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Reviews

Pharmacological Mechanisms of Hepatoprotection by Monoterpenes: A Review

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Abstract

Liver is a key to the process of detoxication, metabolism, and physiological homeostasis that makes it very sensitive to damage by xenobiotics, pharmaceuticals, and environmental toxins. Hepatotoxicity remains a critical health concern of the world worldwide, and there is still a necessity to find safer and more effective treatment measures. The naturally occurring compounds have been of special interest in this regard and specifically, monoterpenes which are common compounds that form essential oils. The present review is an in-depth discussion on the chosen monoterpenes such as geraniol, myrcene, α-pinene, limonene, nerol, and camphene with references to their pharmacological activities and hepatoprotective capacity. It has been shown through experiment that these compounds have protective effects toward liver injury in many ways such as mediating oxidative stress, supporting endogenous antioxidant defense systems, and regulating key signaling pathways. Remarkably, monoterpenes turned out to stimulate nuclear factor erythroid 2-related factor 2 (Nrf2) pathway and suppress nuclear factor kappa B (NF-κB) and mitogen-activated protein kinase (MAPK) signaling to reduce inflammation, oxidative damage and cell dysfunction. All these results support the therapeutic value of monoterpenes as multi-targets agents in the treatment of liver diseases.

Keywords

Monoterpenes, Hepatoprotective, Oxidative stress, Essential oils, Signaling pathways

Article History

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1. Introduction

The liver is a vital organ that performs a wide range of physiological and biochemical functions, including metabolism, detoxification, energy production, and maintenance of homeostasis [1]. Due to its central role in the biotransformation of xenobiotics and drugs, the liver is highly susceptible to toxic insults. Most hepatotoxic agents induce liver injury primarily through oxidative stress and lipid peroxidation, leading to cellular dysfunction and tissue damage. Liver diseases represent a major global health burden, contributing significantly to morbidity and mortality worldwide. According to the World Health Organization, approximately 354 million people globally are affected by chronic liver diseases, including hepatitis B and hepatitis C. Additionally, liver diseases account for nearly 2 million deaths annually, making them one of the leading causes of death worldwide. Alcohol consumption is one of the most common contributing factors to liver disease, alongside viral infections, metabolic disorders, and drug-induced hepatotoxicity [2]. There is a wide range of hepatotoxic agents such as chemotherapeutic drugs, thioacetamide and carbon tetrachloride (CCl_4) that have been known to cause liver damage [3]. Moreover, due to constantly exposing the liver to reactive metabolites during the process of detoxification, the liver becomes susceptible to damage and, due to this, a broad range of liver disorders with differing etiologies is obtained [4]. Complementary and alternative medicine has become the focus of recent years in the management of acute and chronic liver diseases. Traditional hepaprotective drugs like L-ornithine, L-aspartate, ondansetron, and metadoxine are mainly used to relieve the symptoms, and are identified to cause side effects such as dizziness, fatigue, and other systemic complications. As an extension of this, herbal and plant-based therapies are increasingly gaining interest as seen to provide safer and less costly options. However, the majority of these natural remedies did not receive a proper scientific validation and despite the achievements of the modern medicine, the suitable and efficient hepatoprotective medications have yet to be discovered [5]. A major focus has been the investigation of monoterpenes which is a major class of natural plant secondary metabolites having a diverse array of pharmacological activity that include antioxidant, anti-inflammatory, anti-tumor, anti-diabetic, cardioprotective, neuroprotective and hepatoprotective activities [6,7]. Monoterpenes are structurally made of two isoprene units ($C_{10}H_{16}$) and are broadly classified as acyclic, monocyclic, bicyclic, and tricyclic. Acyclic monoterpenes (geraniol, linalool, citronellol, and citral) and monocyclic monoterpenes (limonene, carvacrol, p-cymene and perillyl alcohol) are examples. Monoterpenes that are bicyclic are alpha-pinene (α-pinene), camphene, and borneol whereas tricyclic are less common and comprise tricyclene. Another strength of monoterpenes is their accessibility and bioavailability, and some of the compounds have shown clinical potential in medicine use [8]. Monoterpenes have hepatoprotective effects by regulating various molecular pathways that mediate oxidative stress, inflammation and apoptosis [9]. They control the synthesis of cytokine and also modulate important signaling pathways including mitogen-activated protein kinase (MAPK) and nuclear factor kappa B (NF-κB) which are vital in the survival, inflammation and cell death of hepatocytes [10]. Moreover, the nuclear factor erythroid 2-related factor 2 (Nrf2) pathway, when activated, improves the cellular antioxidant defense mechanism by modulating the expression of detoxification and reactive oxygen species and elimination of electrophiles genes [11]. The Nrf2 pathway is highly regulated by the help of regulatory proteins like Keap1 and Cul3-RBX1 and is triggered by the response to oxidative stress and inflammatory stimuli [12]. The focus of the current review is on the chosen monoterpenes, such as geraniol, myrcene, α-pinene, limonene, nerol, and camphene, out of the relative consistency of the available experimental data and mechanistic understanding of their hepatoprotective action. Several other monoterpenes like perillyl alcohol, carvacrol, thymol, borneol and linalool are also reported to possess hepatoprotective potential but were excluded because of relatively small or less detailed mechanistic information. Through this keen method, it is possible to analyze better-defined compounds more critically and comparatively. Figure 1. demonstrates the key molecular mechanisms of the hepatoprotective action of monoterpenes, such as antioxidant, anti-inflammatory, and anti-apoptotic.

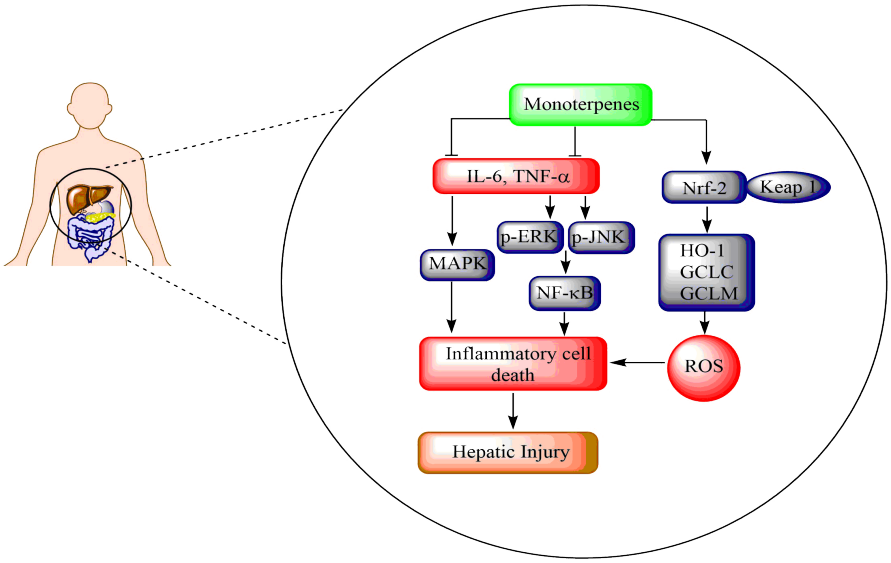

Figure 1. Pathways involved in alleviating hepatotoxicity.

2. Inclusion and Exclusion Criteria

The review is based on a narrow selection strategy to make it analytically deep and mechanistically clear. Monoterpenes were incorporated because they had sufficient experimental evidence of hepatoprotective effects, especially articles that shed light on the molecular mechanisms underlying this effect, e.g. antioxidant and anti-inflammatory pathways. Compounds such as geraniol, myrcene, α-pinene, limonene, nerol and camphene were chosen because there is comparatively stable and well characterized data which demonstrates their biological activity in a number of researches. Conversely, monoterpenes with a low, scattered, or mostly initial evidence, e.g. studies that had not been mechanistically assessed or were based on isolated findings alone were not subject to further examination. Also, the papers that had low methodological clarity, lacked reproducibility, or were not directly connected to hepatoprotection were not taken into consideration. The reason behind using this selective method was to enable a more critical and comparative assessment of established compounds, whereas it does not represent the whole range of monoterpenes that have the potential to act as hepatoprotectants.

3. Monoterpene Involved in Hepatoprotection

Phytochemicals in Table 1 are a variety of monoterpenes, which are mainly derived out of essential oils. It is interesting to note that compounds such as Alpha-pinene and Myrcene exhibit a high range of experimental dosages (5 mg/kg to as high as 250 mg/kg) in different literature sources indicating dose-dependent pharmacological actions.

Table 1. Natural sources and pharmacological dose ranges of selected monoterpenes in preclinical studies.

S.No.	Compound	Source	Dose	Ref.
1.	Geraniol	*Monarda fistulosa*, geranium oil, ninde oil, palmarosa oil, rose oil, and citronella oil	100 mg/kg	[13]
			12.5 mg/ml	[14]
2.	Myrcene	*Cannabis indica,* lemon grass, verbena, bay as well as citrus fruits.	20, 50 mg/kg	[15]
			100 mg/kg or 200 mg/kg	[16]
3.	Alpha pinene	eucalyptus oils as well as oils of aromatic plants such as rosemary, mint, holy basil, camphor, bupleurum, and Psidium	5 mg/kg and 10 mg/kg	[17]
			250 mg/kg	[18]
			20 mg/kg	[19]
			0.1 mg/kg and 0.2 ml/kg	[20]
			5.52 mg/kg	[21]
4.	Nerol	Essential oils of lemon grass, neroli oil	100 mg/kg and 50 mg/kg	[22]
			200 mg/kg and 400 mg/kg	[23]
5.	limonene	Natural fruits like grapefruit, tangerine, orange, mandarin, lemon and elemi.	10 mg/kg	[24]

4. Monoterpene Involved in Hepatoprotection

4.1 Alpha Pinene

Alpha pinene is a kind of monoterpene, found mainly in eucalyptus oils as well as oils of aromatic plants such as rosemary, mint, holy basil, amphor, bupleurum, and Psidium. It plays a significant role as an antimicrobial, apoptotic, anti-metastatic, and antibiotic. It acts as an anti-inflammatory agent by modulating the MAPKs as well as the NF-κB pathway. Research showed that the essential oil of rosemary that contains several monoterpenes including α-pinene exerts a hepatoprotective effect in doses of 5 mg/kg and 10 mg/kg for seven consecutive days by decreasing the level of aspartate aminotransferase (AST) and alanine aminotransferase (ALT) up to two-fold in the serum of albino Wistar rats Rosemary essential oil (REO) Malondialdehyde (MDA) level that demonstrates that REO is able to maintain cellular integrity and this can be determined as the result of the free radical scavenging activity identified by 2,2-diphenylpicrylhydrazyl (DPPH) activity [25]. It is also useful to eliminate the activities of antioxidant enzymes catalase, peroxidase, glutathione peroxidase and glutathione reductase on liver homogenates. Hence, it has been proven to show free radical scavenging activity. The study also shows that the essential oil of *Myrtus communis* reduces oxidative stress at the dose of 250 mg/kg body weight (b.w.)for 14 consecutive days in rats by preventing the generation of free radicals. The monoterpene present in this essential oil helps to decompose free radicals by quenching Reactive oxygen species (ROS) as well as trapping radicals before they reach the cellular targets [26].The essential oil of *Salvia officinalis L.* was examined at the dose of 20 mg/kg b.w. in Wistar male rats for 4 weeks that showed significant hepatoprotective potential by decreasing AST and ALT levels and additionally decreasing the level of MDA. A notable increase observed in cell viability as well as the antioxidant activity with the reduction of MDA was also observed [27]. Essential oil of *Pistacia chinensis ssp. Integerrima* that contains α-pinene is effective against CCl_4-induced

hepatotoxicity at the doses of 0.1 ml/kg and 0.2 ml/kg in mice. Pretreatment of this oil is attributed to its free radical scavenging capacity, which inhibits lipid peroxidation, and elevates antioxidant enzymes like Superoxide dismutase (SOD), and catalase as well as non-enzymatic antioxidant glutathione (GSH) [28]. *Foeniculum vulgare* Miller is effective as hepatoprotective in CCl_4-treated Sprague-Dawley rats at the dose of 5.52 mg/kg for seven days. It helps to reduce the AST, ALT as well as alkaline phosphatase (ALP) levels [29-30]. Mechanisms of α-Pinene in hepatoprotection through free radical scavenging and modulation of NF-κB and MAPK signaling pathways is shown below in (Figure 2).

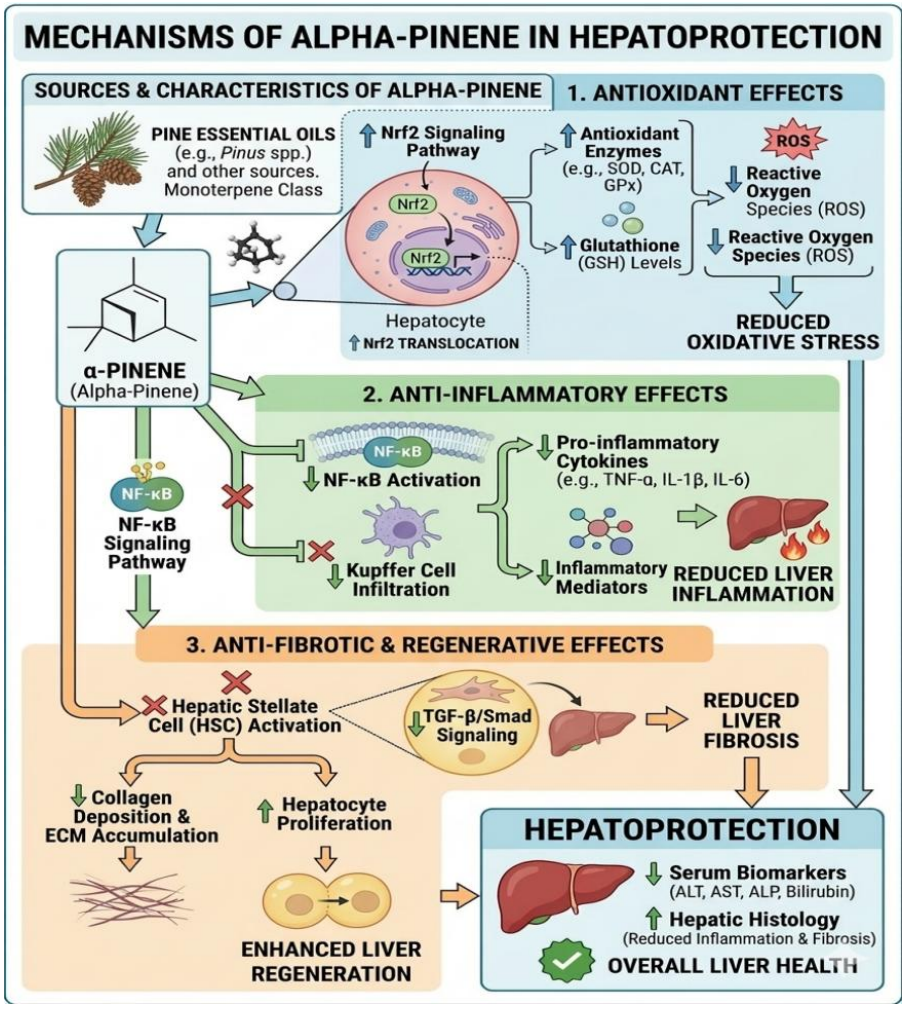

Figure 2. Mechanisms of α-pinene in hepatoprotection through free radical scavenging and modulation of NF-κB and MAPK signaling pathways.

4.2 Geraniol

Geraniol (3,7-dimethylocta-trans-2,6-dien-1-ol) is a water-soluble acyclic monoterpene [14] possessing the chemical formula $C_{10}H_{18}O$. It's commonly found in several essential oils from the following sources ninde oil, palmarosa oil, *Monarda fistulosa*, rose oil, and citronella oil [31]. Geraniol has diverse pharmacological activities like anti-inflammatory, antimicrobial, antioxidant, and neuroprotective effects [13,14]. It shows free radical scavenging activities against the DPPH radical [13]. Geraniol elevates the cell viability remarkably as well as exhibiting a 120% increase in glutathione content, 455 increases in superoxide content, and restoration of mitochondrial membrane potential. It also helps in the reduction of lipid peroxidation; it inhibits nitric oxide (NO) release as well as the generation of ROS in pretreated cells. Geraniol significantly protects the liver against ROS [32]. It is extensively used in lung inflammatory diseases where the most critical control point is oxidative stress. Also in research, it was found that geranium, lemongrass, and spearmint oils as well as their major constituent terpenoids distinctly suppressed TNF-α induced neutrophil adherence [33]. Geraniol also shows an effect on sham-operated rats for the regeneration of the liver rat the dose of 100 mg/kg after 70% partial hepatectomy. Geraniol helps in increasing the mitotic activity in hepatocytes which in turn triggers the regeneration process. It also assists in TNF-α and IL-6 gene expression 24 and 48 h following partial hepatectomy results. The level of ALT declined after administration of erythropoietin 48h. Liver cells undergo cell cycle within some few minutes following the loss of hepatocytes. TNF-α and IL-6 cause G0 to G1 transition in the cell cycle, [13] Similarly, researchers expressed that Intravenous treatment of 12.5mg/dl geraniol over 4 weeks in male Sprague-Dawley rats revealed greater anti-oxidant effects with no level of liver toxicity It elevates the hepatic catalase, NADPH Quinoline oxidoreductase 1 (NQO1) and SOD. Geraniol also aids in increasing the expression of Nrf2 protein

and in turn, activates Nrf2-mediated antioxidants pathways [14]. The CYP3A1/2, CYP2E1, CYP1A2 down-regulation, as well as up-regulation of the anti-oxidant defense, may have specific therapeutic interest but have virtually no toxicity [34]. Geraniol is an emerging hepatoprotective compound through Nrf2/HO1 antioxidant pathway. Besides this, geraniol is also found to trigger the activation of Nrf2 and the increase in the expression of HO1 [35]. In addition, geraniol is known to be an antioxidant by stimulating antioxidant capacity and GSH expression [36]. iNOS, COX-2 and TNF-α are also suppressed by geraniol, and this demonstrates the anti-inflammatory effects of geraniol. Also, Geraniol showed decrease in anti-apoptotic effects, Bax and caspase-3, 9 effects in liver tissue [37]. The Mechanistic overview of geraniol in hepatoprotection via activation of Nrf2/HO-1 signaling and suppression of inflammatory and apoptotic pathways is presented below in (Figure 3).

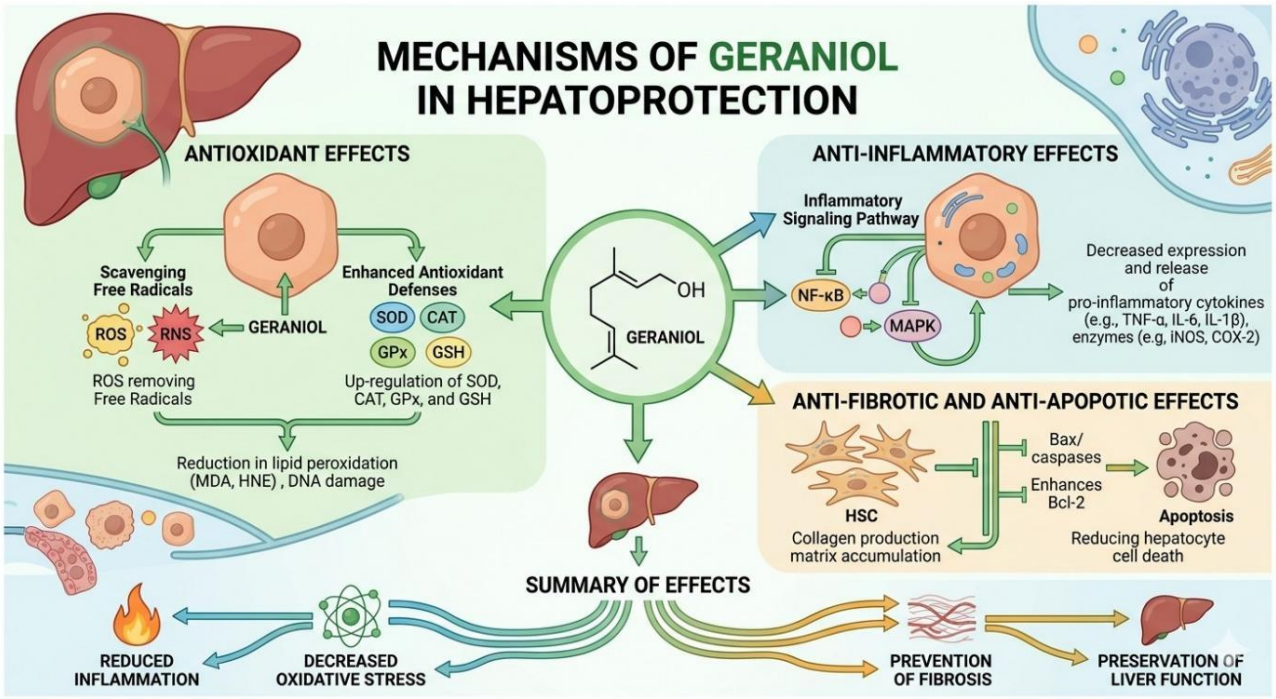

Figure 3. Mechanistic overview of geraniol in hepatoprotection via activation of Nrf2/Ho-1 signaling and suppression of inflammatory and apoptotic pathways.

4.3 Nerol

Nerol monoterpenoid alcohol (2Z)-3,7-Dimethylocta-2,6-dien-1-ol originally isolated from neroli oil. It is also obtained from the essential oils of lemon grass [38]. Researchers have reported many different activities of nerol until now such as antioxidants, antispasmodic, antifungal, anthelmintic and even cardiovascular diseases such as arrhythmias. Moreover, its hepatoprotective activity has also been proved by Islam et al., [22]. Researchers have proved the hepatoprotective activity of nerol by inducing liver toxicity through paracetamol (640 mg/kg) in rats. Animals received two different doses (50 mg/kg, 100 mg/kg) of nerol for 14 days and its hepatoprotective action was checked by comparing it with the standard drug silymarin (50 mg/kg). After 14 days, the researcher performed biochemical analysis and histopathological studies in which ALT, AST, ALP, and LDH (lactate dehydrogenase) levels decreased compared to the vehicle-treated group 100mg/kg dose of nerol significantly reversed the paracetamol induced hepatotoxicity whereas 50 mg/kg dose resulted in hepatoprotection along with little inflammation. Lipid peroxidation and cholesterol levels also got altered with nerol treatment. The mechanism through which nerol presented its hepatoprotective activity is still required to understand in further studies [22]. Nerol is also obtained from neroli oil which is extracted from aromatic flowers through hydro distillation. The hepatoprotective activity of neroli oil against paracetamol-induced hepatotoxicity has been proved by Patil et al., he proved this activity by taking three different doses of neroli oil (low 100 mg/kg, medium 200 mg/kg, high 400 mg/kg) and giving them to the Wistar rats for 30 days. After that animal was sacrificed by anesthetizing with ether, and further blood was collected from the positive control group for biochemical analysis which resulted in a decrease in ALT, AST, and ALP levels when compared to normal control. Also, Neroli oil decreased the level of Thio barbituric Acid Reactive Substances (TBARS), whereas GSH, MDA, and SOD levels increased in liver homogenate proving the hepatoprotective activity of neroli oil. So, Nerol a constituent of neroli oil may also possess hepatoprotective activity with different mechanisms [23]. Another researcher, Givianetal, proved biochemical and histological parameters of nerolin non-alcoholic fatty liver disease in naval medical research institute mice. Here, the animals were divided into 7 groups with 8 animals each. Fatty liver was induced by giving a high-fat diet for four weeks. Three experimental groups with doses (30 mg/kg, 60 mg/kg, and 90 mg/kg) were given oral gavage for four weeks. After anesthetizing the mice with either inhalation, the histological and biochemical assessment was done. The results showed a decrease in AST, ALT, and ALP as compared to the fatty liver group. The SOD levels increased after nerol treatment. Nerol (90 mg/kg) repaired the fatty liver tissue, showing nerolis as hepatoprotective

compound [39]. The mechanism of hepatoprotection of nerol is unexplored but the other potential regulative pathways that could be involved in the management of the toxicity of liver through nerol are Nrf2/HO1 pathway, inflammatory factors, IL-1β, IL-6, TNF-α, NF-κB and apoptotic (Caspase-3, Caspase-9, Bcl2, and Bax) factors, as well as autophagic factors [40]. Mechanisms of nerol in hepatoprotection via regulation of oxidative stress, inflammatory cytokines, and apoptotic pathways is shown below in (Figure 4).

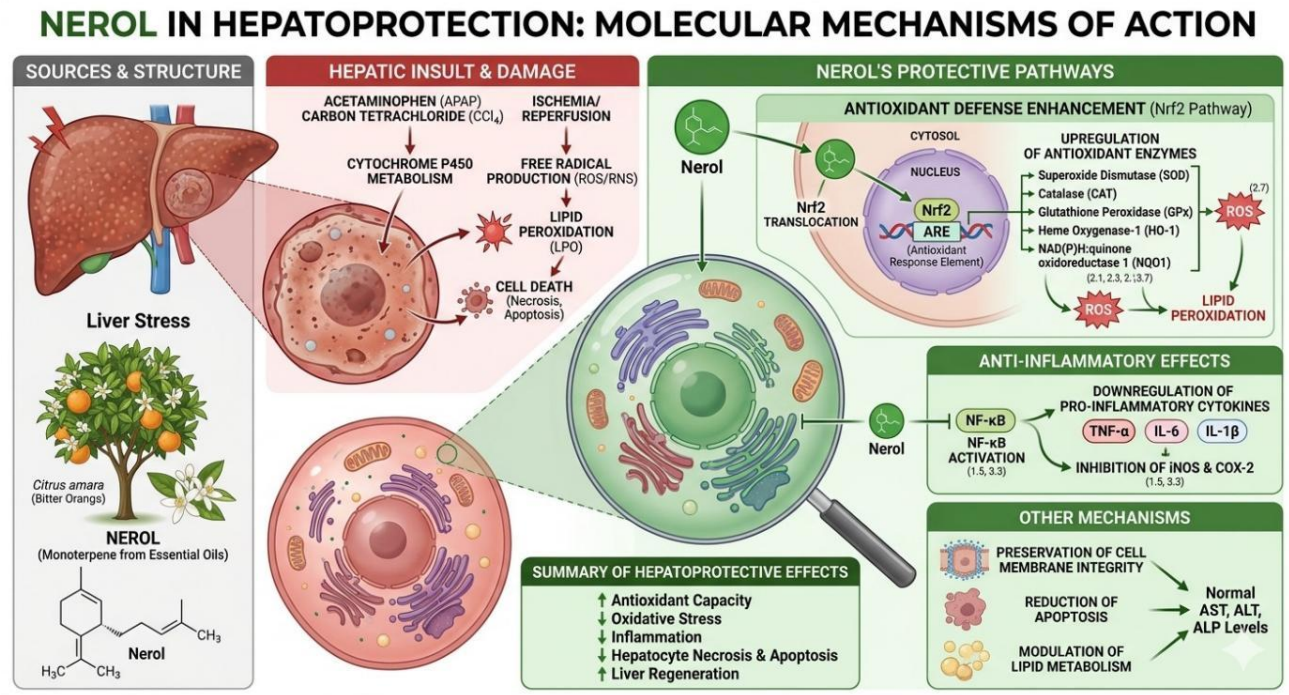

Figure 4. Mechanisms of nerol in hepatoprotection via regulation of oxidative stress, inflammatory cytokines, and apoptotic pathways.

4.4 Limonene

Limonene (1-methyl-4- (1-methylethenyl) cyclohexane) is a monoterpene present in Rutaceae family of plants and it is present in natural fruits like grapefruit, tangerine, orange, mandarin, lemon and elemi [41]. It is often utilized as a scent component in cosmetic items and as a food supplement because it is regarded as secure [42]. Limonene is an organic compound that exists in two visual isomeric forms, d-limonene and l-limonene, as well as the racemic combination dipentene [24]. Absorption of limonene often occurs through the gastrointestinal tract in both humans and animals. As a result, absorbed limonene was distributed throughout the body, including the liver, lungs, and kidneys [43]. Eventually according to reports, d-limonene is not only non-mutagenic but also non-carcinogenic in people. It also exhibits low toxicity even when taken continuously for up to many years [44]. According to Anandakumar et al., 2020, the study indicated the hepatoprotective properties of limonene in male Wistar rats that were exposed to prolonged immobility. The effect of orally administered limonene (10 mg/kg b.w) on stress-immobilized rats was a good working procedure on the liver enzymes of AST, ALT as well as the reduction of MDA. The expression of the genes of IL-1, IL-6, TNF-α, and NF-κB was highly suppressed in rats treated with D-Limonene. Liver histology showed that there was less inflammatory cell invasion in the liver than in the untreated groups. The antioxidant, anti-inflammatory, and antiapoptotic properties of limonene are presumed to mediate the hepatoprotective effect of the substance [24]. Mechanistic insights into limonene-mediated hepatoprotection via antioxidant, anti-inflammatory, and anti-apoptotic pathways is shown below in (Figure 5).

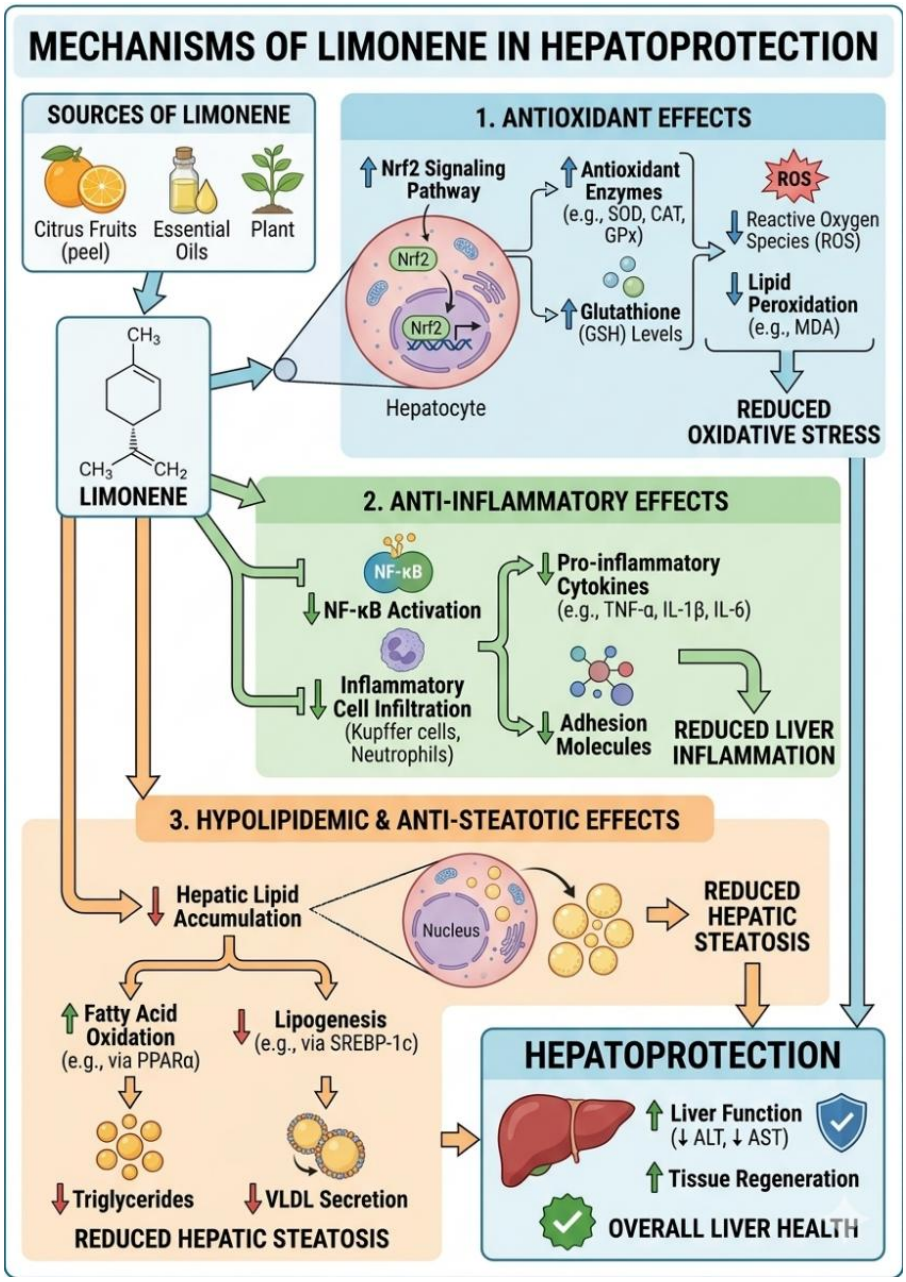

Figure 5. Mechanistic insights into limonene-mediated hepatoprotection via antioxidant, anti-inflammatory, and anti-apoptotic pathways.

4.5 Camphene

Camphene (2, 2-dimethyl-3-methylenebicyclo[2.2.1]heptane) [45] is found in *Rosamarinus officinalis, zingiber officinale,* turpentine, cypress oil and minorly in camphor oil, neroli, mango etc. Camphene was obtained from isomerization of α-pinene [46]. Camphene has been reported to possess activities like antifungal, antioxidant, antiviral, anti-bacterial and anti-diabetic [47]. As reported by researcher's, camphene regulates different cytokines in liver such as TNF-α or IL-6 and it also reduces high fat diet-induced increase in liver weight, decreases liver lipid deposition. Furthermore, camphene also elicited AMPK activation in liver [48]. As reported by researcher camphene likely exerts its hypolipidemic effect by upregulating SREBP-1 and inhibiting MTP in response to reduced intracellular cholesterol [49]. Daoudi et al. mentioned that camphene is found to be an active ingredient of various plants such as *Rosmarinus officinalis,* neroli oil, *Foeniculum vulgare* which are reported to show hepatoprotective action against different chemical induced hepatoxicity like CCl_4-induced, paracetamol-induced, and CCl_4-induced models respectively [50-52]. On the basis of above proved actions in liver, camphene can be used as hepatoprotective compound. Mechanistic overview of camphene-mediated hepatoprotection via antioxidant, anti-inflammatory, and hypolipidemic pathways is shown below in (Figure 6).

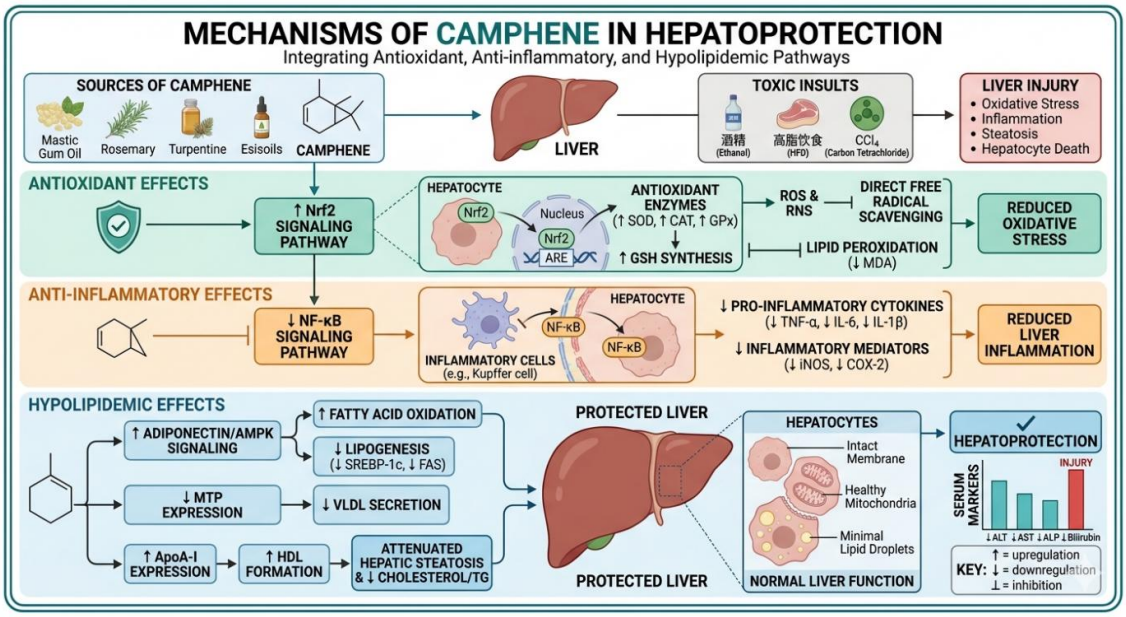

Figure 6. Mechanistic overview of camphene-mediated hepatoprotection via antioxidant, anti-inflammatory, and hypolipidemic pathways.

4.6 Myrcene

Myrcene (7-Methyl-3-methylocta-1,6-diene) is a monoterpene, an oily liquid and insoluble in water. It is a plant metabolite that is an anti-inflammatory agent and a volatile oil component. Pretreatment with myrcene was shown to attenuate liver injury and restore hepatic cellular function and integrity, as evidenced by a reduction in serum aminotransferase levels [16]. Oral administration of *Ferulagocampestris* for three consecutive days at doses of 20 mg/kg, 50 mg/kg that contain myrcene blocked D-galactosamine/lipopolysaccharide GalN/LPS-induced serum raised the levels of AST, ALT, and MDA. It also highly improved liver damage. Moreover, F. campestris in the treatment of liver tissues suppressed GalN/LPS-induced mRNA IL-1β, IL-6 inducible NO synthase and thus reduced oxidative stress and inhibited cytokines [15]. β-myrcene is confirmed to have hepatoprotective effect against acetaminophen induced hepatotoxicity in Balb/c mice. Myrcene cause of liver damage can be prevented by pretreating the Acetaminophen at 100 mg/kg or 200mg/kg so as to reduce the liver enzymes. It also re-establishes the functions of the hepatic cells and in addition, hepatic integrity contributes to reducing the release of serum aminotransferases to the forces of the blood circulation. In this study, it has been proved that pretreatment of myrcene is able to reduce the elevated amount of NO as well as myeloperoxidase which are the precursors of oxidative stress. It proves that it's a potent antioxidant [16]. Hepatoprotective mechanisms of myrcene through inhibition of oxidative stress and suppression of pro-inflammatory mediators is shown below in (Figure 7).

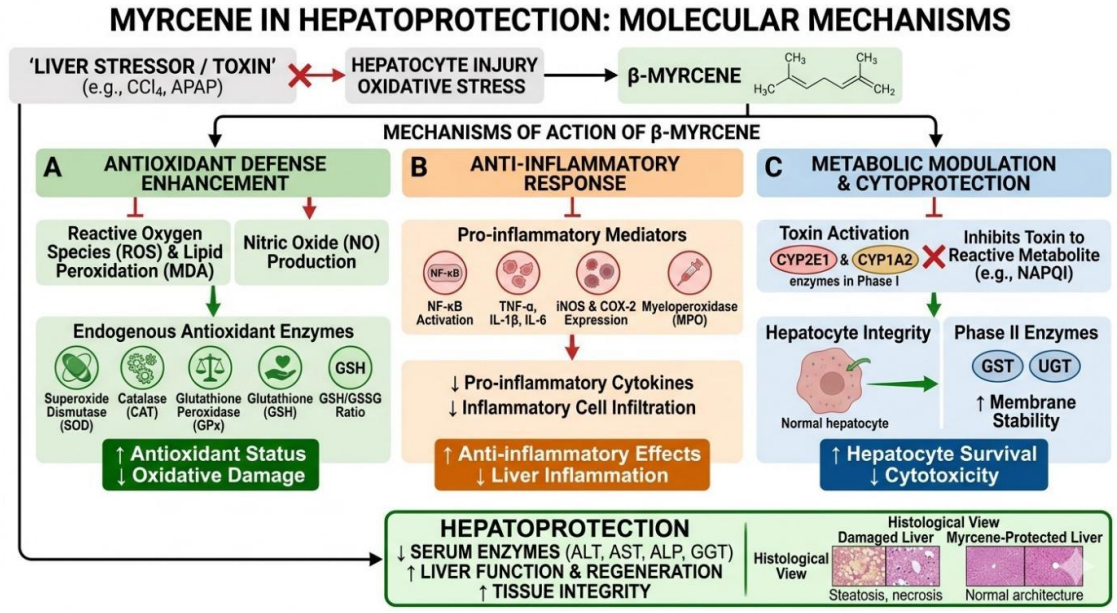

Figure 7. Hepatoprotective mechanisms of myrcene through inhibition of oxidative stress and suppression of pro-inflammatory mediators.

5. Limitations and Future Directions

This review has a number of limitations. It is largely descriptive and mostly relies on in vitro and in vivo research, and does not provide critical assessment of the study quality or comparative analysis across models. Experimental design and models of hepatotoxicity vary and reduce consistency of conclusions. The aspects of structure-activity relationship (SAR) are not fully addressed and limit the in-depth mechanistic understanding. The translational relevance is also restricted, with, mostly, preclinical evidence only, and lack of information about dose feasibility, pharmacokinetics, bioavailability, and human long-term safety. The review also tends to deal with less than a large number of monoterpenes only and overlooks other possible relevant compounds like perillyl alcohol, carvacrol, thymol, borneol, and linalool. Further studies must focus on critical evaluation of study, systematic analysis of SAR and optimally designed clinical studies to enhance mechanistic insight and facilitate clinical translation of monoterpenes in the treatment of liver diseases.

6. Discussion and Conclusion

A critical synthesis of the literature reveals that monoterpenes are a structurally diverse class of plant-derived compounds with significant hepatoprotective potential; however, their biological effects are not consistent and strongly depend on chemical structure, dosage, and experimental context. While hydrocarbon monoterpenes like limonene and α-pinene are more often linked to the modulation of inflammatory signaling pathways, oxygenated monoterpenes like geraniol and nerol typically show more prominent antioxidant activity through the enhancement of endogenous defense systems. Although there are still few direct comparative studies, this distinction points to an emerging structure–activity relationship. Attenuation of oxidative stress and inflammation through modulation of important pathways, such as Nrf2, NF-κB, and MAPK, is a common mechanistic theme across studies. These pathways seem to function in concert, suggesting that monoterpene hepatoprotection is a multi-target process rather than a single-pathway effect. However, the majority of research reports associative results, and comprehensive molecular interactions remain inadequately described. Significantly, the majority of the evidence currently available comes from in vitro and animal studies, with a wide range of experimental designs, dosage schedules, and hepatotoxicity models. This lack of standardization reduces the overall translational relevance and restricts the comparability of results. Moreover, pharmacokinetics, bioavailability, and long-term safety data are scarce and well-designed human clinical studies are conspicuously lacking. Standardized experimental procedures, systematic structure-activity relationship analyses, and mechanistic studies that elucidate pathway interactions should be given top priority in future research. Most importantly, to determine the safety and effectiveness of monoterpenes in human liver diseases, carefully monitored clinical trials are needed. Extending research beyond a narrow range of compounds to encompass a wider array of monoterpenes will yield a more thorough comprehension of their therapeutic potential. To gain a more complete understanding of the hepatoprotective potential of monoterpenes and to find more candidates with therapeutic relevance, future studies must include a wider range of monoterpenes, such as perillyl alcohol, carvacrol, thymol, borneol, and linalool. In conclusion, although monoterpenes exhibit encouraging hepatoprotective characteristics, existing evidence is still in its infancy, necessitating extensive research prior to their complete clinical implementation.

Author Contributions

S.V. and D.K. conducted the literature survey and wrote the manuscript. S.V. also created the figures.

Conflict of Interest

The authors declare no competing interests.

Generative AI Statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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