. The occurrence and severity of infections caused by microbial pathogens illustrate the need for the identification and characterization of novel antimicrobial agents of natural origin. This review discusses a well-known coniferous genus *Abies* Mill. in terms of antimicrobial potential. Data regarding the antibacterial, antifungal, and antiviral properties of *Abies* species were collected and summarized in this review. It was found that 13 different *Abies* species are recognized as potential sources of antimicrobial compounds. The most investigated species was *A. spectabilis* (syn. *A. webbiana*), followed by *A. alba*, *A. cilicica*, *A. sibirica*, *A. nordmanniana*, *A. numidica*, *A. koreana*, *A. balsamea*, *A. holophylla*, and *A. concolor*. Individual studies on *A. firma*, *A. beshanzuensis*, and *A. cephalonica* were also taken into account. The largest number of analyzed results were related to the antibacterial activity of *Abies*-derived products, but studies on antifungal, and particularly antiviral capacity were also noted. The most investigated products were essential oils and extracts. The broadest antimicrobial activity was observed for *A. cilicica*. This study noted that some endemic and endangered *Abies* species were being used for antimicrobial purposes. In that term, the rationalization of the sampling practices and the implementation of the conservation activities are of great importance. This review represents a comprehensive overview of the current knowledge on the antimicrobial potential of the genus *Abies*.

Key words: *Abies, Antimicrobial activity, Antimicrobial resistance, Fir, Plant antimicrobials, Review, Secondary metabolites.*

INTRODUCTION - *Uvod*

Antimicrobial resistance (AMR) is one of the most challenging problems of global health in the 21st century (Hernando-Amado *et al.*, 2019). According to O'Neill (2016), AMR is related to 750,000 annual human deaths worldwide, and by the year 2050, that number could increase up to 10 million. As humanity, we are indeed faced with the lack of new antimicrobials, the rise of AMR, the toxicity of synthetic antimicrobial drugs, and their many potential side effects, as well as the economic burden that is unavoidable in the constant race with microbes to develop efficient and affordable medicines. In the abovementioned issues, plants could represent a potential solution (Chassagne *et al.*, 2021), since they produce secondary metabolites, well-known for their bioactive capacity.

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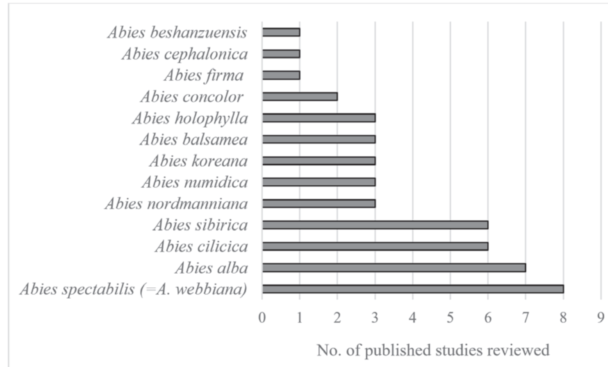
Coniferous plants, comprising eight families, 70 genera, and about 630 species distributed worldwide, are considered an important source of bioactive phytochemicals (Macovei *et al.*, 2023). According to Garzoli *et al.* (2021), the family Pinaceae is the largest family of nonflowering seed plants and includes 11 genera and approximately 230 species. Genus *Abies* Mill. encompasses approximately 50 species, with wide distribution in the Northern Hemisphere, especially within the northern boreal forest zone (Debreczy & Rácz, 2011). The largest number of *Abies* species live in the temperate zone, while a few of them occurs in subtropical habitats (Xiang *et al.*, 2007). Yang *et al.* (2008) stated that around 300 components are isolated from 19 *Abies* species. These compounds are mostly terpenoids, flavonoids, and lignans, followed by phenols, steroids, and other minor constituents. Different products derived from *Abies* species could be used for medicinal purposes, but one of the most frequently used are extracts and essential oils. The crude extracts and individual metabolites possess various bioactive properties including antitumor, antimicrobial, anti-ulcerogenic, anti-inflammatory, antihypertensive, etc. (Yang *et al.*, 2008), as well as the essential oils due to the richness in their chemical composition (Garzoli *et al.*, 2021).

MATERIAL AND METHODS – *Materijal i metode*

This review discusses the genus *Abies* in terms of antimicrobial potential. Despite the fact that there are individual published results regarding the antimicrobial activity of particular *Abies* species, to the best of our knowledge there is no systematic overview that debates the antibacterial, antifungal, and antiviral properties of the genus *Abies* in a comprehensive manner. Available data regarding the antimicrobial potential of *Abies* species were extracted from scientific databases Web of Science, Scopus, and PubMed, by using the search terms such as: "Abies", "antimicrobial activity", "antimicrobial resistance", "phytochemical composition", and "plant antimicrobials".

RESULTS AND DISCUSSION – *Rezultati i diskusija*

This review revealed that 13 *Abies* species were recognized in terms of antimicrobial potential. The total number of published studies for each species that is taken into consideration is presented in Graph 1.



Graph 1. Number of published studies about the antimicrobial activity of *Abies* species reviewed in this paper

Grafikon 1. Broj publikacija o antimikrobnom djelovanju Abies *vrsta analiziranih u ovom radu*

Details regarding the antimicrobial potential of particular species are presented below. Species are listed in accordance with their phylogenetic similarity (Xiang *et al.*, 2018).

Abies alba Mill.

Abies alba, known as the European Fir or Silver Fir is native to the mountains of Europe, but successfully cultivated in North America. It occurs at altitudes of 300 to 1,700 m, on mountains with rainfall over 1,000 mm per year (Simonetti & Simonetti, 1990; Farjon, 2017). Bağci and Diğrak (1996) reported a modest antibacterial activity of the essential oil (EO) made from *A. alba* twigs. Broznić *et al.* (2018) investigated the antibacterial properties of the fir honeydew honey against *Staphylococcus aureus*, *S. epidermidis*, and *Acinetobacter baumannii*. All strains were sensitive to the tested compound, with *Staphylococcus* strains being more susceptible (MIC values ranged from 0.0125 to 0.025 g/ml). This study highlighted many bioactive polyphenol compounds such as chrysin, galangin, quercetin, kaempferol, acacetin, pinocembrin, pinobanksin, caffeic acid, and apigenin. Truchan *et al.* (2019) observed the antibacterial effects of *A. alba* EO against several pathogens and noted very large inhibition zones: *Escherichia coli* (25.7 ±1.13 mm), *S. aureus* (23.8 ±1.25 mm), *Pseudomonas aeruginosa* (22.4 ±1.1 mm), and *Klebsiella pneumoniae* (19.4 ±0.98 mm). Similarly, Salamon *et al.* (2019) reported the antibacterial activity of *A. alba* EO against *E. coli*, *Enterococcus faecalis*, and *Candida albicans*, with the excessive activity observed against fungi, where the zone of inhibition was 30.00±1.25 mm. This EO was also effective against the clinical strain of *C. albicans*. These results could be related to the compounds such as α-pinene, boranyl acetate, borneol, and limonene. An earlier investigation by Yang *et al.* (2009) revealed some constituents of *A. alba*

EO: bornyl acetate, camphene, 3-carene, tricyclene, limonene, α-pinene, caryophyllene, β-phellandrene, borneol, bicyclo[2.2.1]hept-2-ene,2.3-dimethyl, and α-terpinene. The presented results are in accordance with Garzoli *et al.* (2021), who detected the most abundant components of the liquid phase of *A. alba* EO: α-pinene, β-pinene, limonene, and γ-terpinene. This EO exhibited antibacterial activity against *E. coli*, *Pseudomonas fluorescens*, *Acinetobacter bohemicus*, *Kocuria marina*, and *Bacillus cereus*. Values of the minimum inhibitory concentration and the minimum bactericidal concentration (MIC and MBC) were 51.28 mg/ml for *E. coli*, *P. fluorescens*, and *K. marina*, while lower MIC and MBC values were noted for *A. bohemicus* and *B. cereus* (12.82 mg/ml and 25.64 mg/ml, respectively). The MBC/MIC ratio defined the *A. alba* EO as bactericidal against all tested bacterial strains.

Abies cilicica (Antoine et Kotschy) Carrière

Abies cilicica (Cilician Fir) occurs in the mountains adjacent to the northeastern Mediterranean coast of Turkey, Syria, and Lebanon (Gardner & Knees, 2013). This species is dominant in the Abieti-Cedrion phytocoenosis, a type of forest that occurs between 800 and 2,100 m elevation. The annual precipitation is typically 1,000-1,500 mm, mostly falling in winter (Boydak, 2007).

Bağci and Diğrak (1996) investigated the antimicrobial activity of essential oils made from twigs of *A. cilicica* subsp. *cilicica* and *A. cilicica* subsp. *isaurica* against series of microorganisms: *E. coli*, *Bacillus megaterium*, *B. cereus*, *B. subtilis*, *B. brevis*, *P. aeruginosa*, *Listeria monocytogenes*, *K. pneumoniae*, *Enterobacter aerogenes*, *S. aureus*, *Saccharomyces cerevisiae*, and *C. albicans*. This study recorded a very high antimicrobial effect of the tested EOs, with stronger antifungal potential, and low activity against the Gram-negative pathogen *E. coli*. The main components of the *A. cilicica* subsp. *cilicica* EO are δ-3-carene, α-pinene, longipinene, β-caryophyllene, α-humulene, and germacrene D (Bağci & Diğrak, 1996). Kizil *et al.* (2002) proved the antimicrobial potential of the resins obtained from the roots and stems of *A. cilicica* on a panel of microorganisms: *S. aureus*, *Streptococcus pyogenes*, *Bacillus thurigiensis*, *B. brevis*, *B. subtilis*, *B. megatherium*, *B. cereus*, *P. aeruginosa*, *E. coli*, and *C. albicans*. Results suggested that increasing the resin concentration (from 40 to 80 μg per disk) led to the formation of broader inhibition zones. Later investigation by Dayisoylu *et al.* (2009) tested the antimicrobial properties of the EO from the resin of the cones of *A. cilicica* subsp. *cilicica* and included a wide list of microbial species: *Corynebacterium xerosis*, *B. brevis*, *B. megatherium*, *B. cereus*, *Mycobacterium smegmatis*, *P. aeruginosa*, *S. aureus*, *K. pneumoniae*, *E. faecalis*, *Micrococcus luteus*, *E. coli*, *Kluyveromyces fragilis*, *Rhodotorula rubra*, and *S. cerevisiae*. Interestingly, all strains except for *E. coli* were successfully inhibited by this EO. The values of minimum inhibitory concentration (MIC) of EO for inhibited bacteria were in the range of 0.50-3.50 μg/ml and for yeasts 0.50-1.75 μg/ml. The EO from the resin of the investigated plant contains limonene, β-pinene, α-pinene, and myrcene, with limonene being the most effective in terms of antibacterial potential, and myrcene as an antifungal agent. The aqueous and ethanolic extracts of resin obtained from cones of *A. cilicica* subsp. *isaurica* were investigated in terms of antimicrobial potential by Yavaşer *et al.* (2015). Activity is proven only for the ethanolic extract against *S. aureus* (11 mm), *B. cereus* (17 mm), and *M. luteus* (18 mm). However, there were no inhibition zones in the case of *E. faecalis*, *E. coli*, and *L. monocytogenes*. The resins are rich in terpenes and extracts may contain terpenoids, steroids, tannins, glycosides, anthraquinones, saponins, flavonoids, alkaloids, etc. The antibacterial activity of the ethereal extract made from *A. cilicica* is recorded by Erylmaz *et al.* (2016), against *S. aureus* (including methicillin-resistant strain, MRSA), *B. subtilis*, *E. coli*, *P. aeruginosa*, and *K. pneumoniae*, while the same substance did not show antifungal properties against *C. albicans*. The crude extracts from the leaf and flowering cones of *A. cilicica* subsp. *cilicica* were active against *E. faecalis*, *Proteus vulgaris*, *K. pneumoniae*, *C. albicans*, and *Aspergillus niger*. The growth of bacteria and fungi isolates was inhibited by methanolic, ethanolic, and acetonic extracts to different degrees, according to the tested organisms, plant fraction, and examined solvent (Saleh & Al-Mariri, 2016).

Abies nordmanniana (Steven) Spach

Abies nordmanniana (Nordmann Fir or Caucasian fir) is indigenous to the mountains south and east of the Black Sea, in Turkey, Georgia, and the Russian Caucasus. Typically, it occurs at altitudes of 900 to 2,200 m on mountains characterized by precipitation of over 1,000 mm (Tarkhnishvili *et al.*, 2011). In the study of Bağci and Diğrak (1996), the essential oils of two subspecies were investigated *A. nordmanniana* subsp. *nordmanniana* and *A. nordmanniana* subsp. *bornmiielleriana*, and proven for their high antimicrobial activity against *Bacillus megaterium*, *B. brevis*, *B. subtilis*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Enterobacter aerogenes*, *Klebsiella pneumoniae*, and *Listeria monocytogenes*. Antimicrobial activity of the methanolic and ethanolic extracts of leaves, cones, twigs, and stem barks of *A. nordmanniana* subsp. *equi-trojani* were detected against *Mycobacterium smegmatis*, *B. subtilis*, *Salmonella typhimurium*, *Sarcina lutea*, *E. coli*, *S. aureus*, *Candida utilis*, and *S. cerevisiae* in the research of Sakar *et al.* (1998). Observed effects are in relation to diterpenoids, flavonoids, and tannin precursors. Erylmaz *et al.* (2016) noted relatively narrow antibacterial activity of *A. nordmanniana* ethereal extract, but interestingly, inhibition was observed against Gram-negative *E. coli* and *P. aeruginosa*, known for their extended antimicrobial resistance. The same study debates the antimicrobial activity of species refer as *Abies equi-trojani*, but according to the Euro+Med PlantBase, this is the synonym of *A. nordmanniana* subsp. *equi-trojani*. The ethereal extract showed antibacterial activity against *B. subtilis* and *P. aeruginosa*.

Abies numidica de Lannoy ex Carrière

Abies numidica is an endemic Algerian plant, growing in a high-altitude Mediterranean climate at 1,800-2,004 m with an annual precipitation of 1,500 to 2,000 mm (Yahi *et al.*, 2011). Tlili Ait Kaki *et al.* (2012) found that pure essential oil of *A. numidica* was not active against investigated microorganisms, while particular dilution performed activity against MRSA, *E. coli*, *K. pneumoniae*, *P. aeruginosa*, *Acinetobacter* sp., and *S. epidermidis*. Inhibition zones were detected for all the investigated microorganisms at the dilution of 1/1000 (using dimethyl sulfoxide). The essential oil of *A. numidica* used in the investigation of Ramdani *et al.* (2014) was very active against *B. cereus*, *E. coli*, and *E. faecalis*. Modest activity was noted for *S. aureus*, *S. epidermidis*, and *M. luteus*, while low antibacterial activity was described for *K. pneumoniae*. Antifungal effects were very strong against *S. cerevisiae*. Unlike essential oils, Mostefa *et al.* (2016) investigated the phytochemical composition and antimicrobial potential of *A. numidica* hydro-methanolic cones extract. Chromatography revealed several new chemical compounds for this species, mainly abietane diterpenes. Investigated extract, as well as the individual compounds, performed antibacterial activity against *B. subtilis* (MIC=62.50 μg/ml), *E. faecalis*, *S. aureus*, *M. luteus*, and *Listeria innocua* (MIC≤250 μg/ml).

Abies sibirica Ledeb.

Abies sibirica or Siberian Fir is native to the taiga ecosystems in Siberia, Turkestan, Xinjiang, Mongolia, and Heilongjiang. The species inhabits a cold boreal climate at elevations of 1,900-2,400 m (Katsuki *et al.*, 2011) where average annual precipitation exceeds 600 mm (Bazhina, 2014). As one of the dominant tree species in European Russia, as well as of the Siberian taiga, it has been used in conventional and traditional medicine since ancient times (Makarova *et al.*, 2013). *Abies sibirica* is recognized as a source of agents with anti-inflammatory, antimicrobial, wound healing, regenerating, and antifungal properties (Ayupova *et al.*, 2014). Noreikaitė *et al.* (2017) showed that EO from *A. sibirica* exhibits antifungal activity against *C. albicans*. Truchan *et al.* (2019) detected the mild antibacterial effects of essential oil of this plant species against *P. aeruginosa* and MRSA strain, with clear inhibition zones of 9.40±0.1 mm, and 9.40±0.25 mm, respectively. The antiviral potential of polyprenols from *A. sibirica* is proven against the Influenza virus (Boldyrev *et al.*, 2000; Safatov *et al.*, 2000; Safatov *et al.*, 2005). Furthermore, Sokolova *et al.* (2018) investigated compounds like borneol and camphor from this plant in order to design novel inhibitors for the Vaccinia virus.

Abies koreana E.H.Wilson

Abies koreana or Korean Fir is endemic species, native to the higher mountains of South Korea and occurs in habitats at 1,000 to 1,900 m of altitude, characterized by high rainfall, with cool and humid summers and heavy winter snowfall (Kim *et al.*, 2011). Bağci and Diğrak (1996) observed the extensive antimicrobial potential of the essential oil of this plant species against different microorganisms, including Gram-positive and Gram-negative bacteria, as well as fungi. Furthermore, the antibacterial activity of *A. koreana* EO against several bacterial strains is reported by Jeong *et al.* (2007). The results obtained from the disk diffusion method indicated that tested EO exhibits a variable degree of antibacterial activity on different tested strains, with *Staphylococcus epidermidis* being the most susceptible strain, followed by MSSA and MRSA, *Staphylococcus haemolyticus*, *S. simulans*, and *S. flexneri*. Gram-negative strains displayed variable degrees of susceptibility, with the maximum activity observed against *E. coli* and *P. aeruginosa*. Oh *et al.* (2007) identified 47 compounds from the *A. koreana* essential oils, with limonene being the most abundant, followed by bornyl acetate, α-pinene, camphene, β-himachalene, β-myrcene, γ-selinene, γ-gurjunene, β-eudesmene, β-pinene, and other minor constituents. The same investigation confirmed the inhibitory activity of this EO against *E. coli*, *S. epidermidis*, and *C. albicans*. *S. epidermidis* was more sensitive in comparison to *E. coli*, while investigated EO led to extensive inhibition of *C. albicans* with the inhibition zones of 34.0±2.83 mm.

Abies balsamea (L.) Mill.

Abies balsamea, known as the Balsam Fir, is species native to most of eastern and central Canada and the northeastern USA (Farjon, 2013a). This species is shade tolerant and grow in cool climates, with a mean annual temperature of 4 °C, with consistent moisture at their roots (Walters & Reich, 2000). Pichette *et al.* (2006) investigated the chemical profile and antimicrobial activity of *A. balsamea* essential oil. The analysis revealed β-pinene to be the main component, followed by δ-3-carene, α-pinene, and bornyl acetate. Tested EO showed antibacterial activity against *S. aureus* (MIC value was determined at 56 µg/ml), while individual compounds were effective against *E. coli* as well. The antibacterial potential of the *A. balsamea* needle extract was investigated by Vandal *et al.* (2015), while Coté *et al.* (2016) studied the antibacterial effects of *A. balsamea* oleoresin. The latter substance was effective against *S. aureus*, including the MRSA strain. According to this research, oleoresin is mainly composed of monoterpenes, sesquiterpenes, and diterpenes. Resin acids, isopimaric and levopimaric acids detected in the sample are also related to the antibacterial properties of the whole oleoresin.

Abies concolor (Gordon) Lindl. ex Hildebr.

Abies concolor, commonly known as the White Fir, is species native to the mountains of western North America, with typical occurrence at elevations between 900 and 3,400 m (Farjon, 2013b). The essential oil of this species is tested by Bağci and Diğrak (1996) against various microorganisms, but antimicrobial activity was not detected. Nevertheless, the antibacterial properties of the seed and cone EO of *A. concolor* were observed in the study of Wajs-Bonikowska *et al.* (2017) against *S. aureus*, *Enterococcus faecium*, *E. faecalis*, *E. coli*, and *K. pneumoniae*. Obtained results showed that seed EO was more efficient in comparison to cone EO. This investigation also debates the chemical profile of the investigated EOs. As the main constituent was noted β-pinene, followed by limonene, camphene, β-phellandrene, and α-pinene.

Abies spectabilis (D.Don) Mirb. /syn. _Abies webbiana_ (Wall ex D.Don) Lindl./

Abies spectabilis (East Himalayan Fir) is the dominant tree in the forests of the central and western Himalayas, especially from 3,000 m to 4,050 m, with occasional occurrences on ridges below this height (Thomas, 2019). The study performed by Vishnoi *et al.* (2007) investigated the antimicrobial activity of *A. spectabilis* methanolic extract in the range of 625 µg/ml to 5 mg/ml, and obtained significant results against several bacterial and fungal species: *S. aureus*, *S. epidermidis*, *M. luteus*, *E. coli*, *Salmonella typhi*, *Vibrio cholerae*, *Shigella dysenteriae*, *A. niger*, and *C. albicans*. The inhibition zones were larger with the increased concentration of the extract. Constituents that are probably related to the observed antibacterial activity are abiesin, methyl betuloside, and betuloside identified in the leaves. Ambre *et al.* (2019) investigated compounds present in *A. spectabilis* chloroform leaf extract that are responsible for inhibitory activity against *S. aureus*. Authors identified seven metabolites, namely betuloside, 2,7-dihydroxy-4'-methoxyisoflavanone, genistein 7-O-beta-D-glucoside, β-sitosterol, abietane, coniferol, and 1-(3,4-dihydroxyphenyl)-1-decene-3,5-dione-Pos. Previous studies also recorded the antimicrobial potential of this species. Donovan *et al.* (2009) noted that genistein 7-O-beta-D-glucoside-isoflavone possesses antiviral activity; Ododo *et al.* (2016) presented an inhibitory effect of β-sitosterol against *S. aureus* and *E. coli*; González (2015) reported the antibacterial activity of diterpene abietane against *S. aureus*, *B. subtilis*, *P. aeruginosa*, and *E. coli*; Makwana *et al.* (2015) noted activity of monolignol coniferol on *E. coli*. These results are in accordance with the investigation of Timothy *et al.* (2021) who tested the ethanolic extract of *A. spectabilis* on various microorganisms: *S. aureus*, *Streptococcus mutans*, *E. faecalis*, and *C. albicans*, which exhibited very good antimicrobial properties. Furthermore, a recent study by Gautam *et al.* (2022) on ethanolic extract made from *A. spectabilis* leaves showed a wide antimicrobial range of activity, with fungal species being more susceptible to the tested compound in comparison to the bacteria. The authors stated that high phenolic content could be in relation to the described properties.

Abies holophylla Maxim.

Abies holophylla or Manchurian Fir is native to a mountainous region of northern Korea (Katsuki *et al.*, 2013). This species has pronounced heat tolerance, and it is exceptionally winter hardy, capable of withstanding temperatures up to -34 °C. Manchurian fir grows in the mountains, but also at lower elevations and in valleys where it is exposed to hot summer temperatures (Meyer, 2010). The investigation of Lee and Hong (2009) revealed 38 compounds that mainly comprised *A. holophylla* essential oil, with the main constituents being bicyclo[2.2.1]heptan-2-ol, δ-3-carene, α-pinene, camphene, limonene, β-myrcene, trans-caryophyllene, and α- bisabolol. This EO exhibited antibacterial activity against *E. coli*, *Klebsiella oxytoca*, *B. subtilis*, and *S. aureus*. Furthermore, when MIC values were tested, promising results were gained in the cases of *Enterobacter aerogenes*, *E. cloacae*, *K. pneumoniae*, *B. subtilis*, *Candida glabrata*, and *Cryptococcus neoformans*. Lee and Hong (2009) observed the antibacterial effects of *A. holophylla* EO, with interesting results of stronger inhibition of the Gram-negative species such as *E. coli* and *K. pneumoniae*. Later research by Lee *et al.* (2014) confirmed the antibacterial activity of EO against *K. pneumoniae*, *Haemophillus influenzae*, *S. pyogenes*, *Streptococcus pneumoniae*, and *Neisseria meningitidis*. As the major constituents α-pinene,

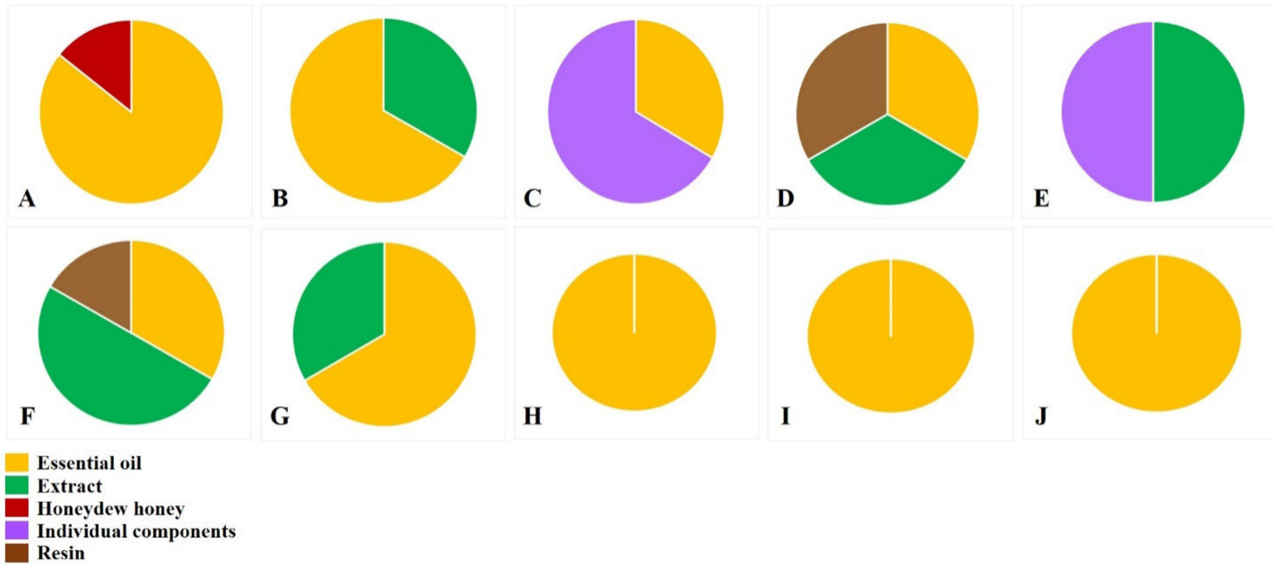


Figure 1. Plant products of *Abies* species investigated in terms of antimicrobial activityA: *A. alba*; B: *A. nordmanniana*; C: *A. sibirica*; D: *A. balsamea*; E: *A. spectabilis* (=*A. webbiana*); F: *A. cilicica*; G: *A. numidica*; H: *A. koreana*; I: *A. concolor*; J: *A. holophylla*

Slika 1. Biljni produkti Abies *vrsta istraživani u smislu antimikrobne aktivnosti A: A. alba; B: A. nordmanniana; C: A. sibirica; D: A. balsamea; E: A. spectabilis (=A. webbiana); F: A. cilicica; G: A. numidica; H: A. koreana; I: A. concolor; J: A. holophylla*

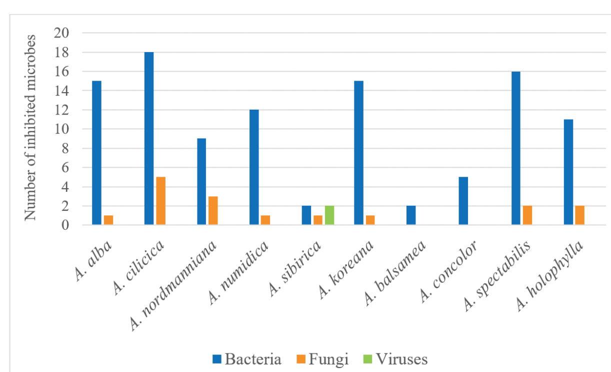
camphene, β-pinene, 3-carene, limonene, bornyl acetate, borneol, β-caryophyllene, α-caryophyllene, caryophyllene oxide, and α-bisabolol were identified.

There is also some isolated data regarding the antimicrobial activity of other *Abies* species, such as *Abies firma* Siebold & Zucc. (Bağci & Diğrak, 1996), *Abies beshanzuensis*M.H.Wu (Hu *et al.*, 2016), and *Abies cephalonica* Loudon (Tsasi *et al.*, 2022). Furthermore, a recent study by Baser *et al.* (2023) debates *Abies*-derived compounds as antiviral agents, including the inhibition of the novel virus SARS-CoV-2.

This review showed that the most investigated products in terms of antimicrobial potential were essential oils and extracts. Additionally, the antimicrobial activity of resin, honeydew honey, and some individual chemical compounds was also investigated. Studied products for each species are presented in Figure 1. The representation in Figure 1 refers to those *Abies* species for which more than one study on antimicrobial activity was available.

Overall analyses revealed that different products derived from *Abies* species have proven inhibitory activity against 44 Gram-positive and Gram-negative species of bacteria, including some multidrug-resistant strains. Furthermore, inhibitory effects were detected against eight species of fungi and two viruses (Table 1).

The broadest antimicrobial activity was noted in *A. cilicica*, with proven inhibitory action against 18 bacteria and five fungi. Very high antimicrobial properties were observed in *A. spectabilis*, *A. alba*, *A. koreana*, *A. numidica*, and *A. holophylla* (Graph 2).



Graph 2. Antimicrobial capacity observed in *Abies* species

Grafikon 2. Antimikrobni kapacitet uočen kod Abies *vrsta*

Table 1. Microbes that are inhibited by the products derived from particular *Abies* species

Tabela 1. Mikrobi inhibirani produktima izvedenim iz određenih Abies *vrsta*

BACTERIA			
No.	**Tested microbe**	***Abies* species**	**References**
1.	*Acinetobacter baumannii*	*A. alba*	Broznić *et al.*, 2018
2.	*Acinetobacter bohemicus*	*A. alba*	Garzoli *et al.*, 2021
3.	*Acinetobacter* sp.	*A. numidica*	Tlili Ait Kaki *et al.*, 2012
4.	*Bacillus brevis*	*A. alba* *A. cilicica* *A. nordmanniana* *A. koreana* *A. firma*	Bağci & Diğrak, 1996; Kizil *et al.*, 2002; Dayisoylu *et al.*, 2009
5.	*Bacillus cereus*	*A. alba* *A. cilicica* *A. nordmanniana* *A. numidica* *A. koreana* *A. firma*	Bağci & Diğrak, 1996; Kizil *et al.*, 2002; Dayisoylu *et al.*, 2009; Ramdani *et al.*, 2014; Yavaşer *et al.*, 2015; Garzoli *et al.*, 2021
6.	*Bacillus megatherium*	*A. alba* *A. cilicica* *A. nordmanniana* *A. koreana*	Bağci & Diğrak, 1996; Kizil *et al.*, 2002; Dayisoylu *et al.*, 2009
7.	*Bacillus pumilus*	*A. spectabilis*	Gautam *et al.*, 2022
8.	*Bacillus subtilis*	*A. cilicica* *A. nordmanniana* *A. numidica* *A. koreana* *A. spectabilis* *A. holophylla* *A. firma*	Bağci & Diğrak, 1996; Sakar *et al.*, 1998; Kizil *et al.*, 2002; Lee & Hong, 2009; González, 2015; Erylmaz *et al.*, 2016; Mostefa *et al.*, 2016; Gautam *et al.*, 2022
9.	*Bacillus thurigiensis*	*A. cilicica*	Kizil *et al.*, 2002
10.	*Corynebacterium xerosis*	*A. cilicica*	Dayisoylu *et al.*, 2009
11.	*Enterobacter cloacae*	*A. holophylla*	Lee & Hong, 2009
12.	*Enterobacter aerogenes*	*A. alba* *A. cilicica* *A. koreana* *A. firma* *A. holophylla*	Bağci & Diğrak, 1996; Lee & Hong, 2009
13.	*Enterococcus faecalis*	*A. alba* *A. cilicica* *A. numidica* *A. concolor* *A. spectabilis*	Dayisoylu *et al.*, 2009; Ramdani *et al.*, 2014; Mostefa *et al.*, 2016; Saleh & Al-Mariri, 2016; Wajs-Bonikowska *et al.*, 2017; Salamon *et al.*, 2019; Timothy *et al.*, 2021
14	*Enterococcus faecium*	*A. concolor*	Wajs-Bonikowska *et al.*, 2017

BACTERIA			
No.	**Tested microbe**	***Abies* species**	**References**
15	*Escherichia coli*	*A. alba* *A. cilicica* *A. nordmanniana* *A. numidica* *A. koreana* *A. balsamea* *A. concolor* *A. spectabilis* *A. holophylla*	Sakar *et al.*, 1998; Kizil *et al.*, 2002; Pichette *et al.*, 2006; Jeong *et al.*, 2007; Oh *et al.*, 2007;Vishnoi *et al.*, 2007; Lee & Hong, 2009;Tlili Ait Kaki *et al.*, 2012; Lee *et al.*, 2014; Ramdani *et al.*, 2014; González, 2015; Makwana *et al.*, 2015; Erylmaz *et al.*, 2016; Ododo *et al.*, 2016;Wajs-Bonikowska *et al.*, 2017; Salamon *et al.*, 2019; Truchan *et al.*, 2019; Garzoli *et al.*, 2021; Gautam *et al.*, 2022
16.	*Haemofillus influenzae*	*A. holophylla*	Lee *et al.*, 2014
17.	*Klebsiella pneumoniae*	*A. alba* *A. cilicica* *A. numidica* *A. koreana* *A. concolor* *A. holophylla* *A. firma*	Bağci & Diğrak, 1996; Dayisoylu *et al.*, 2009; Lee & Hong, 2009;Tlili Ait Kaki *et al.*, 2012; Lee *et al.*, 2014; Ramdani *et al.*, 2014; Erylmaz *et al.*, 2016; Saleh & Al-Mariri, 2016;Wajs-Bonikowska *et al.*, 2017;Truchan *et al.*, 2019
18.	*Klebsiella oxytoca*	*A. holophylla*	Lee & Hong, 2009
19.	*Kocuria marina*	*A. alba*	Garzoli *et al.*, 2021
20.	*Listeria inocua*	*A. numidica*	Mostefa *et al.*, 2016
21.	*Listeria monocytogenes*	*A. alba* *A. cilicica* *A. koreana* *A. firma*	Bağci & Diğrak, 1996
22.	*Micrococcus luteus*	*A. cilicica* *A. numidica* *A. spectabilis*	Vishnoi *et al.*, 2007; Dayisoylu *et al.*, 2009; Ramdani *et al.*, 2014;Yavaşer *et al.*, 2015; Mostefa *et al.*, 2016
23.	MRSA	*A. cilicica* *A. numidica* *A. sibirica* *A. koreana* *A. balsamea*	Jeong *et al.*, 2007;Tlili Ait Kaki *et al.*, 2012; Coté *et al.*, 2016; Erylmaz *et al.*, 2016; Truchan *et al.*, 2019
24.	*Mycobacterium smegmatis*	*A. cilicica* *A. nordmanniana*	Sakar *et al.*, 1998; Dayisoylu *et al.*, 2009
25.	*Neisseria meningitidis*	*A. holophylla*	Lee *et al.*, 2014
26.	*Proteus vulgaris*	*A. cilicica*	Saleh & Al-Mariri, 2016
27.	*Pseudomonas aeruginosa*	*A. alba* *A. cilicica* *A. numidica* *A. sibirica* *A. koreana* *A. spectabilis* *A. firma*	Bağci & Diğrak, 1996; Kizil *et al.*, 2002; Jeong *et al.*, 2007; Dayisoylu *et al.*, 2009; Tlili Ait Kaki *et al.*, 2012; González, 2015; Erylmaz *et al.*, 2016;Truchan *et al.*, 2019
28.	*Pseudomonas fluorescens*	*A. alba*	Garzoli *et al.*, 2021

BACTERIA			
No.	**Tested microbe**	***Abies* species**	**References**
29.	*Salmonella enterica*	*A. spectabilis*	Gautam *et al.*, 2022
30.	*Salmonella typhi*	*A. spectabilis*	Vishnoi *et al.*, 2007; Gautam *et al.*, 2022
31.	*Salmonella tipymurium*	*A. nordmanniana*	Sakar *et al.*, 1998
32.	*Sarcina lutea*	*A. nordmanniana;*	Sakar *et al.*, 1998
33.	*Staphylococcus aureus*	*A. alba* *A. cilicica* *A. nordmanianna* *A. numidica* *A. koreana* *A. balsamea* *A. concolor* *A. spectabilis* *A. holophylla* *A. firma*	Bağci & Diğrak, 1996; Sakar *et al.*, 1998; Kizil *et al.*, 2002; Pichette *et al.*, 2006; Jeong *et al.*, 2007; Vishnoi *et al.*, 2007; Dayisoylu *et al.*, 2009; Lee & Hong, 2009; Ramdani *et al.*, 2014; González, 2015; Yavaşer *et al.*, 2015; Coté *et al.*, 2016; Erylmaz *et al.*, 2016; Mostefa *et al.*, 2016; Ododo *et al.*, 2016; Wajs-Bonikowska *et al.*, 2017; Broznić *et al.*, 2018; Ambre *et al.*, 2019; Truchan *et al.*, 2019; Timothy *et al.*, 2021; Gautam *et al.*, 2022
34.	*Staphylococcus epidermidis*	*A. alba* *A. numidica* *A. koreana* *A. spectabilis*	Jeong *et al.*, 2007; Oh *et al.*, 2007; Vishnoi *et al.*, 2007; Tlili Ait Kaki *et al.*, 2012; Ramdani *et al.*, 2014; Broznić *et al.*, 2018
35.	*Staphylococcus haemolyticus*	*A. koreana*	Jeong *et al.*, 2007
36.	*Staphylococcus simulans*	*A. koreana*	Jeong *et al.*, 2007
37.	*Shigella boydii*	*A. spectabilis*	Gautam *et al.*, 2022
38.	*Shigella dysenteriae*	*A. spectabilis*	Vishnoi *et al.*, 2007; Gautam *et al.*, 2022
39.	*Shigella flexneri*	*A. koreana* *A. spectabilis*	Jeong *et al.*, 2007; Gautam *et al.*, 2022
40.	*Shigella soneii*	*A. spectabilis*	Gautam *et al.*, 2022
41.	*Streptococcus mutans*	*A. spectabilis*	Timothy *et al.*, 2021
42.	*Streptococcus pneumoniae*	*A. holophylla*	Lee *et al.*, 2014
43.	*Streptococcus pyogenes*	*A. cilicica* *A. holophylla*	Kizil *et al.*, 2002; Lee *et al.*, 2014
44.	*Vibrio cholerae*	*A. spectabilis*	Vishnoi *et al.*, 2007; Gautam *et al.*, 2022

FUNGI			
No.	**Tested microbe**	***Abies* species**	**References**
1.	*Aspergillus niger*	*A. cilicica* *A. spectabilis*	Vishnoi *et al.*, 2007; Saleh & Al-Mariri, 2016
2.	*Candida albicans*	*A. alba* *A. cilicica* *A. sibirica* *A. nordmanniana* *A. koreana* *A. spectabilis*	Bağci & Diğrak, 1996; Kizil *et al.*, 2002; Oh *et al.*, 2007; Vishnoi *et al.*, 2007; Saleh & Al-Mariri, 2016; Noreikaitė *et al.*, 2017; Salamon *et al.*, 2019; Timothy *et al.*, 2021
3.	*Candida glabrata*	*A. holophylla*	Lee & Hong, 2009
4.	*Candida utilis*	*A. nordmanniana*	Sakar *et al.*, 1998
5.	*Cryptococcus neoformans*	*A. holophylla*	Lee & Hong, 2009
6.	*Kluyveromyces fragilis*	*A. cilicica*	Dayisoylu *et al.*, 2009
7.	*Rhodotorula rubra*	*A. cilicica*	Dayisoylu *et al.*, 2009
8.	*Saccharomyces cerevisiae*	*A. cilicica* *A. nordmanniana* *A. numidica* *A. koreana*	Bağci & Diğrak, 1996; Sakar *et al.*, 1998; Dayisoylu *et al.*, 2009; Ramdani *et al.*, 2014
VIRUSES			
No.	**Tested microbe**	***Abies* species**	**References**
1.	Influenza virus	*A. sibirica* *A. beshanzuensis*	Boldyrev *et al.*, 2000; Safatov *et al.*, 2000; Safatov *et al.*, 2005; Hu *et al.*, 2016
2.	Vaccinia virus	*A. sibirica*	Sokolova *et al.*, 2018

CONCLUSIONS – *Zaključci*

After conducting research, it is established that 13 different species of the genus *Abies* were investigated in terms of antimicrobial potential, namely *Abies alba*, *A. cilicica*, *A. nordmanniana*, *A. numidica*, *A. sibirica*, *A. koreana*, *A. balsamea*, *A. concolor*, *A. spectabilis* (syn. *A. webbiana*), *A. holophylla*, *A. firma*, *A. beshanzuensis*, and *A. cephalonica*. All listed species exhibit antibacterial, antifungal, or antiviral properties, due to their various secondary metabolites. According to the number of published results, the most investigated species is *A. spectabilis* (syn. *A. webbiana*), with eight published studies; followed by *A. alba* with seven studies; *A. cilicica* and *A. sibirica* with six studies; *A. nordmanniana*, *A. numidica*, *A. koreana*, *A. balsamea*, and *A. holophylla* with three studies; *A. concolor* with two studies; and *A. firma*, *A. beshanzuensis*, and *A. cephalonica* with one published research regarding the antimicrobial activity for every species. Overall insight revealed that the most investigated plant product of *Abies* species in terms of antimicrobial activity was essential oil, followed by the analysis of different extracts, resin, honeydew honey, and individual compounds isolated from particular species. The vast number of reviewed studies debate the antibacterial effects of different *Abies* products, including the impact on multidrug-resistant pathogens. Furthermore, antifungal investigations were also detected, as well as studies directed toward the identification of natural antiviral compounds.

Since there are endemic species in the genus *Abies* (Xiang *et al.*, 2018), investigations of bioactive potential should consider that fact, mostly because of the sampling behavior, but also in terms of correct understanding of generated results. This review noticed that some endemic *Abies* species were investigated in terms of antimicrobial potential: *A. koreana* (Korea Peninsula), *A. cephalonica* (Greece), *A. firma* (Japan), *A. numidica* (Algeria), and *A. beshanzuensis* (China). Furthermore, the conservation status of the reviewed species varies from least concern to critically endangered. Thus, the near-threatened *Abies* species that are likely to become endangered in the near future are *A. holophylla*, *A. cilicica*, and *A. spectabilis*; *A. koreana* holds endangered status, and it is characterized by a higher risk of extinction in the wild; while *A. numidica* and *A. beshanzuensis* are considered critically endangered species with the highest risk of extinction in the wild. Due to the presented issues, bioprospecting of novel antimicrobial agents from mentioned species should be rationalized, and due to the already recognized antimicrobial potential, conservational practices and *in vitro* elicitation of desirable chemical compounds should be implemented.

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SAŽETAK

Antimikrobna rezistencija predstavlja jedan od najvećih izazova globalnog zdravlja kod ljudi. Teške infekcije uzrokovane mikroorganizmima razlog su velikog broja smrtnih slučajeva diljem svijeta svake godine. Osim smanjene učinkovitosti, sintetski antimikrobni lijekovi mogu imati i veći broj nuspojava, te ozbiljne toksikološke implikacije. Sve navedeno ilustrira potrebu za pronalaskom novih prirodnih antimikrobnih supstanci. Biljke su oduvijek korištene u svrhe liječenja, a moderna nauka potvrđuje njihov veliki bioaktivni potencijal, koji se najprije odnosi na veliki hemijski diverzitet njihovih sekundarnih metabolita. Ova pregledna studija razmatra dobro poznati četinarski rod *Abies* Mill. (jela) kao potencijalni izvor antimikrobnih spojeva. Studija je pretragom naučnih baza podataka izdvojila i analizirala objavljene podatke o antimikrobnom djelovanju različitih vrsta roda *Abies*. Analiza podataka je pokazala da je ukupno 13 različitih vrsta istraživanog roda izučavano u antimikrobnom smislu (Grafikon 1). Kao najviše istraživana vrsta, prema broju publiciranih naučnih članaka, izdvojila se vrsta *A. spectabilis* (syn. *A. webbiana*). Najčešće testirani produkti *Abies* vrsta su bili eterična ulja i ekstrakti (Slika 1). Najveći broj analiziranih istraživanja je testirao antibakterijske odlike, ali su detektovane i studije o antifungalnom i antivirusnom potencijalu *Abies* vrsta. Najširi spektar antimikrobnog djelovanja uočen je kod vrste *A. cilicica* (Grafikon 2). Detaljan pregled antimikrobnog potencijala *Abies* vrsta je prezentiran u Tabeli 1. Ovaj pregled je uočio da su kao potencijalni izvori antimikrobnih supstanci analizirane i određene endemične vrste jela, uključujući i one koje konzervacijski status opisuje kao kritično ugrožene. U tom smislu, potrebno je implementirati racionalne strategije sakupljanja, kao i optimalnu metodologiju identifikacije i izolacije aktivnih supstanci. Kod ugroženih i endemičnih vrsta sa antimikrobnim potencijalom, ističe se posebna potreba za primjenom različitih metoda konzervacije, s ciljem očuvanja nativnih populacija. S obzirom da ovaj pregled literature potvrđuje veliki antimikrobni potencijal roda *Abies*, buduća istraživanja trebaju biti usmjerena na izolaciju pojedinačnih komponenti, uz poštivanje mjera racionalnog sakupljanja i eventualne implementacije *in vitro* elicitacije željenih supstanci.

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