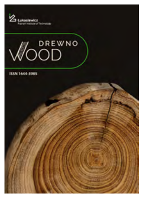
Article citation info:
Gürgen A., Uysal İ, Ünlü N., Sevindik M. 2025. The Power of Sandalwood (*Santalum album*): Industrial Use, Biological Activity, and Phytochemical Contents. *Drewno. Prace naukowe. Doniesienia. Komunikaty*. https://doi.org/10.53502/wood-202680

Łukasiewicz Poznań Institute of Technology

Drewno. Prace naukowe. Doniesienia. Komunikaty
Wood. Research papers. Reports. Announcements

Journal website: https://drewno-wood.pl



The Power of Sandalwood (*Santalum album*): Industrial Use, Biological Activity, and Phytochemical Contents

Ayşenur Gürgen[a*]
İmran Uysal[a]
Nida Ünlü[b]
Mustafa Sevindik[a]

[a] Osmaniye Korkut Ata University, Osmaniye, Turkey
[b] Niğde Ömer Halisdemir University, Niğde, Turkey

Article info
Received: 11 August 2024
Accepted: 6 March 2025
Published: 16 May 2025

Keywords
industrial use
sandalwood
biological activity
chemical contents

Plants consist of organic materials that are utilized by people worldwide for a variety of purposes. Pharmacological properties, nutritive qualities, and industrial applications are some of their distinguishing attributes. To determine the extent to which plants can be utilized, it is essential to evaluate their functional qualities. In this study, information on *Santalum album* (sandalwood) is compiled from the existing literature. This includes data on the biological activity of *S. album*, its phytochemical components, industrial applications, and actions against plant diseases. The literature shows that *S. album* possesses considerable antioxidant antimicrobial, and anticancer characteristics, which make it an extremely important natural resource. In addition to this, it has been revealed to be a potential source of a variety of chemical substances that are documented to be contained within it. It has also been demonstrated to be effective against diseases that affect plants. In terms of its industrial application, the species has been shown to fulfill a variety of roles, in such fields as paper production, furniture manufacture, and landscaping. The literature review shows that *S. album* has the capacity to perform a range of functions based on both biological and practical properties.

DOI: 10.53502/wood-202680

Introduction

Plants have been used by humans for a variety of purposes since prehistoric times. In addition to being important natural resources in the realm of medicine, plants are distinguished by their nutritional attributes (Gürgen et al., 2024). Numerous studies have proven that plants possess a variety of useful properties, such as antioxidant, antiproliferative, anti-aging, anti-inflammatory, anticancer, antimicrobial, hepatoprotective, and DNA protective capabilities (Unal et al., 2022; Sevindik et al., 2023a; Uysal et al., 2023; Mohammed et al., 2024). The evaluation of the biological characteristics of plants is of the utmost importance in the context of their application in medicine (Mohammed et al., 2022). The purpose of this study is to present a comprehensive review of the numerous properties of the plant *Santalum album* (sandalwood) that have been reported in previous research. Apart from general attributes, these properties include biological activity, potential for application in the fight against plant diseases, industrial potential, and chemical components.

* Corresponding author: aysenurgurgen@osmaniye.edu.tr

General characteristics and uses of *Santalum album*

Santalum album has a wide distribution, and is very common in such regions as India and Southeast Asia. Typically, the height of a sandalwood tree can range from 12 to 15 meters. In its early phases of development, it is most likely to flourish in locations that receive a restricted amount of sunlight. Grazing and fire are two environmental elements to which it may be vulnerable. A wide range of colors can be seen in the bark of sandalwood, including dark brown, reddish, dark gray, and sometimes practically black. The leaves are normally symmetrical, oval, or elliptical in shape, and they are thin and smooth along their edges. A bluish-purple coloration can be seen in the blooms. A spherical shape, a fleshy texture, and the presence of hard seeds are all characteristics of the fruit (Benencia and Courreges, 1999; Burdock and Carabin, 2008; Sindhu et al., 2010; Kausar et al., 2014; Kumar et al., 2015). The oil that is extracted from the seeds and leaves of the sandalwood plant is extensively used for its therapeutic properties. These include sedative, diuretic, expectorant and antipyretic properties, as well as uses in the treatment of bronchitis, gonorrhea, scabies, hemorrhoids, gastrointestinal problems, eye infections, dandruff and hair problems, muscle spasms, skin disorders, ulcers, headaches, and hiccups (Dikshit, 1984; Desai et al., 1991; Prasad et al., 2007; Misra and Day, 2013; Kumar et al., 2015; Moy and Levenson, 2017). Additionally, the tree is utilized in the production of wooden decorative items; the oil extracted from the tree and the flower of the plant are utilized in the cosmetics and perfume industry; the seed is utilized in oil paints; and the root, bark, and leaf components of the plant are used in the treatment of those suffering from liver diseases (Khan et al., 2021; Nazar et al., 2022; Aftab et al., 2023).

As the literature data show, sandalwood (*S. album*) is an important tree species both ecologically and economically. Its adaptation to tropical and subtropical climates has enabled it to spread over a wide geographical area. However, despite this prevalence, it faces various threats in its natural habitats. Especially fires and overgrazing can negatively affect the growth of young saplings and make natural renewal difficult. The morphological structure of the plant reveals various features that it has developed to adapt to its environment. Its wood bark, which can be found in different colors, provides protection against external factors, while the bluish-purple tones of its flowers may be a feature that supports pollination. The fleshy structure and hard seed of its fruit are indicators of an adaptation that allows its seeds to be spread by animals. Sandalwood has a wide range of uses in the medical and cosmetic fields, especially due to the essential oils that it contains. It is widely used in aromatherapy thanks to its soothing and relaxing effects, and is also known to be beneficial in skin and hair care. However, this high commercial value may lead to overexploitation over time and threaten natural populations. Therefore, the development of sustainable agricultural methods and conscious consumption are of great importance. There are regions where sandalwood is in danger of extinction due to its valuable wood and oil. Careful policies should be developed for the cultivation and harvesting of this species to protect natural resources and maintain the ecological balance. Controlled production and reforestation efforts can play a critical role in both ecological and economic sustainability.

Biological activity

In their natural environment, plants have developed defense mechanisms to protect themselves from a variety of external factors. This results in the production of secondary metabolites that are of fundamental importance to biological processes. The secondary metabolites produced by a plant are the primary markers of its biological activity (Mohammed et al., 2020; Mohammed et al., 2023a). In our research, we collated the investigations on the biological activity of *S. album* that have been reported in the literature. In these studies, a variety of extracts have been utilized. These include n-hexane, methanol, aqueous, ethanol, acetone, callus extract, sandalwood oil, chloroform, ethyl acetate, butanol, hydroalcoholic, diethyl ether, essential oil, petroleum ether, and dichloromethane. Table 1 provides a summary of studies that have been conducted into the biological activity of *S. album*.

Antioxidant activity

The production of oxidant chemicals occurs in various quantities in every living organism due to metabolic activity. These oxidant compounds are safe in low concentrations, but when present in higher concentrations, they have the potential to cause considerable damage to cells (Gürgen and Sevindik, 2022). The antioxidant defense system is responsible for reducing or eliminating the effects of oxidant substances (Bal et al., 2023). However, there are some circumstances in which the concentrations of oxidant chemicals can be high enough to render the antioxidant defense system insufficient, which ultimately results in the occurrence of oxidative stress conditions (Krupodorova and Sevindik, 2020). There is a correlation between oxidative stress and DNA and RNA damage, which in turn can play a role in the development of neurological diseases, diabetes, cancer, and cardiovascular issues (Mushtaq et al., 2020; Selamoğlu et al., 2020; Mohammed et al., 2021a). Antioxidants

Table 1. Biological activities of *Santalum album*

Biological activities	Solvents	Used parts	Geographic regions	References
Antioxidant, antimicrobial, hepatoprotective, antihyperglycemic and antihyperlipidemic, cytotoxic, antihelmintic, anti-inflammatory, antiviral, anticancer, larvicidal	n-hexan, methanol, aqueous, ethanol, acetone, callus extract, sandalwood oil, chloroform, ethylacetate, butanol, hydroalcoholic, diethyl ether, essential oil, petroleum ether, dichloromethane	Fruit, Whole plant, callus, heartwood, seed, leaf, stem, wood, bark	South Korea, India, Pakistan, Malaysia, Indonesia, Iran, Austria, China, America, Japan	(Jirovetz et al., 2006; Kumar et al., 2006; Kim, 2008; Zhu et al., 2008; Matsuo and Mimaki, 2010; Patil et al., 2011; Hire and Dhale, 2012; Kulkarni et al., 2012; Misra and Dey, 2012; Tu et al., 2013; Karunakar et al., 2014; Matsuo et al., 2014; Mishra et al., 2014; Shamsi et al., 2014; Gupta and Chaphalkar, 2015; Santha and Dwivedi, 2015; Damle et al., 2016; Surain et al., 2016; Sharmila et al., 2017; Shivatare and Nagore, 2018; Gull et al., 2019; Shivatare, 2020; Umdale et al., 2020; Shivashankara et al., 2021; Yousefsani et al., 2022; Suastika et al., 2023)

taken in supplement form have the potential to effectively diminish the effects of oxidative stress (Bal et al., 2022). Plants are very important natural sources of supplemental antioxidants. In the literature reviewed in this review, many studies on the antioxidant capacity of *S. album* are included. In a study conducted in South Korea, the antioxidant properties of extracts obtained from *S. album* using n-hexane, methanol, ethanol, acetone and water solvents were evaluated and the analyses were carried out with the DPPH test. As a result of the study, 50% lethal concentration (LC_{50}) values were reported as 871.2 µg/mL for n-hexane, 35.8 µg/mL for methanol, 47.2 µg/mL for ethanol, 18.6 µg/mL for acetone and 57.8 µg/mL for water, respectively (Kim, 2008). In another study conducted in India, the antioxidant capacity of aqueous and methanolic extracts obtained from *S. album* was evaluated by tests such as phosphomolybdenum, ABTS, FRAP and DPPH. As a result of the ABTS test, 18.26 mg TE/100 g was obtained for the aqueous extract and 96.16 mg TE/100 g for the methanolic extract. According to the FRAP test, the amount of Fe(II) was found to be 24.27 mg/100 g in the aqueous extract and 78.27 mg/100 g in the methanolic extract. In the DPPH test, the aqueous sample showed an activity of 8.32%, while this rate was determined as 83.95% in the methanolic sample. In the phosphomolybdenum test, the total antioxidant capacity of the aqueous extract was reported as 2.01 mg AAE/100 g, while this value was reported as 1.76 mg AAE/100 g in the methanolic extract (Umdale et al., 2020). In another study conducted in Malaysia, antioxidant capacities of callus extract and sandalwood oil extracts obtained from the callus section of *S. album* were investigated using reducing power determination, hydroxyl radical scavenging, metal ion chelating activity, FRAP, total antioxidant capacity, NO free radical scavenging, ABTS, DPPH and lipid peroxidation inhibition tests. In this context, 0.13 µg/mL and 0.14 µg/mL values were obtained for callus extract and sandalwood oil in the reducing power test. In the hydroxyl radical scavenging test, callus extract showed 94.5% and sandalwood oil showed 98.3% activity. In the metal ion chelating test, callus extract reached 1025.5 µg/mL and sandalwood oil reached 23.5 µg/mL values. As a result of the FRAP test, callus extract exhibited an activity level of 55 µM Fe(II)/g and sandalwood oil exhibited an activity level of 1056 µM Fe(II)/g. As a result of the total antioxidant capacity test, callus extract reached 61.2 µmol/g. In the NO radical scavenging test, callus extract showed an activity level of 0.5% and sandalwood oil showed an activity level of 4.2%. According to the ABTS test, extract concentrations of 175 mM/100 mg and 4.5 mM/100 mg were determined for callus extract and sandalwood oil. In the DPPH test, LC_{50} values were calculated as 1.17 µg/mL for callus extract and 0.87 µg/mL for sandalwood oil. Finally, in the lipid peroxidation inhibition test, the LC_{50} value was determined as 4.8 µg/mL for callus extract and 12.4 µg/mL for sandalwood oil (Misra and Dey, 2012). The antioxidant properties of various extracts obtained from the wood part of *S. album* were investigated in a study conducted in Pakistan using different solvents such as n-hexane, chloroform, acetone, ethylacetate, ethanol, butanol and water. The evaluation was done by DPPH test and the highest inhibition rate was reported in the ethanol extract with 84.3% (Gull et al., 2019). In another study conducted in Indonesia, the antioxidant capacity of sandalwood oil obtained from *S. album* was evaluated by FRAP and DPPH tests; FRAP value was reported as 484.51 mg/L and DPPH value as 36 mg/L (Suastika et al., 2023). In another study conducted in India, the antioxidant capacity of the aqueous extract obtained from *S. album* callus was investigated using DPPH, FRAP and hydroxyl radical scavenging tests. As a result of these tests, it was reported that the DPPH inhibition rate was between 11.2% and 48.7%, the FRAP value was between 0.3–1.0 μmol/mL and the hydroxyl radical scavenging capacity was between 14.5% and 53.2% (Shivashankara et al., 2021). In another study, the antioxidant activity of the methanol extract obtained from *S. album* seeds was analyzed by DPPH test and the EC_{50} value was reported to be in the range of 3.9–4.1 mg/mL (Shivatare, 2020). In another study from India, it was reported that the EC_{50} percentage of the ethanol extract obtained from *S. album* seeds varied between 49.96% and 74.85% according to the DPPH test (Shivatare and Nagore, 2018). In another study conducted in India, the total antioxidant capacity of the extract obtained from *S. album* leaves was evaluated using silver nanoparticles; DPPH radical scavenging activity was reported as 7.56 mg/g and reducing power as 28.5 mg/g (Damle et al., 2016). In another study, it was reported that the aqueous extract obtained from *S. album* had high antioxidant potential with DPPH and FRAP tests (Shamsi et al., 2014). All these findings clearly show that the *S. album* plant has the potential to be evaluated as a strong natural antioxidant source.

Studies on the antioxidant capacity of *S. album* (sandalwood) show that the antioxidant activity of extracts obtained using different solvents varies. It is noteworthy that extracts prepared with organic solvents such as methanol and ethanol show higher antioxidant activity than those using water-based solvents. This may be linked to solubility properties resulting from polarity differences of antioxidant compounds. The values obtained in tests vary depending on the method used and the part of the plant from which the extract was taken. Variation in the results seen especially in tests such as DPPH, ABTS and FRAP may be directly related to environmental factors in the place where the plant grows, extraction conditions, and chemical content. In addition, studies comparing the antioxidant activities of callus extract and sandalwood oil show that different parts of the plant offer different antioxidant capacities. These results support the conclusion that sandalwood can be used as a natural antioxidant source. However, a more detailed investigation of issues such as bioavailability, toxicity and interactions is important for determining safer and more effective uses in the medical and pharmacological fields. To exploit the potential of sandalwood compounds in the pharmaceutical and food industries, further biochemical analyses are needed. In particular, *in vivo* studies may provide a better understanding of the real effects of these compounds on human health.

Antimicrobial activity

Microorganisms play a crucial part in the development of a wide variety of chronic disorders. Today, antibiotics are utilized in the fight against microorganisms (Sevindik et al., 2024). Nevertheless, the effectiveness of these antimicrobial drugs has become insufficient. It is believed that the most important factor contributing to this situation is the excessive use of antibiotics, which has led to the spread of drug-resistant germs (Islek et al., 2021; Saridogan et al., 2021). Natural antimicrobial resources have become a primary focus of research, because of the potential harmful responses that are linked with the medications currently available (Baba et al., 2020; Eraslan et al., 2021; Sevindik et al., 2023b). Plants play a crucial role as natural sources of antimicrobial activity (Sevindik et al., 2017). A review of literature data on *S. album* revealed a number of reports concerning its antimicrobial properties. In a study carried out in Pakistan, researchers studied the antimicrobial activities of a number of different extracts produced from the heartwood of *S. album*. A variety of solvents, including n-hexane, chloroform, acetone, ethylacetate, ethanol, butanol, and water, were utilized in the testing process. An evaluation was conducted to determine whether the plant was effective against the bacteria *Staphylococcus aureus*, *Escherichia coli*, *Streptococcus pyrogenes*, *Shigella sonnei*, and *Neisseria gonorrhoeae*. It was found that the inhibition zone values of the strains used lay between 15 and 16.33 mm (Gull et al., 2019). In a study conducted in India, the antimicrobial effects of aqueous extracts obtained from the leaves and stems of the Santalum album plant were evaluated, and the inhibition levels of these extracts on Escherichia coli, Staphylococcus aureus and Pseudomonas species were compared. As a result of the study, it was reported that the leaf extract showed higher inhibition against all test microorganisms compared to the stem extract (Kumar et al., 2006). Another independent study conducted in India concerned the effectiveness of an aqueous extract obtained from *S. album* against several microorganisms, including *Bacillus subtilis*, *Aeromonas* sp., *S. aureus*, *E. coli*, *Klebsiella pneumoniae*, *K. oxytoca*, and *P. aeruginosa*. The largest inhibition percentage (78.1%) was obtained against *E. coli* (Shamsi et al., 2014). A separate study conducted in India reported that diethyl ether, n-hexane, methanol, water extracts and essential oils of *S. album* were effective against *E. coli, S. aureus, K. pneumoniae, P. aeruginosa, P. valgaris, P. syringae, X. malvacearum, S. typhi, B. cereus* and *E. fecalis* at different concentrations (Hire and Dhale, 2012). The bacteria *S. aureus*, *E. coli*, *K. pneumoniae*, *P. aeruginosa*, and *Candida albicans* were tested in a study carried out in Austria to evaluate the antimicrobial effectiveness of essential oil extracted from the heartwood of *S. album*. Of the strains investigated, the highest inhibition zone size (15 mm) was obtained for *S. aureus* (Jirovetz et al., 2006). In a separate study conducted in India, the antimicrobial abilities of palladium nanoparticles synthesized from an extract of *S. album* leaves were tested for their ability to inhibit the growth of bacteria such as *E. coli, P. aeruginosa, S. aureus* and *B. subtilis*. According to the findings of the study, the largest inhibition zone was reported as 31 mm in diameter against *E. coli* (Sharmila et al., 2017). In a further study in India, the antimicrobial activities of ethanol, methanol, acetone, petroleum ether, and dichloromethane extracts produced from the bark of *S. album* were investigated against *C. albicans* and *C. krusei*. The inhibition zone for *C. albicans* was found to be the larger, at 34.6 mm (Surain et al., 2016). Another Indian study concerned the antimicrobial capabilities of an ethanol extract obtained from the seeds of *S. album*, using the pathogens *B. subtilis*, *S. aureus*, *P. aeruginosa*, *E. coli*, and *C. albicans*. The largest inhibition zone (9.01 mm) was obtained against *B. subtilis* (Patil et al., 2011).

Studies on the antimicrobial properties of *S. album* have shown that extracts obtained using different solvents and different parts of the plant exhibit varying levels of antimicrobial and antifungal activity. While the most tested bacteria in the studies include *S. aureus, E. coli, B. subtilis* and *K. pneumoniae, C. albicans* has also been frequently examined as a fungal species. It is particularly noteworthy that heartwood and leaf extracts from the plant have significant antimicrobial activity. This suggests that the biologically active compounds contained in sandalwood act against microorganisms through different mechanisms. While the fact that heartwood extracts create higher inhibition zones reveals the effect of the volatile oils and phenolic compounds they contain, leaf extracts are also seen to be effective against certain pathogens. However, it is understood that extraction methods and solvent selection significantly affect antimicrobial activity. It would be beneficial for future studies to include more detailed analyses to determine the antimicrobial effects of specific components of *S. album*. In particular, examining the mechanisms of action of compounds derived from the plant at the molecular level may provide a better understanding of the potential of sandalwood for pharmaceutical and medical uses. In addition, with the increasing problem of antimicrobial resistance, compounds derived from natural sources such as *S. album* are expected to play an important role in the development of new-generation antimicrobial agents.

Anticancer and cytotoxic activity

In recent years, in response to the increase in cancer-related mortality and morbidity rates, researchers have begun to develop various therapeutic approaches. Among these approaches, herbal medicines are the focus of many studies (Sevindik et al., 2020; Mohammed et al., 2021a). Studies evaluating the anticancer properties of *S. album* are also included in the literature. In a study conducted in Iran, the cytotoxic potential of the hydroalcoholic extract obtained from *S. album* was investigated. In this study, the effects of the extract on human melanoma cell lines A375 and SK-MEL-3 and normal human fibroblast cell line AGO-1522 were evaluated. The findings revealed that the cell death rate was significantly increased in A375 and SK-MEL-3 melanoma cells (Yousefsani et al., 2022). In another study conducted in Japan, the cytotoxic effects of the methanol extract obtained from the wood part of *S. album* were investigated. In the study, the effects of the extract on human promyelocytic leukemia cells (HL-60), human lung adenocarcinoma cells (A549), human oral squamous cell carcinoma cell lines (HSC-2 and HSC-4) and normal human diploid fibroblast cell line TIG-3 were evaluated. According to the findings, the LC_{50} value observed in HL-60, A549, HSC-2, HSC-4 and TIG-3 cell lines was found to be above 40 μM (Matsuo et al., 2014). In another experiment conducted in Japan, the cytotoxic effects of the ligand called (7R,8R)-5-O-demethylbilagrewin isolated from the wood part of *S. album* were investigated. The effects of this compound on human promyelocytic leukemia cells (HL-60) and human lung adenocarcinoma cells (A5509) were investigated. As a result of the research, LC_{50} values were reported as 1.5–4.3 μM for HL-60 cells and 13.6–19.9 μM for A5509 cells (Matsuo and Mimaki, 2010). It has been determined that α-santalol, a sesquiterpene obtained from sandalwood, exhibits anticancer properties in various cancer models. These studies include chemically induced skin carcinogenesis models in CD-1 and SENCAR mice, ultraviolet-B induced skin carcinogenesis models in SKH-1 mice, and in vitro models for melanoma, non-melanoma skin cancers, breast and prostate cancer (Santha and Dwivedi, 2015). In another study conducted in India, the potential anticancer effects of the extract obtained from *S. album* seeds with dichloromethane were evaluated. In this study conducted on the human breast cancer-associated MDA-MB-231 cell line, the LC_{50} value was determined as 2.06 μg/mL (Mishra et al., 2014).

Studies on the anticancer properties of *S. album* have shown that extracts and specific components obtained from the plant can have cytotoxic effects against various cancer cell lines. In particular, it has been observed that sesquiterpenes specific to sandalwood, such as α-Santalol, are effective against cancer cells by inducing programmed cell death (apoptosis) and stopping the cell cycle. It is noteworthy that the cytotoxicity levels of extracts obtained using different solvents vary between studies. This is important in terms of understanding how the extraction method and the solvent used affect the bioavailability of the plant components. In addition, the fact that sandalwood acts only on cancer cells and exhibits lower toxicity to healthy cells indicates that this plant can be considered a selective anticancer agent. It is important that future studies examine the molecular mechanisms of the active components obtained from sandalwood in more detail and determine how they act, especially in cancer cells. In this context, focusing on *in vivo* studies and clinical studies will contribute to a better understanding of the pharmacological potential of sandalwood.

Other activity

S. album is among the plants that have been intensively researched in the scientific literature due to its antioxidant, antimicrobial and anticancer properties. In addition to these basic properties, there are also studies on some other biological effects of *S. album*. In a study conducted in India, the hepatoprotective (liver-protective) properties of the hydroalcoholic extract obtained from *S. album* leaves were investigated. According to the study findings, the hydroalcoholic extract administered orally showed a significant protective effect against carbon tetrachloride (CCl_4) and paracetamol-induced liver damage. *S. album* leaf extract administered at doses of 200 and 400 mg/kg provided significant decreases in serum enzyme levels, bilirubin amounts and lipid peroxidation rates against toxicity in the liver (Karunakar et al., 2014). In another study conducted in India, the hypoglycemic effects of *S. album* and their roles on lipid disorders were investigated. In this study, pet ether fraction of *S. album* was administered orally to rats with 70 mg/kg body weight twice daily for 60 days. As a result, a significant decrease in blood sugar levels was observed by an average of 140 mg/dL. The extract concentration was determined as 10 μg/kg (Kulkarni et al., 2012). In another study conducted in China, the antiparasitic effects of extracts obtained from *S. album* using chloroform, methanol, ethylacetate and water were evaluated. In the study, the effect of *S. album* against *Gyrodactylus elegans* and *Dactylogyrus intermedius* parasites seen in the golden fish species *Carassius auratus* was investigated. EC_{50} values of methanol and ethylacetate extracts on *G. elegans* were determined as 37.18 mg/L and 70.41 mg/L, respectively. The most effective methanol extract doses on *D. intermedius* were reported as 15.98 mg/L for EC_{50} and 27.19 mg/L for EC_{90} (Tu et al., 2013). In another study from India, the antiviral and anti-inflammatory effects of the aqueous extract obtained from *S. album* roots were evaluated. The immune system responses against hepatitis B surface antigen (HBsAg) and Newcastle disease virus (NDV) were examined; it was observed that the extract applied at high doses (0.5–30 mg/mL) in human peripheral blood mononuclear cells (PBMC) suppressed cell proliferation, nitric oxide production and CD14 monocyte surface markers. These findings revealed that *S. album* root extract has both antiviral and anti-inflammatory potential (Gupta and Chaphalkar, 2015). In another study conducted in China, the larvicide effect of essential oil obtained from *S. album* was investigated. The focus of the study was to determine the lethal effect on *Aedes albopictus*, *Aedes aegypti* and *Culex pipiens* species. At the applied dose of 0.2 mg/mL, LT_{50} and LT_{90} values were reported as 1.06 h and 3.24 h for *A. aegypti*, respectively. These times were determined as 1.82 and 3.33 h for *A. albopictus*, while a time to death of 1.55 h was recorded for *A. aegypti*. The LT value was reported as 3.91 h for *C. pipiens* (Zhu et al., 2008).

Studies on the biological effects of *S. album* show that this plant has diverse pharmacological properties. The verification of its hepatoprotective, hypoglycemic, antiparasitic, antiviral, anti-inflammatory and larvicidal effects in different experimental models reveals that the use of *S. album* in traditional medicine is based on scientific principles. In particular, its hepatoprotective and hypoglycemic effects may be related to basic disease mechanisms such as oxidative stress and inflammation. This suggests that *S. album* may be a potential phytotherapeutic agent in cases of liver diseases and metabolic disorders. Similarly, its antiparasitic and antiviral properties indicate that the bioactive components of the plant may have immunomodulatory effects. In the light of these findings, a more in-depth examination of the biological activities of *S. album* and the isolation of its bioactive components are of great importance. Future research should focus on determining its pharmacokinetic and toxicological profiles, especially with the support of clinical studies. In this way, it may be possible to introduce *S. album* to medical use in a safe and effective way.

Chemical contents

Plants are capable of producing bioactive compounds that boast a wide range of pharmacological capabilities (Mohammed et al., 2023b; Yazar et al., 2024). A number of studies have been carried out into the chemical composition of *S. album*. The findings are summarized in Table 2 and will be discussed below.

In a study conducted in China, the chemical composition of the root part of the *S. album* plant was analyzed and a large number of compounds were identified. These compounds include α-santhalene (1.0%), β-santhalene (1.7%), (E)-α-bisabolene (3.6%), bisabolenol C (2.4%), bisabolenol B (1.7%), β-bisabolol (2.5%), Z-α-santhalol (19.6%), (Z)-α-trans-bergamotol (2.5%), epi-β-santhalol

Table 2. Chemical contents of *Santalum album*

Geographic regions	Used Parts	Essential oil content	References
China	Root	α-santalene (1.0%), β-santalene (1.7%), (E)-α-bisabolene (3.6%), bisabolenol C (2.4%), bisabolenol B (1.7%), β-bisabolol (2.5%), Z-α-santalol (19.6%), (Z)-α-trans-bergamotol (2.5%), epi-β-santalol (2.0%), Z-β-santalol (12.5%), (Z)-nuciferol (3.9%), cis-β-santalol (1.5%), (Z)-lanceol (2.0%), (Z)-γ-curcumen-12-ol (1.8%), bisabolenol-A isomer 3 (8.9%), bisabolenol C isomer 1 (3.9%), bisabolenol B isomer 2 (7.0%), β-santaldiol (2.2%)	(Xin-Hua et al., 2012)
India, Sri Lanka, Italy, Austria, China, Germany	Heartwood, wood	α-santalol (35.0-54.28%), β-santalol (9.42-25.94%), (z)-α-transbergamotol (5.2-12%), (z)-lanceol (6.57%), epi-β-santalol (1.5-6.8%), docosahexaenoic acid (2.54%), β-trans-santalol (2.24%), β-costol (1.41%), (z)-β-curcumen12-ol (1.02-9.71%), cis-α-santalol (17.84-41.1%), cis-α-transbergamatol (0.15-5.89%), epi-α-bisabalol (0.47-1.98%), cis-β-santalol (6.35-17.38%), cis-nuciferol (0.65-3.4%), γ-curcumen12-ol (1.19-2.15%), cis -lanceol (0.47-4.63%), α-santalene (0.4-4.8%), β-santalene (1.2-6.92%), e-cis-epi-β-santalol (2.7-5.5%), trans-β-santalol (1.5-27.9%), epi-β-santalene (1.32-5.2%), α-santalal (1.9%), z-nuciferol (5.2%), pyrazine (7.7%), g-neoclovene (5.17%), cyclotetradecane (3.76%), n-hexadecane (3.35%), longifolene (2.94%), n-octadecane (2.35%), n-tetradecane (1.93%), teresantalol (1.90%), cis-α-bergamotene (2.54%), trans-α-santalol (0.4-18.54%)	(Braun et al., 2003; Marongiu et al., 2006; Jirovetz et al., 2006; McComb, 2009; Sindhu et al., 2010; Liu et al., 2013; Misra and Dey, 2013; Subasinghe et al., 2013; Krishnakumar and Parthiban, 2018; Bisht et al., 2019; Mohankumar et al., 2019; Bisht et al., 2020; Yan et al., 2020; Hoseini and Sharifi, 2023)

(2.0%), Z-β-santhalol (12.5%), (Z)-nuciferol (3.9%), cis-β-santhalol (1.5%), (Z)-lanceol (2.0%), (Z)-γ-curcumen-12-ol (1.8%), bisabolenol-A isomer 3 (8.9%), bisabolenol C isomer 1 (3.9%),, bisabolenol B isomer 2 (7.0%) and β-santaldiol (2.2%) (Xin-Hua et al., 2012). In various studies conducted in India, Sri Lanka, Italy, Austria, China and Germany, the chemical components obtained from the wood part and other lignified structures of *S. album* were studied in detail. The major compounds identified in these studies are: α-santhalol (35.0–54.28%), β-santhalol (9.42–25.94%), (Z)-α-trans-bergamotol (5.2–12%), (Z)-lanceol (6.57%), epi-β-santhalol (1.5–6.8%), docosahexaenoic acid (DHA) (2.54%), β-trans-santhalol (2.24%), β-costol (1.41%), (Z)-β-curcumen-12-ol (1.02–9.71%), cis-α-santhalol (17.84–41.1%), cis-α-trans-bergamatol (0.15–5.89%), epi-α-bisabolol (0.47–1.98%), cis-β-santalol (6.35–17.38%), cis-nuciferol (0.65–3.4%), γ-curcumen-12-ol (1.19–2.15%), cis-lanceol (0.47–4.63%), α-santalene (0.4–4.8%), β-santalene (1.2–6.92%), e-cis-epi-β-santalol (2.7–5.5%), trans-β-santalol (1.5–27.9%), epi-β-santalene (1.32–5.2%), α-santhalal (1.9%), Z-nuciferol (5.2%), pyrazine (7.7%), γ-neoclovene (5.17%), cyclotetradecane (3.76%), n-hexadecane (3.35%), longifolene (2.94%), n-octadecane (2.35%), n-tetradecane (1.93%), teresanthalol (1.90%), cis-α-bergamotene (2.54%) and trans-α-santhalol (0.4–18.54%) (Braun et al., 2003; Marongiu et al., 2006; Jirovetz et al., 2006; McComb, 2009; Sindhu et al., 2010; Misra and Dey, 2013; Krishnakumar et al., 2019; Bisht et al., 2020 and Sharifi, 2023).

Studies on the chemical composition of *S. album* have shown that the plant contains bioactive compounds in different proportions in its root, heartwood and other woody parts. The most notable of these compounds are the santalol isomers, and especially the proportions of α-santalol and β-santalol are of great importance in terms of the biological effects of the species. The fact that chemical components vary depending on regional and environmental factors emphasizes the effect of the geographical location where *S. album* grows and its genetic variations on the composition of the essential oil. This reveals the need for quality standardization in terms of pharmacological and industrial use. It is of great importance that future studies investigate the mechanisms of these bioactive compounds in more detail, supported by clinical studies, and determine their effective uses in pharmaceutical formulations.

Efficacy of *Santalum album* against plant diseases

Significant difficulties arise as a result of the existence of diseases and pests in places where plants are harvested. Both biotic and abiotic variables have a significant impact on the quality of the goods obtained as well as the amount of products that is lost. Bacteria, fungi, viruses, and pests such as worms, rodents, and slugs are the principal biotic agents that have a substantial impact. Other biotic agents might also have some effects (Mondal and Pal, 2015). There is currently a rising emphasis on alternative methods of controlling plant diseases and pests. This is because the utilization of synthetic pesticides has been discovered to have detrimental effects on the health of both humans and animals, in addition to disrupting the ecological balance (Balestra et al., 2009; Gurjar et al., 2012; Belgüzar et al., 2016). Research is increasingly focusing on novel methodologies as potential substitutes for chemical control and the synthesis of new chemical substances (Karabüyük and Aysan, 2019). The use of herbal extracts and essential oils obtained from plants that naturally possess antimicrobial characteristics is one route that might be taken. Plant-derived biochemicals are extremely promising since they are easily accessible and biodegradable, are not hazardous to humans or animals, and do not leave any residues in produce in which they are used (Hartmann, 2007; Mondal and Khalequzzaman, 2009; Al-Rezaa et al., 2010; Walia et al., 2017). Studies have been conducted on the use of extracts and essential oils derived from various plants, including *Thymus vulgaris*, *Cinnamomum ceylanicum*, *Eucalyptus globulus*, *Rosmarinus officinalis*, *Melaleuca alternifolia*, *Salvia officinalis*, *Lavandula stoechas*, *Tagetes minuta*, *Cistus ladaniferus*, *Satureja hortensis*, *Mentha pulegium*, *Allium sativum*, *Allium cepa*, *Carum carvi*, *Nigella sativa* and *Hypericum perforatum*, to combat plant diseases and pests. Such studies include those by Daferera et al. (2003), Iacobellis et al. (2005), Mihajilov-Krstev et al. (2010), Kotan et al. (2013), Gakuubi et al. (2016), Nikolova et al. (2017), Benali et al. (2020), Bozkurt et al. (2020), Steglińska et al. (2022), Kolozsváriné Nagy et al. (2023), and El-Chaghaby et al. (2024).

Several studies have investigated the effectiveness of extracts obtained from *S. album* in the treatment of plant diseases. An investigation carried out in China considered herbal extracts derived from 67 different Chinese medicinal herbs. *S. album*, which was one of these herbs, was tested against eight different plant pathogenic bacteria (*Acidovorax citrulli*, *Burkholderia cepacia*, *B. gladioli* pv. *gladioli*, *Pectobacterium carotovorum*, *P. chrysanthemi*, *Ralstonia solanacearum*, *Xanthomonas euvesicatoria*, and *X. citri* pv. *citri*). According to the results of the investigation, *S. album* did not demonstrate any antimicrobial activity (Feng et al., 2012). In another study, volatile oils that were generated from or contained *S. album* (Indian sandalwood) as well as 29 other plant species were put through a series of tests to determine how effective they were against the plant pathogenic bacteria *Erwinia amylovora*, *Xanthomonas campestris* pv. *campestris* and *Pseudomonas syringae* pv. The detrimental impact of these bacteria on plant production was evaluated using the agar-diffusion assay method *in vitro*. The researchers reported that *S. album* did not exhibit any discernible activity (Popović et al., 2018). In further research, seventeen different herbal essential oils, including *S. album*, were examined for antimicrobial effects against *Xylella fastidiosa*, a serious bacterial pathogen responsible for infectious diseases, and the study reported significant effects (Santiago et al., 2018). In a separate investigation, a number of different coating materials, such as chitosan (CH), zinc oxide nanoparticles (ZNPs), and Indonesian sandalwood essential oil (SEO), were tested in a variety of combinations (CH, CH/ZNPs, CH/SEO, and CH/ZNPs/SEO) to determine how effective they were against *Penicillium italicum*, a fungus that causes post-harvest losses in tangerines. SEO and ZNPs form an edible coating material that was discovered to have the potential to reduce reliance on chemical substances for post-harvest product coating The researchers discovered that a mixture that contained 0.8% CH, 0.025% ZNPs, and 0.5% SEO had the most effective anti-fungal impact against *Penicillium italicum* (Wardana et al., 2022).

Studies examining the effects of *S. album* on plant diseases and pests show that the antimicrobial and antifungal potential of this plant varies depending on certain conditions. In particular, some studies show that *S. album* is ineffective against certain bacteria, while it can exhibit antifungal activity in some combinations. These results emphasize that the biological activity of herbal extracts and essential oils should be evaluated not alone but with different formulations and synergistic compounds. New approaches, especially nanotechnology and biopolymer coating, have the potential to increase the effectiveness of herbal compounds. Although *S. album* has limited activity against certain pathogens, its use in combination with other herbal components may offer alternative biological solutions for agricultural disease control. Future studies may help develop innovative approaches to reduce dependency on chemical pesticides by investigating a broader spectrum of effects of these components and different application methods.

Industrial use

S. album (Santalaceae) is a tropical tree species used for a variety of purposes. A pleasant aroma, medicinal benefits, and a high-quality wood texture are some of the commercially useful characteristics that this tree possesses. Sandalwood is the material of choice for afforestation projects in some locations, and it can also be used with the goal of increasing the aesthetic appeal of an area (Ratnaningrum et al., 2016). Sandalwood is a commonly utilized ingredient in the fragrance industry (Kumar et al., 2015) and is favored in cosmetic products (Khan et al., 2021). The aroma of sandalwood is frequently used in aromatherapy due to its calming effects (Das and Khan, 2022). The use of this substance as a treatment for skin conditions in some civilizations has been documented (Hosen et al., 2023). On certain religious and spiritual occasions, sandalwood is used as an incense because of its aromatic properties (Yadav et al., 2020; Royyani et al., 2024). Sandalwood timber exhibits exceptional durability and is highly valued (Ramulu et al., 2021). It finds application in the production of furniture as well as in the cutting and shaping of wood (Liu et al., 2013; Bansal, 2021). Kavitha and Ramachandran (2016) report that the application of sandalwood extract to non-woven fabrics may enable the production of textiles with antimicrobial properties. Additionally, there is a possibility that sandalwood fibers can be exploited in the production of paper (Luo et al., 2021; Chan and Yi, 2023).

S. album (sandalwood) has a wide range of uses in different industries thanks to its unique properties. From its uses in the perfume and cosmetic sectors to its medicinal benefits, the versatile functionality of this tree contributes to its high commercial value. Sandalwood essential oil is used for both therapeutic and spiritual purposes due to its calming effects, and it has an important place in cultural practices. Continuing research on sandalwood's antimicrobial properties and potential textile uses show that the full potential of this tree needs to be explored. For example, the use of sandalwood extracts in textile and paper production may offer environmentally friendly solutions as an alternative to synthetic chemicals, a development that is in line with trends toward sustainability in production. This versatility underscores the importance of continuing investigation into the uses of sandalwood in the development of more sustainable and health-oriented consumer products. At a time of increasing demand for natural and environmentally friendly products, the discovery of applications for herbal substances such as sandalwood becomes even more important.

Conclusion and future perspectives

The majority of the global supply of sandalwood comes from India, Indonesia, and some Pacific islands. The dense and beautifully textured wood of this exceptional tree and the fragrant oil it produces contribute greatly to its significant value. This review has considered studies in existing literature that have investigated various aspects of sandalwood, such as its biological activity, chemical composition, and industrial applications. Sandalwood is thought to have the potential to be used as a food additive due to its antioxidant and antimicrobial properties. It has also been determined that it has natural properties that can effectively combat some diseases that may occur in plants. In the industrial sector, it is widely used in areas such as paper production and furniture-making. In addition, it has been shown that sandalwood has the potential to function as a natural storehouse of chemical compounds. Therefore, the evaluation of sandalwood as a versatile natural product is important in terms of developing a wide range of uses. Sandalwood has broad potential, in the light of current research and applications. In the future, a more in-depth study of the biological activity of sandalwood may lead to new discoveries, especially in areas such as cancer treatment. In addition, the antioxidant and antimicrobial properties that it provides for the food industry may play an important role in the search for natural additives. In terms of environmental sustainability, considering the rapidly depleting resources of sandalwood, it is of great importance to develop more efficient and sustainable agricultural techniques for the cultivation of this plant. In the industrial field, the biological and chemical properties of sandalwood will enable the development of natural and innovative products, especially in the cosmetics and pharmaceutical sectors. With this is mind, it is expected that sandalwood will find wider areas of application in the future, and its economic value will increase even more.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

References

Aftab, A., Sultana, S., Rashid, A., Akram, M., Anwar, H. (2023). *Santulum album*: medicinal and pharmacological properties. Journal of Medicine and Health Research, 9-14.

Al-Reza, S. M., Rahman, A., Ahmed, Y., Kang, S. C. (2010). Inhibition of plant pathogens in vitro and in vivo with essential oil and organic extracts of *Cestrum nocturnum* L. Pesticide Biochemistry and Physiology, 96(2), 86-92.

Baba, H., Sevindik, M., Dogan, M., & Akgül, H. (2020). Antioxidant, antimicrobial activities and heavy metal contents of some Myxomycetes. Fresenius Environmental Bulletin, 29(09), 7840-7846.

Bal, C., Baba, H., Akata, I., Sevindik, M., Selamoglu, Z., & Akgül, H. (2022). Biological activities of wild poisonous mushroom *Entoloma sinuatum* (Bull.) P. Kumm (Boletales). KSU J. Agric. Nat, 25(1), 83-87.

Bal, C., Eraslan, E. C., & Sevindik, M. (2023). Antioxidant, antimicrobial activities, total phenolic and element contents of wild edible mushroom *Bovista nigrescens*. Prospects in Pharmaceutical Sciences, 21(2), 37-41.

Balestra, G. M., Heydari, A., Ceccarelli, D., Ovidi, E., Quattrucci, A. (2009). Antibacterial effect of *Allium sativum* and *Ficus carica* extracts on tomato bacterial pathogens. Crop Protection, 28(10), 807-811.

Bansal, A. K. (2021). Sustainable trade of wood and wood based products in ındia. NCCF Policy Paper, 1(2021), 1-15.

Belgüzar, S., Yilar, M., Yanar, Y., Kadioğlu, İ., & Doğar, G. (2016). Antibacterial activities of *Thymus vulgaris* L. (thyme) extract and essential oil againts *Clavibacter michiganensis* subsp. michiganensis. Turkish Journal of Weed Science, 19(2), 20-27.

Benali, T., Bouyahya, A., Habbadi, K., Zengin, G., Khabbach, A., & Hammani, K. (2020). Chemical composition and antibacterial activity of the essential oil and extracts of *Cistus ladaniferus* subsp. ladanifer and *Mentha suaveolens* against phytopathogenic bacteria and their ecofriendly management of phytopathogenic bacteria. Biocatalysis and Agricultural Biotechnology, 28, 101696.

Benencia, F., Courreges, M. C. (1999). Antiviral activity of sandalwood oil against herpes simplex viruses-1 and-2. Phytomedicine, 6(2), 119-123.

Bisht, S. S., Chandra, G., Ravindra, M., Kumar, R. (2020). Evaluation of chemical and physical properties of commercial sandalwood essential oils and their comparison with essential oil extracted from *Santalum album* L. Journal of Essential Oil Bearing Plants, 23(2), 345-355.

Bisht, S. S., Ravindra, M., Gayathri, D. N. (2019). Variability in yield and composition of oil from Indian Sandalwood (*Santalum album* L.) trees grown in homogeneous conditions. Tropical Plant Research, 6(1), 31-36.

Bozkurt, İ. A., Soylu, S., Merve, K. A. R. A., & Soylu, E. M. (2020). Chemical composition and antibacterial activity of essential oils isolated from medicinal plants against gall forming plant pathogenic bacterial disease agents. KSU Journal of Agriculture and Nature, 23(6), 1474-1482.

Braun, N. A., Meier, M., Pickenhagen, W. (2003). Isolation and chiral GC analysis of β-bisabolols—trace constituents from the essential oil of *Santalum album* L.(Santalaceae). Journal of Essential Oil Research, 15(2), 63-65.

Burdock, G. A., Carabin, I. G. (2008). Safety assessment of sandalwood oil (*Santalum album* L.). Food and Chemical Toxicology, 46(2), 421-432.

Chan, C. K., & Yi, X. (2023). Raw Materials of Chinese Traditional Handmade paper. Paper and Biomaterials, 8(3).

Daferera, D. J., Ziogas, B. N., Polissiou, M. G. (2003). The effectiveness of plant essential oils on the growth of *Botrytis cinerea*, *Fusarium* sp. and *Clavibacter michiganensis* subsp. michiganensis. Crop Protection, 22(1), 39-44.

Damle, P., Hegde, D., Nayak, S., Vaman, C. R. (2016). Green synthesis of silver nanoparticles from *Santalum album* Tender leaf extract and evaluation of its antioxidant capacity. Indian Journal of Advances in Chemical Science S1, 253, 257.

Das, S.S., Khan, S.Y. (2022). Aromatherapy of *Santalum album* Linn. and its antiviral activity. Journal of Medicinal and Aromatic Plant Sciences, 44(1-2), 12-20.

Desai, V. B., Hiremath, R. D., Rasal, V. P., Gaikwad, D. N., Shankarnarayana, K. H. (1991). Pharmacological screening of HESP and sandal oils. Indian Perfumer, 35, 69-70.

Dikshit, A. (1984). Antifungal action of some essential oils against animal pathogens. Fitoterapia, 55, 171-176.

El-Chaghaby, G. A., Mohammed, F. S., Rashad, S., Uysal, I., Koçer, O., Lekesiz, Ö., Sevindik, M. (2024). Genus Hypericum: general properties, chemical contents and biological activities. Egyptian Journal of Botany, 64(1), 1-26.

Eraslan, E. C., Altuntas, D., Baba, H., Bal, C., Akgül, H., Akata, I., & Sevindik, M. (2021). Some biological activities and element contents of ethanol extract of wild edible mushroom *Morchella esculenta*. Sigma Journal of Engineering and Natural Sciences, 39(1), 24-28.

Feng, C. T., Su, H. J., Chen, C. T., Ho, W. C., Tsou, Y. R., Chern, L. L. (2012). Inhibitory effects of Chinese medicinal herbs on plant-pathogenic bacteria and identification of the active components from gallnuts of *Chinese sumac*. Plant Disease, 96(8), 1193-1197.

Gakuubi, M. M., Wagacha, J. M., Dossaji, S. F., Wanzala, W. (2016). Chemical composition and antibacterial activity of essential oils of *Tagetes minuta* (Asteraceae) against selected plant pathogenic bacteria. International Journal of Microbiology, https://doi.org/10.1155/2016/7352509.

Gull, S., Mushtaq, A., Umer, M., Mehmood, S. (2019). *Santalum album*: in vitro antibacterial and antioxidant activities of *Santalum album* and cymbopogon by sequential extraction. The Professional Medical Journal, 26(05), 717-722.

Gupta, A., Chaphalkar, S. R. (2015). Immunopharmacological screening of aqueous root extract of *Santalum album*. Journal of HerbMed Pharmacology, 5(1), 7-11.

Gurjar, M. S., Ali, S., Akhtar, M., Singh, K. S. (2012). Efficacy of plant extracts in plant disease management. Agricultural Sciences, 3(3), 19046.

Gürgen, A., Sevindik, M., Krupodorova, T., Uysal, I., Unal, O. (2024). Biological activities of *Hypericum spectabile* extract optimized using artificial neural network combined with genetic algorithm application. BMC Biotechnology, 24(1), 83.

Gürgen, A., & Sevindik, M. (2022). Application of artificial neural network coupling multiobjective particle swarm optimization algorithm to optimize *Pleurotus ostreatus* extraction parameters. Journal of Food Processing and Preservation, 46(11), e16949.

Hartmann, T. (2007). From waste products to ecochemicals: fifty years research of plant secondary metabolism. Phytochemistry, 68(22-24), 2831-2846.

Hire, K. K., Dhale, D. A. (2012). Antimicrobial effect and insilico admet prediction of *Santalum album* L. International Journal of Pharma and Bio Sciences, 3(4), 727-734.

Hoseini, E., Sharifi, A. (2023). Physicochemical properties evaluation of Sandalwood (*Santalum album* linn) essential oil nanoemulsion. Journal of Food Science and Technology (Iran), 19(133), 265-280.

Hosen, M. E., Supti, S. J., Akash, S., Rahman, M. E., Faruqe, M. O., Manirujjaman, M., 5 Acharjee, U. K., Gaafar, A.Z., Ouahmane, L., Sitotaw, B., Bourhia, M., Zaman, R. (2023). Mechanistic insight of *Staphylococcus aureus* associated skin cancer in humans by *Santalum album* derived phytochemicals: an extensive computational and experimental approaches. Frontiers in Chemistry, 11, 01-17.

Iacobellis, N. S., Lo Cantore, P., Capasso, F., Senatore, F. (2005). Antibacterial activity of *Cuminum cyminum* L. and *Carum carvi* L. essential oils. Journal of Agricultural and Food Chemistry, 53(1), 57-61.

Islek, C., Saridogan, B. G. O., Sevindik, M., & Akata, I. (2021). Biological activities and heavy metal contents of some *Pholiota species*. Fresenius Environmental Bulletin, 30(6), 6109-6114.

Jirovetz, L., Buchbauer, G., Denkova, Z., Stoyanova, A., Murgov, I., Gearon, V., Geissler, M. (2006). Comparative study on the antimicrobial activities of different sandalwood essential oils of various origin. Flavour and Fragrance Journal, 21(3), 465-468.

Karabüyük, F., Aysan, Y. (2019). Antibacterial effects of some plant extracts against tomato bacterial speck disease caused by *Pseudomonas syringae* pv. tomato. Journal of Tekirdag Agricultural Faculty, 16(2), 231-243.

Karunakar, H., Deepak, T. K., Kabitha, K. K. (2014). Hepatoprotective potential of hydroalcoholic extract of *Santalum album* Linn. leaves. International Journal of Pharmaceutical Sciences and Drug Research, 6(3), 224-228.

Kausar, H., Jahan, N., Ahmed, K., Aslam, M., Ahmed, P., Ahmed, S. (2014). Unani perspective and recent studies of sandal safed (*Santalum album* Linn.): a review. World Journal of Pharmacy and Pharmaceutical Sciences, 3(8), 2133-2145.

Kavitha, S., & Ramachandran, T. (2016). Antimicrobial finish on nonwoven fabric using sandalwood extract. In International Conference on Systems, Science, Control, Communication, Engineering and Technology, 2, 855-860.

Khan, S., Ikram, M., Faisal, M. (2021). Commercial, cosmetic, and medicinal importance of sandal (*Santalum album*): A valuable forest resource. Non-Timber Forest Products: Food, Healthcare and Industrial Applications, 129-144.

Kim, T. H. (2008). Antioxidative and biological activities of *Santalum album* extracts by extracting methods. Korean Journal of Food Preservation, 15(3), 456-460.

Kolozsváriné Nagy, J., Móricz, Á. M., Böszörményi, A., Ambrus, Á., Schwarczinger, I. (2023). Antibacterial effect of essential oils and their components against *Xanthomonas arboricola* pv. pruni revealed by microdilution and direct bioautographic assays. Frontiers in Cellular and Infection Microbiology, 13, 1204027.

Kotan, R., Dadasoğlu, F., Karagoz, K., Cakir, A., Ozer, H., Kordali, S., Dikbas, N. (2013). Antibacterial activity of the essential oil and extracts of *Satureja hortensis* against plant pathogenic bacteria and their potential use as seed disinfectants. Scientia Horticulturae, 153, 34-41.

Krishnakumar, N., Parthiban, K. T. (2018). Comparison of phytochemical constituents of the identified sandalwood (*Santalum album* L.) genetic resources in India. Journal of Essential Oil Bearing Plants, 21(3), 658-666.

Krupodorova, T., & Sevindik, M. (2020). Antioxidant potential and some mineral contents of wild edible mushroom *Ramaria stricta*. AgroLife Scientific Journal, 9(1), 186-191

Kulkarni, C. R., Joglekar, M. M., Patil, S. B., Arvindekar, A. U. (2012). Antihyperglycemic and antihyperlipidemic effect of *Santalum album* in streptozotocin induced diabetic rats. Pharmaceutical Biology, 50(3), 360-365.

Kumar, M. G., Jeyraaj, I. A., Jeyaraaj, R., Loganathan, P. (2006). Antimicrobial activity of aqueous extract of leaf and stem extract of *Santalum album*. Ancient Science of Life, 25(3-4), 6.

Kumar, R., Anjum, N., Tripathi, Y. C. (2015). Phytochemistry and pharmacology of *Santalum album* L.: a review. World Journal of Pharmaceutical Research, 4(10), 1842-1876.

Liu, X., Xu, D., Yang, Z., Zhang, N. (2013). Effects of plant growth regulators on growth, heartwood formation and oil composition of young *Santalum album*. Scientia Silvae Sinicae, 49(7), 143-149.

Luo, Y., Cigić, I. K., Wei, Q., & Strlič, M. (2021). Characterisation and durability of contemporary unsized Xuan paper. Cellulose, 28, 1011-1023.

Marongiu, B., Piras, A., Porcedda, S., Tuveri, E. (2006). Extraction of *Santalum album* and Boswellia carterii Birdw. volatile oil by supercritical carbon dioxide: influence of some process parameters. Flavour and Fragrance Journal, 21(4), 718-724.

Matsuo, Y., Mimaki, Y. (2010). Lignans from *Santalum album* and their cytotoxic activities. Chemical and Pharmaceutical Bulletin, 58(4), 587-590.

Matsuo, Y., Sakagami, H., Mimaki, Y. (2014). A rare type of sesquiterpene and β-santalol derivatives from *Santalum album* and their cytotoxic activities. Chemical and Pharmaceutical Bulletin, 62(12), 1192-1199.

McComb, J. A. (2009). Clonal *Santalum album* growth, oil content and composition on different hosts and at different times. Journal of the Royal Society of Western Australia, 92(1), 15-25.

Mihajilov-Krstev, T., Radnović, D., Kitić, D. (2010). Antimicrobial activity of *Satureja* L. essential oils against phytopathogenic bacteria *Erwinia amylovora*. Biologica Nyssana, 1(1-2), 95-98.

Mishra, A., Gauri, S. S., Mukhopadhyay, S. K., Chatterjee, S., Das, S. S., Mandal, S. M., Dey, S. (2014). Identification and structural characterization of a new pro-apoptotic cyclic octapeptide cyclosaplin from somatic seedlings of *Santalum album* L. Peptides, 54, 148-158.

Misra, B. B., Dey, S. (2012). Phytochemical analyses and evaluation of antioxidant efficacy of in vitro callus extract of east Indian sandalwood tree (*Santalum album* L.). Journal of Pharmacognosy and Phytochemistry, 1(3), 07-16.

Misra, B. B., Dey, S. (2013). Developmental variations in sesquiterpenoid biosynthesis in East Indian sandalwood tree (*Santalum album* L.). Trees, 27, 1071-1086.

Mohammed, F. S., Günal, S., Pehlivan, M., Doğan, M., Sevindik, M., & Akgül, H. (2020). Phenolic content, antioxidant and antimicrobial potential of endemic *Ferulago platycarpa*. Gazi University Journal of Science, 33(4), 670-677.

Mohammed, F. S., Kına, E., Sevindik, M., Doğan, M., & Pehlivan, M. (2021a). Antioxidant and antimicrobial activities of ethanol extract of *Helianthemum salicifolium* (Cistaceae). Indian Journal of Natural Products and Resources (IJNPR) [Formerly Natural Product Radiance (NPR)], 12(3), 459-462.

Mohammed, F. S., Sevindik, M., & Uysal, I. (2023a). Total phenolic, flavonoid, protein contents and biological activities of wild mustard. Acta Alimentaria, 52(3), 449-457.

Mohammed, F. S., Sevindik, M., Uysal, I., Sevindik, E., & Akgül, H. (2022). A natural material for suppressing the effects of oxidative stress: biological activities of *Alcea kurdica*. Biology Bulletin, 49(Suppl 2), S59-S66.

Mohammed, F. S., Sevindik, M., Uysal, İ., & Sabik, A. E. (2023b). Quercetin: derivatives, biosynthesis, biological activity, pharmacological and therapeutic effects. Prospects in Pharmaceutical Sciences, 21(3), 49-56.

Mohammed, F. S., Uysal, I., Sevindik, M., Eraslan, E. C., & Akgul, H. (2024). Analysis of phenolic contents and biological activities of wild mint, *Mentha longifolia* (L.) L. Indian Journal of Experimental Biology, 62, 192-198.

Mohankumar, A., Kalaiselvi, D., Levenson, C., Shanmugam, G., Thiruppathi, G., Nivitha, S., Sundararaj, P. (2019). Antioxidant and stress modulatory efficacy of essential oil extracted from plantation-grown *Santalum album* L. Industrial Crops and Products, 140, 111623.

Mondal, A., Pal, D. (2015). Role of abiotic factors in plant disease. International Journal of Research Studies in Biosciences, 102.

Mondal, M., Khalequzzaman, M. (2009). Ovicidal activity of essential oils against red flour beetle, *Tribolium castaneum* (Coleoptera: Tenebrionidae). Journal of Bio-Science, 17, 57-62.

Moy, R. L., Levenson, C. (2017). Sandalwood album oil as a botanical therapeutic in dermatology. The Journal of Clinical and Aesthetic Dermatology, 10(10), 34.

Mushtaq, W., Hayri, B. A. B. A., Akata, I., & Sevindik, M. (2020). Antioxidant potential and element contents of wild edible mushroom *Suillus granulatus*. Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Dergisi, 23(3), 592-595.

Nazar, N., Howard, C., Slater, A., Sgamma, T. (2022). Challenges in medicinal and aromatic plants DNA barcoding—lessons from the Lamiaceae. Plants, 11(1), 137.

Nikolova, M. T., Yordanov, P., Slavov, S., Berkov, S. (2017). Antifungal activity of plant extracts against phytopathogenic fungi: Antifungal activity of plant extracts. Journal of Bioscience and Biotechnology, 6(2), 155-161.

Patil, V. (2011). Absence of antimicrobial activity in alcoholic extract of *Santalum album* Linn. Journal of Pharmaceutical Negative Results, 2(2), 107-109.

Popović, T., Milićević, Z., Oro, V., Kostić, I., Radović, V., Jelušić, A., Krnjajić, S. (2018). A preliminary study of antibacterial activity of thirty essential oils against several important plant pathogenic bacteria. Pesticidi i fitomedicina, 33(3-4), 185-195.

Prasad, M. N. V., Padmalatha, K., Jayaram, K., Raju, N. L., da Silva, J. A. T. (2007). Medicinal plants from Deccan Ecoregion, India: Traditional knowledge, ethnopharmacology, cultivation, utilization, conservation and biotechnology–opportunities and impediments. Medicinal and Aromatic Plant Science and Biotechnology, 1(2), 155-208.

Ramulu, D. R., Murthy, K. S. R., Pullaiah, T. (2021). Sandalwood wood carving. Sandalwood: Silviculture, Conservation and Applications, 49-66.

Ratnaningrum, Y. W., Faridah, E., Indrioko, S., & Syahbudin, A. (2016). Flowering and seed production of sandalwood (*Santalum album*; Santalaceae) along environmental gradients in Gunung Sewu Geopark, Indonesia. Nusantara Bioscience, 8(2), 180-191.

Royyani, M. F., Keim, A. P., Efendy, O., Imadudin, I., Mahmud, M. I., Sy, P., Setyawati, S., Nuralia, L., Hidayat, A., Sujarwo, W. (2024). Incense and Islam in Indonesian context: An ethnobotanical study. Ethnobotany Research and Applications, 28, 1-11.

Santha, S., Dwivedi, C. (2015). Anticancer effects of sandalwood (*Santalum album*). Anticancer Research, 35(6), 3137-3145.

Santiago, M. B., Moraes, T. D. S., Massuco, J. E., Silva, L. O., Lucarini, R., da Silva, D. F., Martins, C. H. G. (2018). In vitro evaluation of essential oils for potential antibacterial effects against *Xylella fastidiosa*. Journal of Phytopathology, 166(11-12), 790-798.

Saridogan, B. G. O., Islek, C., Baba, H., Akata, I., & Sevindik, M. (2021). Antioxidant antimicrobial oxidant and elements contents of *Xylaria polymorpha* and *X. hypoxylon* (Xylariaceae). Fresenius Environmental Bulletin, 30(5), 5400-5404.

Selamoğlu, Z., Sevindik, M., Bal, C., Ozaltun, B., Sen, İ., & Pasdaran, A. (2020). Antioxidant, antimicrobial and DNA protection activities of phenolic content of

Tricholoma virgatum (Fr.) P. Kumm. Biointerface Research in Applied Chemistry, 10(3), 5500-5506

Sevindik, M., Akgul, H., Pehlivan, M., & Selamoglu, Z. (2017). Determination of therapeutic potential of *Mentha longifolia* ssp. longifolia. Fresen Environ Bull, 26(7), 4757-4763.

Sevindik, M., Akgul, H., Selamoglu, Z., & Braidy, N. (2020). Antioxidant and antigenotoxic potential of *Infundibulicybe geotropa* mushroom collected from Northwestern Turkey. Oxidative Medicine and Cellular Longevity, 2020.

Sevindik, M., Bal, C., Eraslan, E. C., Uysal, I., & Mohammed, F. S. (2023b). Medicinal mushrooms: a comprehensive study on their antiviral potential. Prospects in Pharmaceutical Sciences, 21(2), 42-56.

Sevindik, M., Gürgen, A., Khassanov, V. T., & Bal, C. (2024). Biological activities of ethanol extracts of *Hericium erinaceus* obtained as a result of optimization analysis. Foods, 13(10), 1560.

Sevindik, M., Mohammed, F. S., & Uysal, I. (2023a). Autism: plants with neuro-psychopharmacotherapeutic potential. Prospects in Pharmaceutical Sciences, 21(3), 38-48.

Shamsi, T. N., Parveen, R., Afreen, S., Azam, M., Fatma, T., Haque, Q. M. R., Fatima, S. (2014). In-vitro antibacterial and antioxidant activities of sandalwood (*Santalum album*). Austin J Biotechnol Bioeng, 1(4), 1-3.

Sharmila, G., Haries, S., Fathima, M. F., Geetha, S., Kumar, N. M., Muthukumaran, C. (2017). Enhanced catalytic and antibacterial activities of phytosynthesized palladium nanoparticles using *Santalum album* leaf extract. Powder Technology, 320, 22-26.

Shivashankara, A. R., Baliga, M. S., Palatty, P. L. (2021). An in vitro study of antioxidant effect of *Santalum album*, the Indian sandalwood. Journal of Pharmacognosy and Phytochemistry, 10(4), 395-398.

Shivatare, R. S. (2020). In vitro antioxidant activity and stability indicating high-performance thin-layer chromatographic method for ximenynic acid in *Santalum album* seed extract. Asian Journal of Pharmaceutics (AJP), 14(1).

Shivatare, R. S., Nagore, D. H. (2018). Extraction, characterization and antioxidant activities of various solvent extracts of *Santalum album* l. seeds. Pharmaceutical Resonance, 1(2), 23-27.

Sindhu, R. K., Upma, K. A., Arora, S. (2010). *Santalum album* linn: a review on morphology, phytochemistry and pharmacological aspects. International Journal of PharmTech Research, 2(1), 914-919.

Steglińska, A., Bekhter, A., Wawrzyniak, P., Kunicka-Styczyńska, A., Jastrząbek, K., Fidler, M., Gutarowska, B. (2022). Antimicrobial activities of plant extracts against *Solanum tuberosum* L. Phytopathogens. Molecules, 27(5), 1579.

Suastika, K., Weta, I. W., Wihandani, D. M. (2023). Phytochemical, compositions and antioxidant activities of timor sandalwood oil (*Santalum Album* L.): as natural antioxidant agent and potential target therapy for WAT browning. Indonesian Archives of Biomedical Research, 3(1), 1-9.

Subasinghe, U., Gamage, M., Hettiarachchi, D. S. (2013). Essential oil content and composition of Indian sandalwood (*Santalum album*) in Sri Lanka. Journal of Forestry Research, 24(1), 127-130.

Surain, P., Kumar, N., Dhiman, R., Meashi, V. (2016). *Santalum album*: clinical aspects for treatment of Candida infections. International Journal of Pharmaceutical Sciences and Research, 7(7), 2813-2829.

Tu, X., Ling, F., Huang, A., Zhang, Q., Wang, G. (2013). Anthelmintic efficacy of *Santalum album* (Santalaceae) against monogenean infections in goldfish. Parasitology Research, 112, 2839-2845.

Umdale, S., Ahire, M., Aiwale, V., Jadhav, A., Mundada, P. (2020). Phytochemical investigation and antioxidant efficacy of wild, underutilized berries of economically important Indian Sandalwood (*Santalum album* L.). Biocatalysis and Agricultural Biotechnology, 27, 101705.

Walia, S., Saha, S., Tripathi, V., Sharma, K. K. (2017). Phytochemical biopesticides: some recent developments. Phytochemistry Reviews, 16, 989-1007.

Wardana, A. A., Kingwascharapong, P., Wigati, L. P., Tanaka, F., Tanaka, F. (2022). The antifungal effect against *Penicillium italicum* and characterization of fruit coating from chitosan/ZnO nanoparticle/Indonesian sandalwood essential oil composites. Food Packaging and Shelf Life, 32, 100849.

Xin-Hua, Z., Silva, J. A. T. D., Yong-Xia, J., Jian, Y., Guo-Hua, M. (2012). Essential oils composition from roots of *Santalum album* L. Journal of Essential Oil Bearing Plants, 15(1), 1-6.

Yadav, V. K., Choudhary, N., Heena Khan, S., Khayal, A., Ravi, R. K., Kumar, P., Modi, S., Gnanamoorthy, G. (2020). Incense and incense sticks: types, components, origin and their religious beliefs and importance among different religions. J. Bio Innov, 9, 1420-1439.

Yan, T., Chen, Y., Shang, L., Li, G. (2020). Assessment of essential oils from five Santalum species using ATR-Fourier transform mid-infrared spectroscopy and GC-MS combined with chemometric analysis. Journal of Essential Oil Research, 32(2), 150-157.

Yazar, M., Sevindik, M., Polat, A. O., Koçer, O., Karatepe, H. K., Uysal, İ. (2024). General properties, biosynthesis, pharmacological properties, biological activities and daily uses of luteolin. Prospects in Pharmaceutical Sciences, 22(4), 146-154.

Yousefsani, B. S., Bahrami, B., Qobadi, A., Aghazadeh, E., Shirani, K., Pourahmad, J. (2022). The selective cytotoxicity of the hydroalcoholic extract of *Santalum album* linn wood on A375 and SK-MEL-3 human malignant melanoma cells: Cytotoxicity effect of white sandal wood extract. Iranian Journal of Pharmaceutical Sciences, 18(2), 128-137.

Zhu, J., Zeng, X., O'neal, M., Schultz, G., Tucker, B., Coats, J., Xue, R. D. (2008). Mosquito larvicidal activity of botanical-based mosquito repellents. Journal of the American Mosquito Control Association, 24(1), 161-168.

Unal, O., Eraslan, E. C., Uysal, I., Mohammed, F. S., Sevindik, M., & Akgul, H. (2022). Biological activities and phenolic contents of *Rumex scutatus* collected from Turkey. Fresenius Environmental Bulletin, 31(7), 7341-7346.

Uysal, I., Koçer, O., Mohammed, F. S., Lekesiz, Ö., Doğan, M., Şabik, A. E., ... & Sevindik, M. (2023). Pharmacological and nutritional properties: Genus Salvia. Advances in Pharmacology and Pharmacy, 11(2), 140-155.