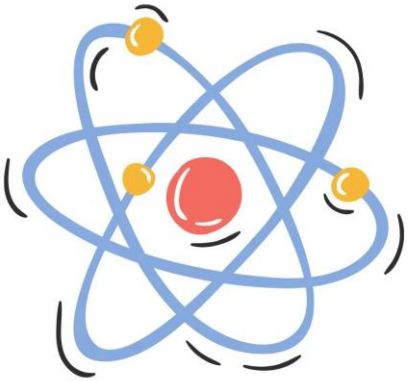

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Abstract: *Pinus roxburghii is an indigenous species of the Himalayas, named in honour of William Roxburgh. It is commonly known as chir pine or Himalayan pine. The extraction of aroma compounds from Pinus roxburghii depends on the plant's chemistry as well as the extraction techniques. The needles, resin, and bark of this pine species are naturally filled with a diverse blend of volatile terpenoids and other aromatic molecules that contribute to their unique olfactory scent. The main challenge lies not just in acquiring these compounds, but also in preserving their quality and maximizing yield with efficiency, purity, and environmental sustainability. Literature reviews of Pinus roxburghii essential oil extracts invariably identify α-pinene, β-pinene, and 3-carene as the major constituents. These volatile organic compounds impart the characteristic fresh, woody, and sharp pine scent. The essential oils and resins have applications in perfumes, cosmetics, medicines, and various industries. The pine needles are a primary source of forest fires in the Himalayan region. One of the main aspects of sustainability emphasized in the use of pine needles is their utilization as a resource for value-added products such as essential oils. Essential oils from pine biomass have traditionally been extracted by hydrodistillation and solvent extraction methods, which are very energy-intensive. These were later replaced by modern techniques such as supercritical fluid extraction, ultrasound-assisted extraction, superheated steam distillation, solvent-free microwave-assisted extraction, and short-path molecular distillation.Recently, Deep Eutectic Solvents (DES) have been recognized as a potential green extraction medium because of their low volatility, adjustable physicochemical properties, and lower environmental impact. Research on DES with reference to pine biomass mostly focuses on how pine needles can be broken down into sugars by hydrothermal or alkali treatment, mainly for the production of biofuels or materials; however, literature demonstrating the use of DES for extracting aromatic compounds from pine needles for perfumery is not available.Conventional methods are still the primary mode of extraction, but there is a need to move toward more intelligent, environmentally friendly extraction techniques to fully exploit the potential of pine for both scent and health applications. This review critically analyzes the extraction techniques and chemical composition of aroma compounds obtained from chir pine with respect to extraction efficiency, aroma preservation, energy consumption, and sustainability factors. Based on data collected from the literature, the ability of DES to selectively and economically extract aroma compounds and active terpenoids from chir pine biomass can be demonstrated. The study also highlights research avenues for the development of green perfume ingredients and forest biomass valorization.*

Key words: *aroma compounds, DES, essential oils, extraction methods, forest fires, Pinus roxburghii, sustainability.*

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Introduction

Pinus roxburghii, a native gymnosperm tree of the Himalayan region belonging to the Pinaceae family, is spread over 394,383.84 hectares. Three varieties—namely sal-pine, oak-pine, and pure pine—cover around 16.15% of the total forest area of Uttarakhand and are distributed across the districts of Almora, Bageshwar, Nainital, Champawat, and Pauri. [1]

Chir pine is found not only in Uttarakhand but also in other states of the country, including Jammu & Kashmir, Punjab, Himachal Pradesh, and Sikkim, as well as in neighbouring countries such as Pakistan, Afghanistan, Nepal, and Bhutan. [1][2] One of the major ecological problems associated with these forests is the accumulation of dry pine needles on the forest floor. Since pine needles are composed mainly of lignocellulose, have a waxy cuticle, and decompose very slowly, they remain on the forest floor and form inflammable surface fuel, which inevitably increases the frequency and intensity of forest fires during the peak summer season. [9][10]

Chir pine forest fires have been found to adversely affect soil organic matter, microbial activity, seedling regeneration, and biodiversity, while also contributing to air pollution and greenhouse gas emissions. [9][10] Besides its environmental impact, the utilization of pine needles also holds considerable social and economic significance. Typically, forest-dependent rural communities have very few livelihood options, and the periodic harvesting of pine needles can provide an additional source of income while fostering community participation in forest management. [10]

In this context, the systematic utilisation of fallen pine needles for the production of high-value products, such as the extraction of essential oils and aroma compounds, can be considered a potential nature-based solution. Essential oils are volatile secondary plant metabolites. Generally, monoterpenes, sesquiterpenes, diterpenes, and phenylpropanoids are the main constituents of essential oils. [6] The research group also emphasised that environmental factors, plant age, plant origin, stage of growth, and the plant part used for extraction influence the chemical composition of the oil. [6]

It has been found that the essential oils of pine contain numerous components, numbering more than 50. However, from various sources, 20 major constituents have been identified, such as β-pinene, camphene, α-pinene, sabinene, 3-carene, myrcene, α-terpinene, terpinolene, limonene, bornyl acetate, caryophyllene, terpinene-4-ol, γ-muurolene, phellandrene, α-terpineol, thujene,

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γ-terpinene, p-cymene, germacrene D, and spathulenol. Among these, α-pinene, β-pinene, camphene, 3-carene, and myrcene are primarily responsible for the formation of pine essential oil. [3]

Compounds such as 12-hydroxydodecanoic acid, 14-hydroxytetradecanoic acid, and 16-hydroxyhexadecanoic acid were extracted by hydrolysis from *Pinus roxburghii* needle wax and converted into macrocyclic lactones. These lactones are used in perfumery as fixatives. [12] A review reported that volatile fractions obtained from *Pinus roxburghii* oleoresin, a species common in the Himalayan mountains of India, are rich in terpenoids with strong bioactivity and significant economic value; therefore, it is worthwhile to develop efficient extraction methods for these compounds. [7]

Chir pine produces resin, which is viscous, sticky, and milky grey in colour. [1] Resin has several industrial applications, including use as a sweetener or in the manufacture of chewing gum. [3] Around 116 resin-based industries are active in Uttarakhand, and it has been reported that 70% rosin and 18% turpentine oil are obtained from chir pine through tapping. [1]

Rosin is transparent, shiny, and brittle in appearance; it is insoluble in water but soluble in organic solvents. [1] It is utilised in the manufacture of paints, lubricants, cosmetics, and pharmaceutical products. [8] Turpentine oil is a clear liquid with a pungent odour and consists mainly of α-pinene, 3-carene, β-pinene, longifolene hydrocarbons, dipentene, and polymeric terpenes. [1] When blended with cedarwood, sandalwood, lemon, and fir needle oils, it can serve as a principal component in natural woody and citrus fragrance formulations. [4]

Turpentine oil can be used as a raw material in pharmaceuticals, cosmetics, perfumes, food flavouring, and aromatherapy. [3][8] Various literature sources indicate that chir pine offers life-supporting compounds, and almost every part of the plant can be utilised, including needles, bark, cones, and seeds. [2]

The research group has also highlighted the traditional uses of chir pine, including the use of “chhilla,” which refers to small, resinous wood chips cut or slashed from the tree, used by locals for lighting homes and as fire starters before kerosene became widely available. [2] The seeds are edible, and the needles can be used as bedding material for livestock to protect them from moisture during the rainy season and from fleas and lice. [2][5] The cones can be used for decorative purposes or in making firecrackers. [2]

In addition to its industrial applications, chir pine also possesses medicinal properties. Pine essential oil has been reported to enhance the activity of white blood cells and exhibits antifungal, antimicrobial, anti-allergenic, antiparasitic, and anti-inflammatory properties. [3] It is known to improve blood circulation, reduce pain, alleviate fatigue, enhance concentration, and slow the ageing process. It is also beneficial in treating colds, coughs, asthma, and sinusitis.

In hair care, pine essential oil acts as a natural cleanser, helps make hair soft and shiny, and prevents dandruff and lice. [5] Its natural antimicrobial properties also aid in product preservation and scalp cleansing formulations. The aroma of pine is widely used in cosmetics, as it provides soothing, rejuvenating, refreshing, hydrating, cooling, and toning effects. [5]

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Morphological characteristics of Pinus roxburghii

Plant part	Morphological description	Relevance to aroma extraction	Bioactive element
Tree height	30-50 m, tall evergreen conifer	Large biomass availability	
Trunk	Straight, cylindrical; thick, scaly bark; diameter of upto 2m.[11]	Source of Oleoresin.	Monoterpenes 28.7% (α-pinene, β-pinene,α-phellandrene, β- phellandrene and limonene). Sesquiterpenes 2.5% (longifolene and β-caryophyllene). 1.5% neutral diterpenes(abienol, isoabienol, isopimaral, pimaral). 62.8% resin acids.[33]
Bark	Reddish-brown, deeply fissured[11]	Resin ducts present	α-pinene (31.29%), 3-carene (28.05%), Longifolene(4.42%), terpineol(2.05%), β-pinene (2.99%), Thunbergol (4.11%).[11]
Needles	Long (20-30 cm), slender, in fascicles of three[11]	Rich in monoterpenes.	α-pinene (22.8%), β-pinene (14.1%),camphene (0.4%), δ-3-carene (50.6%), β-myrcene (1.1%). [11] Needles collected from Nepal Satyal et al., has reported yield of δ-3-carene (2.3%) in 2013.[13]
Cones	Ovoid-conical, 10-20×7.5×13 cm long[11]	Minor aromatic contribution	δ-3-carene(6.8%).[13]
Resin ducts	Abundant in wood, bark, and needles[11]	Primary storage of terpenoids	α-pinene (20-30%), β-pinene (5-10%), β-3-carene (55-65%), longifolene and other terpenoids (2-10%) has been reported.[12]
Root System	Deep tap root with lateral spread	Ecological stability	

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Chemical Composition of Chir Pine Needles and Resin

"The aromatic value of Chir pine arises from its volatile terpenoid profile, which is dominated by monoterpenes and sesquiterpenes. The chemical composition varies depending on the plant part, season, and extraction method." [6]

Major aroma-active compounds in Pinus roxburghii

Compound	Chemical class	Major source
α-Pinene	**Monoterpene**	**Needles, resin**
β-Pinene	**Monoterpene**	**Needles**
Limonene	**Monoterpene**	**Needles**
Camphene	**Monoterpene**	**Needles**
Borneol	**Oxygenated terpene**	**Resin**
Bornyl acetate	**Ester**	**Needles, resin**
δ-3-Carene	**Monoterpene**	**Needles**
Abietic acid	**Diterpenoid**	**Resin**
Pimaric acid	**Diterpenoid**	**Resin**

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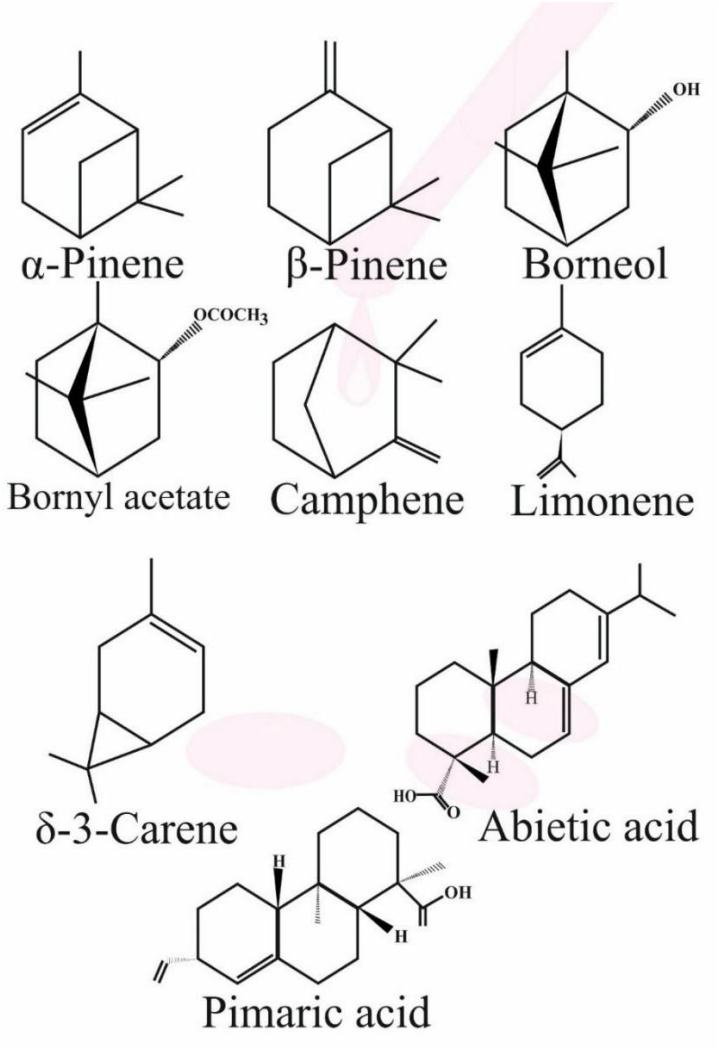

Figure 1: Major constituents and their chemical structures present in the essential oil.

Extraction Techniques

Solvent Extraction

This technique is one of the most commonly and economically employed methods used to extract fragrant compounds from woody and fibrous plant materials.[37] This method uses solvents such as n-hexane, diethyl ether, or ethanol to dissolve the aromatic compounds, followed by evaporation to obtain the "absolute" or oil.[35] This extraction technique was applied to blackcurrant buds using n-hexane for the extraction of aroma compounds and identified 30 major aromatic compounds, including monoterpenes such as δ-3-carene and terpinolene, which contributed a large portion of the final extract.[52] Another research group conclude that 1:1 mixture of diethyl ether and n-hexane was the most effective system for extracting compounds like myristicin, α-phellandrene, and apiol from Apiaceae plant species.[53] Phytochemical analysis of dehydrated leaves of *Pinus roxburghii* using 50% ethanolic extract has confirmed the presence of alkaloids, tannins, saponins, steroids, phenols, terpenoids, flavonoids and glycosides whereas its aqueous extract contained alkaloids,

https://doi.org/10.71058/jodac.v10i05002

terpenoids, tannins, saponins, phenols, flavonoids, glycosides and absence of steroids. Meanwhile, both extracts were devoid of protein and amino acid.[49]

Advantages

1. It is suitable for extracting a wide range of aroma compounds, including heavier sesquiterpenes, compared to distillation.[35]

2. Solvent extraction is simple to operate.[36]

3. It can extract volatile compounds that cannot be obtained through the distillation process.[37]

Disadvantages

1. The use of hexane requires extreme caution, as it is flammable and hazardous to human health.

2. The solvent carries waxes, pigments, and other non-aromatic compounds, requiring further purification.[37]

3. Solvent residues may remain.[37]

Supercritical Fluid Extraction

Supercritical Fluid Extraction is a process in which the extractant is separated from the matrix using supercritical fluids.[38] A supercritical fluid is a solvent with a very high density that has the capability of dissolving substances like liquid; however, it behaves like a gas at the same time. The supercritical fluid is used to extract the plant material and the most common superfluid is carbon dioxide.[3] For the required extraction conditions, the temperature and pressure must be above the critical temperature (31°C) and critical pressure (74 bar) simultaneously. A solvent with gas-like diffusivity and liquid-like solvating power can selectively pull volatile compounds from plant matrices.[38] Supercritical carbon dioxide is a better option for extracting flavor compounds from natural material, as it can separate different flavors and aromas found in pepper, ginger, and allspice.[54] Supercritical fluid extraction technique has been extensively used for the extraction of fragrances from aromatic plants.[54] The article shows the extraction of volatiles from various plant species such as Abies koreana, Eucalyptus globulus, Bidens tripartita, Croton zehntneri, Foeniculum vulgare, Thymus vulgaris and many more, and the results indicate a higher yield.[54] Similarly, it has been found to be very efficient method for isolating several monoterpenes including (+)-α-pinene, (-)-camphene, sabinene, (-)-β-pinene, myrcene, R-(+)-limonene, (-)-bornylacetate, (-)-trans-caryophyllene, a-humulene from needles of different Pinaceae species and walnut tree leaves at their optimum selected parameters (pressure 20/30 MPa, temperature 80/130 C, time of extraction 60/60 min, modifier chloroform/chloroform for needles/leaves).[50]

Advantages

1. It operates at lower temperature than steam or hydrodistillation. Since very little heat is used in the process and the solvent used for extraction is fairly unreactive, the resulting fragrant compounds are often very close to the original aroma of the raw material.[37]

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2. No residues of the solvent remains in the final extract.[37]

3. This method takes only 10 to 60 minutes to complete.[38]

4. Selective extraction is possible by adjusting pressure and density.[38]

Disadvantages

1. In comparison to the conventional liquid extraction, supercritical fluid extraction requires high pressure which increases the cost.[38]

2. Carbon dioxide is relatively non-polar and may not extract polar aroma compounds efficiently without co-solvents.[37][54]

Solvent-Free Microwave Assistance Technique

Solvent-free microwave assisted extraction is considered a clean, green extraction technique.[55][56] The solvent-free microwave extraction method has been developed recently and is now a leading choice for essential oil extraction. It uses microwave heating along with distillation without adding water or organic solvents under normal pressure.[56] Microwave extraction without solvents has been suggested as an environmentally friendly way to extract essential oils from herbs commonly used in food.[55]

This technique has been applied to extract essential oil from fresh rosemary plants, and is concluded that fine-tuned microwave treatment increases oxygenated compounds,[57] and these compounds tend to have stronger scents than monoterpene hydrocarbons.[55] Many reported articles reveal that the extraction time is about 30 minutes, and the quality and quantity are similar to those obtained by traditional hydrodistillation, which takes almost 2 hours to extract the essential oil.[55]

Researchers have tested this method on various fresh and dried plants, including spices such as ajowan, cumin, and star anise; herbs such as basil, mint, and thyme; as well as citrus fruits.[55] Similarly, using this technique, chemical compositions of pine essential oils from different species, namely P. pinea, P. nigra, P. brutia, and P. sylvestris, were determined. GC-MS analysis was carried out on the essential oils, and the major constituents were D-limonene (52.8%), caryophyllene (12.4%), myrcene (2.89%), and total sesquiterpene (25.25%).[40] Microwave-assisted extraction has the potential to produce higher amounts of diterpene alcohols and sesquiterpene hydrocarbons.[40] A report concluded that this technique can be an alternative method for extracting essential oil compared to conventional methods.[57]

Advantages [40]

1. Requires shorter extraction times.

2. Reduces the use of solvent and energy consumption.

3. This method produces high-quality oil because less thermal degradation occurs.

Disadvantage

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1. Most studies have been performed only at the laboratory level. Scaling the equipment to an industrial level is challenging.[39]

Superheated Steam Distillation (SHSD)

Superheated steam extraction is an efficient technique used for the extraction of essential oils. This method is similar to steam distillation but uses steam heated above boiling point (101°C to over 180°C) at a specific pressure.[42] It often provides higher yields due to stronger release of volatile compounds.[41]

This technique has been used to extract volatile compounds from thyme leaves and black pepper fruits. The steam and volatiles pass into a condenser and are separated using solvents. The results revealed that the yield increases over time and is affected by higher steam temperature and flow rates. However, the quality decreases when steam temperature exceeds 175°C.[58]. Some compounds may be degraded by the very high temperature of superheated steam. On the other hand, the concentration of a certain compound in the distilled essential oil is influenced by several factors such as volatility, steam solubility, and the temperature and pressure of the distillation procedure.[44]

The technique was applied for the extraction of oleoresin essential oil on Chir Pine at 160°C and showed the maximum yield (19.92%) compared to steam distillation and supercritical fluid extraction techniques.[41] After extraction GC-MS analysis was performed, revealing that 3-carene, α-pinene, and β-pinene were the major aromatic compounds present in the oleoresin essential oil.[41]

Advantages

1. Improves energy efficiency and reduces environmental impact.[42]

2. This technique shows the potential to generate higher essential oil yields than traditional steam distillation and can be considered an alternative method for extracting essential oils from oleoresin.[41][42]

3. It may help preserve certain bioactive compounds, such as antioxidant and antimicrobial properties.[41]

Disadvantage

1. During high- temperature essential oil extraction, active components may be hydrolyzed more rapidly by heat, which can alter the flavour or scent of the oil.[43]

Ultrasound-assisted extraction

Ultrasound-assisted extraction (UAE) is a next generation eco-friendly green technology.[45] This technique employs acoustic cavitation to disrupt plant cell walls.[45] Ultrasound transmits sound waves into plant cells, which results in the increased release of oil.[46][47] This technique has been used on flowers, leaves and seeds.[48] Laboratory apparatus was reportedly invented in 1950.[47] When ultrasound is used in combination with other methods such as

https://doi.org/10.71058/jodac.v10i05002

solvent extraction and hydrodistillation, it can achieve a more complete and selective extraction of essential oils from plant material.[47]

The ultrasound-assisted extraction technique was applied to rosemary to extract carnosic and rosmarinic acids, which are the primary phenolic acids in hydrophilic rosemary extracts, using ethanol and AmAc:LA. The total ultrasound-assisted extraction time was only 10 minutes, yielding better results.[59] Aromatic compounds from must and wine were extracted using this rapid ultrasound method, and this approach achieved solid recovery, linearity and reproducibility across most compounds.[60] This technique has also been used for the extraction of polyphenols from pine needles of *Pinus elliottii,* and Response Surface Methodology was utilized to find out standard extraction conditions.[45] The highest total phenolic content obtained was 40.37 mg GAE/g pine needles, with a solid-liquid ratio of 1:20, 60% ethanol, 350 W power, a duration of 25 minutes, and a temperature of 45°C.[45]

Advantages

1. This technique reduces processing time and energy requirements further increasing the yield [45]
2. Reduces the volume of solvent used.[45]
3. Suitable for heat-sensitive compounds.[47]

Disadvantage

1. One of the limiting factors is that the characteristic aroma may be reduced or altered in oils extracted using this method.[46]
2. This technique requires expensive equipment.[47]
3. Exposure to excessive ultrasound may damage bioactive compounds.[47]
4. The performance is not consistent across all plant matrices.[47]

Short Path Molecular Distillation

Short-path distillation operates under high vacuum to increase citral levels in lemongrass oil.[61] This method minimizes heat exposure and produces high-quality oil from the distillate stream. Researchers have found this technique to be promising for improving citral yield in lemon grass without altering the base components.[61] This technique has also been applied to other species such as Lavandula angustifolia [62]. Extraction typically begins with the hydrodistillation of oleoresin, followed by molecular distillation to purify the volatile turpentine oil into fractions and sub-fractions.[7] Analysis by GC-MS confirmed the presence of the active fractions and subfractions of *Pinus roxburghii* turpentine essential oil as longifolene, 3-carene, α-pinene, β-pinene.[7]

Advantages

1. Minimum heat is used.[61]
2. Molecular distillation facilitated the effective retrieval of oxygenated compounds.[51]

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Disadvantages

1. Molecular distillation systems tend to be more expensive than traditional distillation systems.

2. Skilled operators are required to run molecular distillation systems.

Hydrodistillation

Among the various extraction techniques available, hydrodistillation remains the standard approach preferred by researchers and industry professionals.[17] This method is a variant of traditional steam distillation, used to extract essential oil by boiling water and plant material.[17] This method was first discovered by Avicenna.[16]

General procedure:

The procedure includes precise identification, selection and preparation of plant material. Pine needles, wood, and stem are first thoroughly cleaned to remove dust and contaminants. The material is then air-dried to reduce water content, which helps concentrate the volatile oils and prevent undesired hydrolysis during extraction. The material is often chopped or cut into smaller pieces to increase surface area, which in turn boosts the efficiency of oil release.

lThe prepared plant material is then placed in a distillation flask along with enough water to fully immerse it.[16] This mixture is subjected to direct boiling, allowing the breakdown of plant's cellular structures and release of its aromatic constituents.[16]17] The distillation system usually employs a Clevenger-type apparatus, which is specifically designed to separate essential oils from water effectively, according to the the European Pharmacopoeia (Clevenger, 1928, Maisonneuve, 1996).[14][16]

As the water boils, steam carries the volatile terpenoids and other aroma compounds upward, where they are condensed back into liquid form in a cooled graduated receiver. Since essential oils are hydrophobic and usually less dense than water, they separate naturally and float to the top, allowing for easy collection.[16] The hydrodistillation process typically lasts two to four hours, and the parameters can be adjusted depending on the desired yield and the properties of the starting material.[15][16]

After collection, the crude essential oil is further dried using anhydrous sodium sulfate, which removes traces of moisture that could otherwise cause degradation or affect the results of subsequent analysis.[15][16] The purified oil is then stored at 4°C to maintain its volatile profile until it is ready for detailed chemical characterization, often by gas chromatography-mass spectrometry (GC-MS).[15]

This analytical step is crucial for identifying the precise composition of the oil,[48] as even small variations in processing or plant origin can significantly influence the final product's aroma, therapeutic potential, and commercial value. The yield from hydrodistillation is calculated as a percentage of the dry weight of the plant material, providing a standardized metric for comparing different extraction runs or plant batches.

$$\text{Yield of essential oil (\%)} = \frac{\text{Mass of essential oil obtained (mL)}}{\text{Amount of raw materials used (g)}} \times 100\ \%$$

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According to the research study conducted by Salem, M.Z.M., and Basalah, M.O. (2014), the essential oils of wood, bark, and needles have shown the presence of twenty two, thirty one, and twenty eight compounds respectively. The study has confirmed the presence of caryophyllene (16.75%), thungbergol (16.29%), 3-carene (14.95%), cembrene (12.08%), α-thujene (10.81%) and terpinolen (7.17%) as main constituents. They reported that most abundant compounds in the bark were α-pinene (31.29%), 3-carene (28.05%), while in the needles, α-pinene (39%) and 3-carene (33.37%) were obtained through hydrodistillation process and confirmed by GC-MS analysis. [18]

A 0.11% yield of essential oil was obtained through hydrodistillation from chir pine (*Pinus roxburghaii*) needles. The chemical composition was determined by GC-MS. The following table shows all the constituents found in the essential oil from the needles of chir pine, as reported. [19]

Component	% yield
α-Pinene	29.3
3-Carene	14.2
α-Terpineol	4.5
Borneol acetate	2.2
Caryophyllene	21.9
α-longipinene	1.2
Caryophyllene oxide	3.1
β-Myrecene	1.1
Terpinyl acetate	1.0

Advantages

1. Hydrodistillation remains widely used due to its simplicity, scalability, and the high-quality oils it can produce. These qualities keep it at the forefront of essential oil extraction from Himalayan pine and similar aromatic plants.

2. Proper heat transfer occurs due to continuous supply of the boiling water in the distilling flask.[17]

3. In hydrodistillation, due to the use of water as a solvent, the extracted volatile oil remains in its pure form.[19]

This process, while is time-tested and relatively straightforward, does have its limitations.

Limitations [17]

1. High temperatures and prolonged exposure to water can sometimes degrade sensitive compounds such as esters. Compounds like acyclic monoterpenes, hydrocarbons and aldehydes can be easily converted to polymers during distillation resulting in hydrolytic reactions that alter the oil's aroma profile.

2. Complete output is not achieved.

https://doi.org/10.71058/jodac.v10i05002

3. Water distillation is a slow process, taking a long time for oil accumulation, and sometimes results in the mixing of oils, leading to inferior yield.

4. This method requires a large area and a greater quantity of fuel.

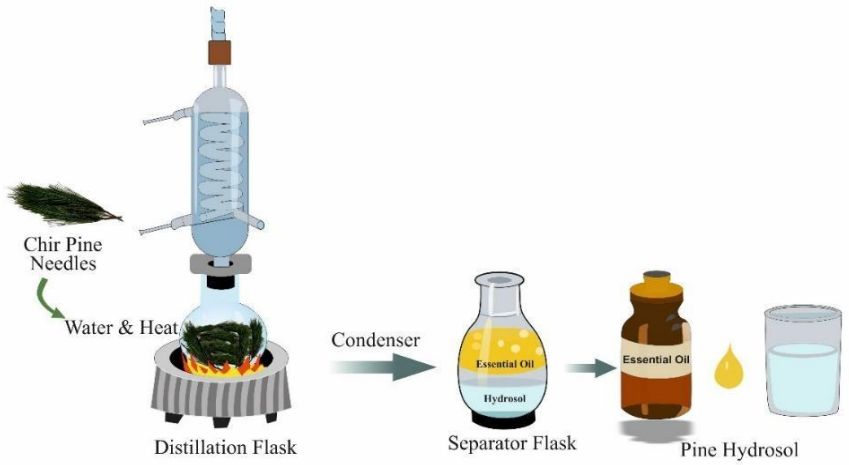

Figure 2: Diagram illustrating the extraction of essential oil through hydrodistillation technique.

Deep Eutectic Solvent (DES) Extraction

A new group of designer solvents known as deep eutectic solvents (DES) is formed by reaction between hydrogen bond donor (HBD), like glycerol, organic acids, or sugars with a hydrogen bond acceptor (HBA), usually choline chloride.[21] The melting point of the product so formed is greatly lowered by the eutectic interaction, resulting in a non-volatile, thermally stable liquid that can dissolve a wide variety of phytochemicals.[22][23]

Concept and solvent design:

In contrast to traditional organic solvents (e.g., hexane or ethanol) which are toxic and hazardous to human health.[24] DES can be customized to improve solubility for specific classes of compounds, such as monoterpenes and oxygenated derivatives that are found in pine needles and resin. Choline chloride :glycerol (1:2), choline chloride : lactic acid (1:2), or choline chloride :glucose (1:1) are some common DES formulations in which polarity and viscosity are modulated by varying molar ratios.[25] To reduce viscosity and enhance mass transfer, water can be added while still maintaining solvent effectiveness.[26]

The green chemistry field has witnessed a growing interest in deep eutectic solvents (DES) and natural deep eutectic solvents (NADES) as eco-friendly replacements for conventional organic solvents.[26][27] Recent literature on DES applications has demonstrated their increased extraction capacity for a variety of plant secondary metabolites, such as flavonoids, phenolics, and terpenoids.[26][29] Thus, DES are liquids with low volatility, polarities that can be adjusted, low toxicity, and the potential to be biodegradable.[27][29].

https://doi.org/10.71058/jodac.v10i05002

The ability of DES to selectively solvate volatile terpenes at low temperatures opens opportunities for higher yields, better aroma preservation, energy savings, and reduced environmental impact. However, viscosity remains a major limitation, as it can hinder mass transfer. Additionally, the recovery of the extracted volatiles sometimes requires back-extraction using ethanol or alternative separation strategies. Studies on process optimization show that careful adjustment of water content and selection of appropriate DES components can reduce viscosity and the improve extraction efficiency.[34]

Verified Research on DES Extraction of Similar Natural Oils

Below are verified DES studies on essential and volatiles oils in other plants, which are the closest analogs published to date:

1. DES-based extraction of delicate oils from sources like agarwood achieved a 2.12 times higher yield compared to traditional water distillation by using biodegradable, low-toxicity mixtures such as choline chloride and lactic acid. DESs act as tailor-made solvents that disrupt plant cell structures, facilitating the release of aromatic components while preserving their volatile integrity. GC-MS analysis revealed a richer profile of sesquiterpenes in DES extracted oil.[28]
2. DES-based extraction has been performed to identify compounds such as D-limonene, linalool and myrcene from orange peel; lycopene from tomato peel; β -carotene, zeaxanthin, violaxanthin, and lutein from melon peel. These compounds are the active ingredients used in perfumes and used in aromatherapy.[21]
3. Aromatic compounds from ginger and mint have also been successfully isolated using DES.[30]

Although many studies have extensively focused on DES for bioactive compound extraction, one area that remains largely unexplored is the targeted extraction of scent compounds from pine biomass for perfume industry applications.

Based on the available literature on the extraction of aroma compounds from other natural sources using DES, this approach shows strong potential for extracting essential oils from pine.

Advantages

Better Extraction: DES has the potential to extract a wide variety of volatile and semi-volatile terpenoids including oxygenated compounds and heavier diterpenoids.

Energy Efficient: DES requires less energy as compared to traditional extraction techniques. [24][31]

Environment friendly: DESs are generally considered safer, biodegradable, and less flammable.[31][29][21]

Challenges

Solvent Thickness: One major challenge is the high viscosity of DES, which can impede diffusivity and slow down the extraction process.[31][24]

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Additional Step: Deterpenation or back-extraction is often required to concentrate the volatile compounds.[24][29][32]

Optimization Required: Solvent composition, water content, and extraction parameters must be optimized to maximize yield while maintaining the true fragrance profile.[24]

Conclusion

Chir pine (*Pinus roxburghii*) is a highly valuable yet underexploited source of natural aroma compounds, with the fragrance, perfumery, and allied industries being the major beneficiaries. Himalayan pine needles and oleoresin are available in great abundance, creating an opportunity to convert a low-value biomass into highly valuable aromatic ingredients while simultaneously addressing long-standing environmental issues such as forest fire risk.

Pine-derived essential oils are mainly extracted by conventional hydrodistillation, which still holds the first place; however, disadvantages of this technique—such as high energy consumption, damage to the oil due to heat, and a limited range of selective components—call for alternative methods.

Green extraction methods are at the forefront, especially Deep Eutectic Solvents (DES), which have been shown to enhance the extraction of aroma compounds, protect the fragrance-active terpenoids, and minimize the environmental impact associated with the production of aroma compounds. Besides functioning as facilitators for the isolation of secondary metabolites, the coupling of green extraction and biomass valorization can act as a catalyst for a circular bioeconomy as well as a source of rural income.

Overall, the studies referred to in this review demonstrate that chir pine biomass is a multifunctional resource that can successfully combine natural product chemistry, environmental sustainability, and socioeconomic development.

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