

# Plant-Based Therapeutics for Ocular Diseases: From Ethnopharmacology to Nanomedicine

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Received: 26<sup>th</sup> Dec, 2025; Revised: 18<sup>th</sup> Feb 2026; Accepted: 22<sup>th</sup> Feb, 2026; Available Online: 30<sup>th</sup> March, 2026

## ABSTRACT

Oxidative stress plays a critical role in the initiation and progression of multiple ocular disorders, including cataract, glaucoma, and age-related macular degeneration, primarily through excessive generation of reactive oxygen species and subsequent cellular damage. The ocular tissues are particularly susceptible to oxidative injury due to their high metabolic activity and constant exposure to environmental stressors. Traditional medicinal plants native to Central India represents a rich source of bioactive compounds with well-documented antioxidant potential and historical relevance in the management of eye diseases. Recent advances in nanotechnology have enabled the development of plant-based nanomedicine systems designed to overcome the limitations associated with conventional phytotherapy, such as poor solubility, low bioavailability, and limited ocular permeability. Incorporation of phytoconstituents such as flavonoids, polyphenols, and terpenoids into nanocarriers including nanoemulsions, liposomes, and solid lipid nanoparticles has demonstrated enhanced stability, improved corneal penetration, and controlled drug release. This review critically examines the integration of ethnopharmacological knowledge with contemporary nanotechnological approaches for the management of oxidative stress-induced ocular conditions. It further discusses formulation strategies, therapeutic potential, and emerging evidence supporting the efficacy of these systems. Additionally, key challenges related to safety, standardization, and clinical translation are addressed. The study underscores the potential of traditional plant-based nanomedicine as a promising and sustainable approach for improving ocular health outcomes.

**Keywords:** Oxidative Stress; Phytoconstituents; Nanomedicine; Ocular Delivery; Antioxidants

**How to cite this article:** Manapure SR, Pande VB, Admane PS, Yadav N and Chandel SS, Plant-Based Therapeutics for Ocular Diseases: From Ethnopharmacology to Nanomedicine. Int J Drug Deliv Technol. 2026;16(3): 727-746. DOI: 10.25258/ijddt.16.3.81

**Source of support:** Nil.

**Conflict of interest:** None

## 1. INTRODUCTION

Oxidative stress represents a fundamental pathological mechanism underlying a wide spectrum of ocular disorders, arising from an imbalance between the production of reactive oxygen species (ROS) and the antioxidant defence capacity of ocular tissues. Due to continuous exposure to light, high oxygen consumption, and rich polyunsaturated lipid content, ocular structures such as the cornea, lens, and retina are particularly vulnerable to oxidative damage. Excessive ROS generation can induce lipid peroxidation, protein modification, mitochondrial dysfunction, and DNA damage, ultimately contributing to cellular apoptosis and tissue degeneration (Bohm et al., 2023; Nita & Grzybowski, 2016).

In cataract formation, oxidative modification of lens proteins leads to aggregation and loss of transparency, while in glaucoma, ROS-mediated damage to trabecular meshwork and retinal ganglion cells contributes to increased intraocular pressure and neurodegeneration (McMonnies, 2018; Masuda et al., 2017). Similarly, oxidative stress plays a central role in the pathogenesis of age-related macular degeneration (AMD) by promoting retinal pigment epithelium dysfunction, chronic inflammation, and photoreceptor degeneration (Abokyi et al., 2020). In diabetic retinopathy, hyperglycemia-induced oxidative stress enhances lipid peroxidation, inflammation, and ferroptosis-related pathways, further aggravating retinal vascular damage (Fan et al., 2022; Olvera-Montano et al., 2019). Additionally, oxidative stress is strongly

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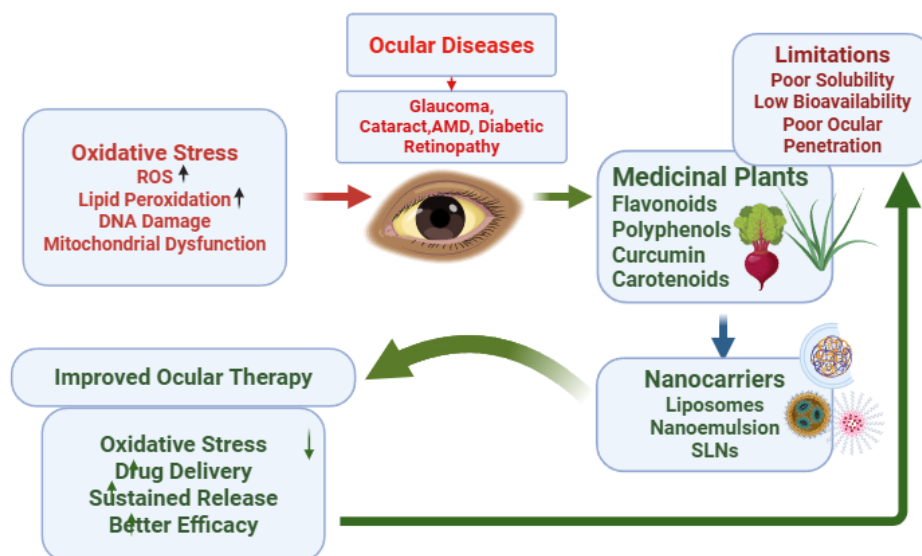
associated with dry eye disease and corneal epithelial injury through activation of pro-inflammatory signaling and mitochondrial impairment (Seen & Tong, 2018; Xiang et al., 2016). Furthermore, biomarkers such as malondialdehyde and inflammatory mediators have been widely reported as indicators of oxidative damage in ocular conditions, highlighting their diagnostic and therapeutic relevance (Ahmad & Ahsan, 2020; Maurya et al., 2021). Collectively, these findings emphasize that oxidative stress is not only a contributing factor but also a central driver in the initiation and progression of major ocular diseases, making it a critical target for therapeutic intervention.

Traditional medicinal systems in Central India, particularly those practiced by indigenous and tribal communities, rely extensively on plant-based therapies for the management of various diseases, including ocular disorders. These ethnomedicinal practices are deeply rooted in regional biodiversity and traditional knowledge, where numerous medicinal plants are utilized for their antioxidant, anti-inflammatory, and cytoprotective properties. Plant-derived bioactive compounds such as polyphenols, flavonoids, carotenoids, and alkaloids have been widely reported to mitigate oxidative stress by scavenging reactive oxygen species (ROS), enhancing endogenous antioxidant defences, and preventing cellular damage (Akbari et al., 2022; Forni et al., 2019). Several medicinal plants commonly used in traditional Indian medicine have demonstrated significant potential in managing oxidative stress-related ocular conditions. For instance, phytochemicals such as curcumin and kaempferol have shown protective effects against retinal oxidative injury by reducing lipid peroxidation and preserving cellular integrity (Mandal et al., 2009; Du et al., 2018). Similarly, bioflavonoids present in traditional herbal formulations have been reported to play a crucial role in preventing cataract formation and other degenerative eye diseases through their strong free radical scavenging and metal-chelating properties (Majumdar & Srirangam, 2010). Ethnopharmacological studies and systematic reviews further indicate that medicinal plants are widely employed in the treatment of common ophthalmic disorders, highlighting their therapeutic relevance and accessibility in resource-limited settings (Alghamdi et al., 2023).

In addition, certain traditional formulations have demonstrated aldose reductase inhibitory activity and anti-

cataract potential, suggesting their role in preventing diabetes-associated ocular complications (Gacche & Dhole, 2011). The protective effects of plant-based antioxidants are also supported by evidence indicating their ability to modulate oxidative stress pathways involved in ageing and chronic diseases, including those affecting ocular tissues (Bungau et al., 2019). Collectively, these findings underscore the importance of traditional plant-based medicine in Central India as a valuable source of antioxidant therapies, which may be further optimized through modern approaches such as nanotechnology for improved efficacy and targeted ocular delivery.

Nanomedicine refers to the application of nanotechnology in the diagnosis, prevention, and treatment of diseases through the use of nanoscale materials and drug delivery systems. In recent years, nanomedicine has emerged as a promising approach for enhancing the therapeutic efficacy of plant-derived bioactive compounds, particularly in the management of oxidative stress-related ocular diseases. Conventional phytochemicals often suffer from limitations such as poor aqueous solubility, low bioavailability, rapid degradation, and limited ocular penetration, which restrict their clinical effectiveness. Nanocarrier-based systems, including liposomes, nanoemulsions, polymeric nanoparticles, and solid lipid nanoparticles, have been developed to overcome these challenges by improving drug stability, controlled release, and targeted delivery to ocular tissues (Bonifácio et al., 2014; Civelek et al., 2024). The integration of phytoconstituents with nanotechnology has shown significant potential in mitigating oxidative stress by enhancing the bioactivity and retention of antioxidant compounds within ocular environments. For instance, nanoformulations of lutein and other plant-derived antioxidants have demonstrated improved protection against oxidative damage induced by light exposure and reactive oxygen species (Chae et al., 2021; Madaan et al., 2017). Similarly, nanotechnology-based delivery systems have been explored for effective management of cataract and retinal disorders by facilitating better penetration across ocular barriers and reducing systemic side effects (Sunkireddy et al., 2013; Krishnaswami et al., 2024). Emerging evidence also highlights the potential of combining herbal constituents with nanocarriers in the treatment of diabetic retinopathy, where oxidative stress plays a central pathogenic role (Ganore et al., 2026).



**Figure 1:** Plant-Based Nanomedicine Strategies for Oxidative Stress-Induced Ocular Diseases

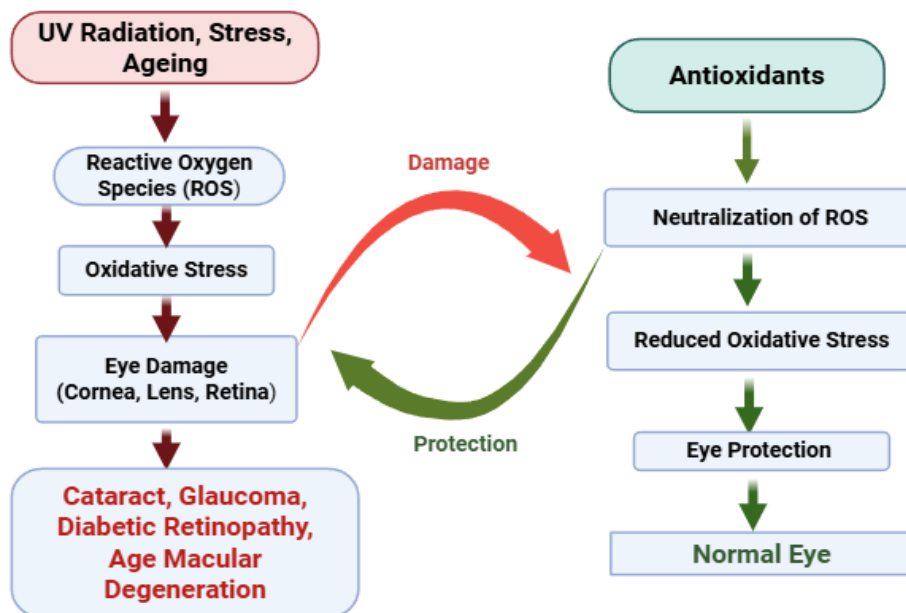
## 2. MECHANISM OF OXIDATIVE STRESS IN OCULAR DISEASES

Oxidative stress is characterized by an imbalance between the production of reactive oxygen species (ROS) and the efficiency of endogenous antioxidant defence mechanisms, resulting in significant cellular and molecular damage. Ocular tissues are particularly susceptible to oxidative stress due to their high metabolic activity, continuous exposure to light, and elevated levels of polyunsaturated fatty acids. At the cellular level, excessive ROS generation disrupts mitochondrial function, induces lipid peroxidation, and promotes oxidative modifications of proteins and nucleic acids, ultimately leading to cellular dysfunction, apoptosis, and tissue degeneration. Mitochondrial impairment further amplifies oxidative damage by reducing ATP production and increasing ROS accumulation, thereby accelerating disease progression (Kimura et al., 2017; Xu et al., 2025; Kowluru and Mishra, 2015; Wu et al., 2018).

Reactive oxygen species, including superoxide anion ( $O_2^-$ ), hydrogen peroxide ( $H_2O_2$ ), hydroxyl radicals ( $\bullet OH$ ), and singlet oxygen, are generated as byproducts of cellular metabolism and in response to environmental stressors. Although ROS play essential roles in cellular signaling under physiological conditions, their excessive accumulation leads to oxidative damage in ocular tissues. Specifically, ROS initiate lipid peroxidation, resulting in membrane destabilization, and induce structural and functional alterations in proteins, leading to enzyme inactivation and aggregation. Additionally, ROS-mediated

DNA damage interferes with gene expression and promotes apoptotic pathways. Persistent oxidative stress also activates inflammatory signaling cascades, further exacerbating tissue injury and contributing to the progression of ocular diseases (Calderon et al., 2017; Li et al., 2022; Hammes, 2018).

Oxidative stress is a central factor in the pathogenesis of several ocular disorders, including cataract, retinal diseases, and glaucoma. In cataractogenesis, oxidative stress leads to the aggregation and denaturation of lens crystallin proteins, resulting in the loss of lens transparency and progressive opacification (Sunkireddy et al., 2013). In retinal diseases such as diabetic retinopathy and age-related macular degeneration (AMD), oxidative stress contributes to mitochondrial dysfunction, vascular abnormalities, and chronic inflammation. Hyperglycemia-induced ROS production promotes retinal cell apoptosis, disruption of the blood-retinal barrier, and pathological angiogenesis. Furthermore, oxidative stress has been implicated in ferroptotic cell death of retinal pigment epithelial cells, thereby exacerbating retinal degeneration (Kowluru and Mishra, 2015; Totsuka et al., 2019; Behl et al., 2016; Ferrington et al., 2017). In glaucoma, oxidative stress induces degeneration of retinal ganglion cells and optic nerve damage through mitochondrial dysfunction, impaired axonal transport, and increased neuronal apoptosis. Additionally, oxidative damage to trabecular meshwork cells contributes to elevated intraocular pressure, a key factor in glaucoma pathogenesis (Kimura et al., 2017).



**Figure 2:** Oxidative Stress-Induced Ocular Damage and Antioxidant Defence Mechanism

### 3. TRADITIONAL PLANT-BASED APPROACHES TO COMBAT OXIDATIVE STRESS

Central India is rich in medicinal flora traditionally used for managing oxidative stress-related ocular disorders. Plants such as *Azadirachta indica* (neem), *Emblica officinalis* (amla), *Moringa oleifera*, *Curcuma longa* (turmeric), and *Coriandrum sativum* (coriander) are known for their potent antioxidant properties due to the presence of bioactive compounds like flavonoids, polyphenols, carotenoids, alkaloids, and vitamins (e.g., Vitamin C and E). These compounds play a crucial role in scavenging reactive oxygen species (ROS), thereby preventing oxidative damage in ocular tissues such as the lens, retina, and cornea. Previous studies have

demonstrated that plant-derived antioxidants, including flavonoids like quercetin and kaempferol, can protect retinal pigment epithelial cells and delay cataract formation by reducing lipid peroxidation and enhancing endogenous antioxidant defences (Orhan et al., 1999; Du et al., 2018; Gao et al., 2023). Additionally, traditional medicinal systems have long utilized these plants in the form of decoctions, eye washes, and dietary supplements to manage conditions such as cataract, diabetic retinopathy, and corneal inflammation (Huynh et al., 2013; Bungau et al., 2019). Thus, the integration of traditional knowledge with modern scientific evidence highlights the therapeutic potential of Central Indian medicinal plants in ocular health management.

**Table 1:** Medicinal Plants Commonly Used in Central India for the Management of Oxidative Stress-Induced Ocular Disorders

Plant Name	Bioactive Compounds	Antioxidant Role	Traditional / Reported Ocular Use	References
<i>Azadirachta indica</i> (Neem)	Flavonoids, limonoids, nimbidin	ROS scavenging, anti-inflammatory	Eye infections, irritation relief	Huynh et al., 2013
<i>Emblica officinalis</i> (Amla)	Vitamin C, polyphenols, tannins	Strong antioxidant, prevents oxidative damage	Cataract prevention, vision improvement	Bungau et al., 2019
<i>Moringa oleifera</i>	Quercetin, chlorogenic acid, vitamins A & C	Reduces oxidative stress, retinal protection	Nutritional support for eye health	Gao et al., 2023
<i>Curcuma longa</i> (Turmeric)	Curcumin (polyphenol)	Anti-inflammatory, inhibits lipid peroxidation	Eye inflammation, oxidative damage protection	Pawlowska et al., 2019
<i>Coriandrum sativum</i> (Coriander)	Flavonoids, terpenoids, Vitamin	Antioxidant, cooling effect	Eye irritation relief (traditional)	Huynh et al., 2013

	C		use)	
<i>Trigonella foenum-graecum</i> (Fenugreek)	Alkaloids, flavonoids	Prevents cataract via antioxidant action	Anti-cataract activity	Gupta et al., 2010
<i>Curcuma longa</i> (Turmeric)	Curcumin (polyphenol)	ROS scavenging, anti-inflammatory, inhibits lipid peroxidation	Cataract, retinal protection	Agarwal et al., 2009
<i>Azadirachta indica</i> (Neem)	Flavonoids, limonoids	Antioxidant, anti-inflammatory	Eye infections, irritation relief	Sharma et al., 2024; Panghal et al., 2010
<i>Emblica officinalis</i> (Amla)	Vitamin C, polyphenols	Strong antioxidant, prevents oxidative damage	Cataract prevention, vision improvement	Sharma et al., 2024
<i>Tinospora cordifolia</i> (Giloy)	Alkaloids, glycosides	Reduces oxidative stress, immunomodulatory	General eye health support	Sharma et al., 2024
<i>Ocimum sanctum</i> (Tulsi)	Eugenol, flavonoids	Antioxidant, anti-inflammatory	Eye irritation, traditional use	Panghal et al., 2010
<i>Terminalia arjuna</i>	Tannins, flavonoids	Antioxidant activity	Supportive role in ocular health	Sharma et al., 2024
<i>Butea monosperma</i>	Flavonoids	Free radical scavenging	Traditional eye applications	Sharma et al., 2024
<i>Aloe vera</i>	Vitamins, polysaccharides	Antioxidant, soothing effect	Eye irritation, inflammation relief	Panghal et al., 2010
Various Indian medicinal plants (study-based)	Phenolics, flavonoids	Aldose reductase inhibition (anti-cataract mechanism)	Cataract prevention	Kumar et al., 2011
<i>Vitex negundo</i>	Luteolin (flavonoid)	Prevents oxidative stress-induced cataract	Cataract management	Rooban et al., 2012

#### 4. NANOMEDICINE IN TRADITIONAL PLANT-BASED TREATMENTS

Nanotechnology has emerged as a promising strategy to overcome the inherent limitations of plant-derived antioxidants, including poor aqueous solubility, low bioavailability, rapid degradation, and limited ocular penetration. Nanoparticle-based drug delivery systems significantly enhance the stability, bioavailability, and controlled release of phytochemicals, thereby improving their therapeutic efficacy in oxidative stress-induced ocular diseases (Sahoo et al., 2008; Li et al., 2023; Lima et al., 2019). Various nanocarrier systems such as liposomes, solid lipid nanoparticles (SLNs), polymeric nanoparticles, dendrimers, nanomicelles, and nanovesicles have been extensively investigated for encapsulating plant-based bioactives and facilitating targeted ocular delivery (Rahman et al., 2020; Olowosoke et al., 2026; Ates et al., 2025). These nanocarriers effectively overcome physiological barriers including corneal impermeability, tear turnover, and nasolacrimal drainage, resulting in enhanced drug retention and bioavailability.

Several studies have demonstrated the successful application of plant-derived nanomedicines in managing oxidative stress-related ocular disorders. For instance,

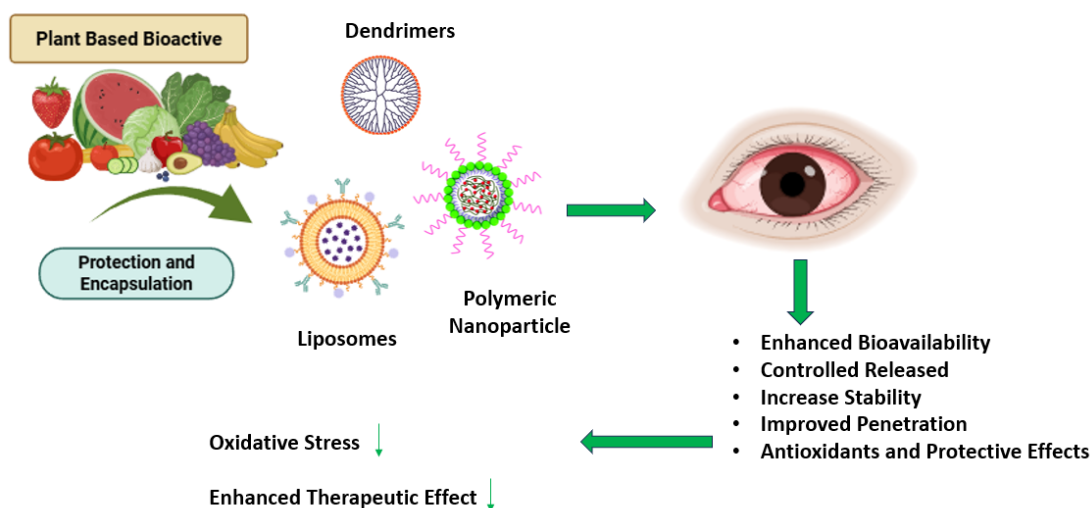
chitosan-based nanoparticles have been employed for the delivery of rosmarinic acid, improving ocular permeability and antioxidant activity (da Silva et al., 2016). Similarly, micelle-nanogel platforms and thermosensitive hydrogels have been developed for sustained release of ferulic acid and other phytochemicals, enhancing therapeutic outcomes in corneal and dry eye conditions (Grimaudo et al., 2020; Tsai et al., 2016; Zhou et al., 2025). Cyclodextrin-based inclusion complexes have also been shown to improve the solubility and ocular delivery of flavonoids such as quercetin and resveratrol (Krstić et al., 2022; Lima et al., 2019). In addition, spanlastic nanovesicles and cubosome-based systems have demonstrated improved anti-inflammatory and antioxidant efficacy for compounds like vanillic acid and zeaxanthin (Ibrahim et al., 2022; Kumari et al., 2025). Advanced nanoformulations such as dendrimer-based nanoparticles and nanozymes further enhance ocular drug transport and provide multifunctional antioxidant effects (Xue et al., 2024; Ates et al., 2025). Moreover, plant-based nanoparticle eye drops formulations, including olive leaf extract systems, have shown promising results in corneal wound healing and oxidative stress reduction (Migone et al., 2025). The underlying mechanisms involve scavenging of reactive oxygen species (ROS), enhancement of

endogenous antioxidant defense systems, and suppression of inflammation in ocular tissues (Sunkireddy et al., 2013; Medoro et al., 2025). Collectively, these findings highlight that integrating nanotechnology with plant-derived

therapeutics offers a highly efficient and targeted approach for the treatment of oxidative stress-induced ocular diseases.

**Table 2.** Overview of plant-derived bioactive compounds incorporated into various nanocarrier systems for ocular applications

Plant Compound	Nanocarrier System	Ocular Application	Key Outcome	Reference
Rosmarinic acid	Chitosan nanoparticles	Ocular delivery	Improved permeability & antioxidant activity	da Silva et al., 2016
Ferulic acid	Micelle-nanogel	Dry eye / corneal protection	Sustained release & enhanced efficacy	Grimaudo et al., 2020
Ferulic acid	Thermosensitive hydrogel	Corneal wound healing	Controlled release & tissue repair	Tsai et al., 2016
Vanillic acid	Spanlastic nanovesicles	Anti-inflammatory ocular therapy	Enhanced bioavailability	Ibrahim et al., 2022
Quercetin / Resveratrol	Cyclodextrin complexes	Ocular delivery	Improved solubility & bioavailability	Krstic et al., 2022
Rosmarinic acid	Gelatin nanogels	Dry eye disease	Enhanced drug delivery & retention	Zhou et al., 2025
Olive leaf extract	Nanoparticle eye drops	Corneal wound healing	Reduced oxidative stress	Migone et al., 2025
Zeaxanthin	Cubosomes	Antioxidant ocular therapy	Improved antioxidant potential	Kumari et al., 2025
Phytochemicals (general)	Polymeric nanoparticles	Retinal diseases	Targeted delivery & sustained release	Olowosoke et al., 2026
Natural plant extracts	Various nanocarriers	Biomedical/ocular use	Improved stability & delivery	Rahman et al., 2020
Multiple antioxidants	Nanozymes	Ocular oxidative stress	ROS scavenging activity	Xue et al., 2024
Plant bioactives	Dendrimer nanoparticles	Glaucoma	Enhanced transport & multifunctional action	Ates et al., 2025



**Figure 3.** Nanocarrier-Mediated Ocular Drug Delivery of Plant Bioactives

### 5. ADVANTAGES OF PLANT-BASED NANOMEDICINES

Targeted drug delivery to ocular tissues has gained significant attention due to its ability to enhance therapeutic efficacy while minimizing systemic side

effects. Advanced intraocular and nanotechnology-based delivery systems enable precise drug localization, overcoming ocular barriers such as corneal impermeability and rapid tear clearance, thereby improving treatment outcomes in diseases like diabetic retinopathy (Sharma et

al., 2020). In addition, nanoencapsulation techniques significantly enhance the solubility, stability, and bioavailability of poorly water-soluble plant-derived compounds such as lutein, allowing improved therapeutic effectiveness in ocular disorders (Permatasari et al., 2024). Furthermore, the use of biocompatible materials such as chitosan in nanocarrier design ensures reduced toxicity, improved biodegradability, and enhanced safety profiles compared to conventional synthetic drug systems (Lv et al., 2024). Collectively, these advances highlight the potential of plant-based nanomedicine to provide safe, targeted, and efficient therapeutic strategies for oxidative stress-induced ocular diseases.

## 6. CURRENT RESEARCH AND APPLICATIONS

Recent advancements in nanotechnology have significantly enhanced the therapeutic potential of plant-based bioactive compounds in the management of oxidative stress-induced ocular diseases. Over the past decade, numerous studies have reported the development of nanoformulations incorporating phytoconstituents such as curcumin, ginsenoside Rg3, lutein, thymol, and other plant-derived extracts, demonstrating improved efficacy in both *in vitro* and *in vivo* models. RGD-functionalized liposomal delivery of ginsenoside Rg3 has been shown to effectively attenuate oxidative stress and suppress choroidal neovascularization in models of age-related macular degeneration (Zhou et al., 2025). Similarly, curcumin-based nanoformulations, including ceria nanoclusters and hyaluronic acid-based nanoparticles, have exhibited pronounced antioxidant and anti-inflammatory activities in experimental models of cataract, uveitis, and dry eye disease through modulation of oxidative stress pathways (Liu et al., 2022; Tang et al., 2025). Moreover, recent studies have demonstrated that extracellular vesicle-like particles derived from *Curcuma longa* can regulate key signaling pathways such as HIF-1 $\alpha$  and NRF2, thereby mitigating retinal neovascularization and oxidative damage (Chen et al., 2026). Additional investigations have highlighted the protective effects of thymol-based nanomicelles and plant extract-loaded PLGA nanoparticles in reducing oxidative injury in corneal epithelial cells (Song et al., 2020; Tsai et al., 2021).

Despite these promising findings, the majority of current research remains confined to preclinical investigations, including cell-based assays and animal models. Several studies have demonstrated enhanced ocular bioavailability, targeted delivery, and sustained drug release using nanoparticle-based systems, such as curcumin-loaded hydrogels and nanozyme-based eye drops, which have shown improved therapeutic outcomes in models of corneal injury and ocular surface diseases (Sohani et al., 2024; Qiao et al., 2025). However, there is a notable paucity of well-designed clinical trials evaluating the safety and efficacy of plant-based nanomedicines in human subjects, thereby limiting their clinical translation.

Furthermore, the development and commercialization of plant-based nanomedicines face several critical challenges.

These include formulation-related issues such as physicochemical instability, scalability, and reproducibility of nanocarrier systems, as well as difficulties in achieving precise drug loading and controlled release. In addition, stringent regulatory requirements for nanomedicine approval necessitate comprehensive toxicological and pharmacokinetic evaluations, which remain insufficiently addressed in current studies. Concerns regarding long-term biocompatibility and potential nanotoxicity further underscore the need for extensive safety assessments. Therefore, although plant-based nanomedicine represents a promising and innovative therapeutic approach for oxidative stress-associated ocular disorders, further clinical validation and regulatory standardization are essential to facilitate its successful integration into clinical practice.

## 7. FUTURE DIRECTIONS

Future research in plant-based nanomedicine for oxidative stress-induced ocular diseases should emphasize innovation through the exploration of underutilized medicinal plant species, particularly those indigenous to Central India, which may serve as rich sources of novel antioxidant phytoconstituents. Integrating ethnopharmacological knowledge with modern nanotechnology could facilitate the identification and development of new bioactive compounds with enhanced therapeutic potential. In parallel, advancements in nanocarrier design, including stimuli-responsive, ligand-functionalized, and multifunctional delivery systems, offer promising opportunities to improve targeted ocular delivery, drug stability, and controlled release profiles (Li et al., 2023).

Another important direction involves the development of personalized therapeutic strategies by combining traditional medicinal knowledge with nanotechnology-based precision delivery systems. Such approaches may enable the customization of treatments based on individual patient profiles, disease progression, and oxidative stress status, thereby enhancing therapeutic efficacy while minimizing adverse effects. Emerging technologies, including nanozyme-based antioxidant therapies, further support the potential for tailored interventions in ocular disorders (Xue et al., 2024).

Additionally, sustainability considerations must be incorporated into the development of plant-based nanomedicines. The use of eco-friendly extraction techniques, green synthesis of nanoparticles, and sustainable sourcing of medicinal plants are essential to ensure environmental compatibility and long-term resource availability. Adoption of green nanotechnology approaches can reduce the environmental impact of production processes while maintaining therapeutic efficiency. Overall, future research should focus on integrating innovation, personalization, and sustainability to advance plant-based nanomedicine toward safe, effective, and clinically translatable solutions for oxidative stress-associated ocular diseases.

## 8. CONCLUSION

Oxidative stress plays a critical role in the pathogenesis of various ocular diseases, including cataract, age-related macular degeneration, diabetic retinopathy, and corneal disorders. Traditional plant-based remedies, rich in bioactive compounds such as flavonoids, polyphenols, and carotenoids, have demonstrated significant antioxidant and therapeutic potential in mitigating oxidative damage in ocular tissues. However, limitations associated with poor solubility, stability, and bioavailability of these phytoconstituents have restricted their clinical application. In this context, the integration of nanotechnology has emerged as a promising strategy to overcome these challenges by enhancing targeted delivery, improving drug stability, and enabling controlled release of plant-derived bioactives.

Recent advancements in plant-based nanomedicine have highlighted the effectiveness of various nanocarrier systems, including nanoparticles, liposomes, nanogels, and nanoemulsions, in improving ocular drug delivery and therapeutic outcomes. Despite encouraging preclinical findings, the translation of these technologies into clinical practice remains limited, underscoring the need for more comprehensive clinical investigations and long-term safety evaluations. Therefore, future research should focus on strengthening interdisciplinary collaboration between traditional medicine and modern nanotechnology, as well as promoting sustainable and innovative approaches for the development of safe, effective, and accessible therapies. Harnessing the full potential of plant-based nanomedicine may pave the way for advanced therapeutic strategies in the prevention and management of oxidative stress-induced ocular diseases.

## 9. REFERENCES

- Bohm EW, Buonfiglio F, Voigt AM, Bachmann P, Safi T, Pfeiffer N, Gericke A. Oxidative stress in the eye and its role in the pathophysiology of ocular diseases. *Redox Biology*. 2023;68: 102967. DOI: 10.1016/j.redox.2023.102967
- Nita M, Grzybowski A. The role of reactive oxygen species and oxidative stress in the pathomechanism of age-related ocular diseases. *Oxid Med Cell Longev*. 2016; 2016:3164734. DOI: 10.1155/2016/3164734
- McMonnies CW. Reactive oxygen species, oxidative stress, glaucoma and hyperbaric oxygen therapy. *J Optom*. 2018;11(1):3–9. DOI: 10.1016/j.optom.2017.06.002
- Masuda T, Shimazawa M, Hara H. Retinal diseases associated with oxidative stress and the effects of a free radical scavenger (Edaravone). *Oxid Med Cell Longev*. 2017;2017: 9208489. DOI: 10.1155/2017/9208489
- Abokyi S, To CH, Lam TT, Tse DY. Central role of oxidative stress in age-related macular degeneration. *Oxid Med Cell Longev*. 2020;2020: 7901270. DOI: 10.1155/2020/7901270
- Fan X, Xu M, Ren Q, Fan Y, Liu B, Chen J, Wang Z, Sun X. Downregulation of fatty acid binding protein 4 alleviates lipid peroxidation and oxidative stress in diabetic retinopathy. *Bioengineered*. 2022;13(4):10540–10551. DOI: 10.1080/21655979.2022.2062533
- Olvera-Montano C, Castellanos-González JA, Navarro-Partida J, et al. Oxidative stress as the main target in diabetic retinopathy pathophysiology. *J Diabetes Res*. 2019; 2019:8562408. DOI: 10.1155/2019/8562408
- Seen S, Tong L. Dry eye disease and oxidative stress. *Acta Ophthalmol*. 2018;96:e412–e420. DOI: 10.1111/aos.13626
- Xiang P, He RW, Han YH, Sun HJ, Cui XY, Ma LQ. Mechanisms of house dust-induced toxicity in primary human corneal epithelial cells: Oxidative stress, proinflammatory response and mitochondrial dysfunction. *Environ Int*. 2016;89–90:30–37. DOI: 10.1016/j.envint.2016.01.008
- Ahmad A, Ahsan H. Biomarkers of inflammation and oxidative stress in ophthalmic disorders. *J Immunoassay Immunochem*. 2020. DOI: 10.1080/15321819.2020.1726774
- Maurya RP, Prajapat MK, Singh VP, Roy M, Todi R, Bosak S, et al. Serum malondialdehyde as a biomarker of oxidative stress in patients with primary ocular carcinoma: Impact on response to chemotherapy. *Clin Ophthalmol*. 2021; 15:871–879. DOI: 10.2147/OPTH.S287747
- Akbari B, Baghaei-Yazdi N, Bahmaie M, Mahdavi Abhari F. The role of plant-derived natural antioxidants in reduction of oxidative stress. *BioFactors*. 2022; 48:1–23. DOI: 10.1002/biof.1831
- Forni C, Facchiano F, Bartoli M, et al. Beneficial role of phytochemicals on oxidative stress and age-related diseases. *Biomed Res Int*. 2019;2019: 8748253. DOI: 10.1155/2019/8748253
- Mandal MNA, Patlolla JMR, Zheng L, et al. Curcumin protects retinal cells from light- and oxidant stress-induced cell death. *Free Radic Biol Med*. 2009;46(5):672–679. DOI: 10.1016/j.freeradbiomed.2008.12.006
- Du W, An Y, He X, Zhang D, He W. Protection of kaempferol on oxidative stress-induced retinal pigment epithelial cell damage. *Oxid Med Cell Longev*. 2018; 2018:1610751. DOI: 10.1155/2018/1610751
- Majumdar S, Srirangam R. Potential of bioflavonoids in the prevention/treatment of ocular disorders. *J*

- Pharm Pharmacol. 2010; 62:951–965. DOI: 10.1211/jpp.62.08.0001
17. Alghamdi AH, Ahmed AAE, Bashir M, et al. The use of medicinal plants in common ophthalmic disorders: A systematic review with meta-analysis. *Heliyon*. 2023;9(4):e15340. DOI: 10.1016/j.heliyon.2023.e15340
  18. Gacche RN, Dhole NA. Profile of aldose reductase inhibition, anti-cataract and free radical scavenging activity of selected medicinal plants. *Food Chem Toxicol*. 2011;49(8):1806–1813. DOI: 10.1016/j.fct.2011.04.032
  19. Bungau S, Abdel-Daim MM, Tit DM, et al. Health benefits of polyphenols and carotenoids in age-related eye diseases. *Oxid Med Cell Longev*. 2019; 2019:9783429. DOI: 10.1155/2019/9783429
  20. Civelek M, Cicha I, Spielvogel H, Tietze R, Iyer S, Janko C, Alexiou C. Nanocarriers for therapeutic phytochemicals. *Nanomedicine*. 2024;19(21–22):1711–1716. DOI: 10.1080/17435889.2024.2380242
  21. Bonifacio BV, da Silva PB, Ramos MAS, Negri KMS, Bauab TM, Chorilli M. Nanotechnology-based drug delivery systems and herbal medicines: a review. *Int J Nanomedicine*. 2014; 9:1-15. DOI: 10.2147/IJN.S52634
  22. Krishnaswami V, Mohanan DP, Raja SAJ, Natarajan B, Velusamy S. Nanotechnology-based advancements for effective delivery of phytoconstituents for ocular diseases. *Nano TransMed*. 2024; 3:100056. DOI: 10.1016/j.ntm.2024.100056
  23. Chae SY, Shin MC, Jeon S, Kang MS, Han DW, Hong SW. Complexation of lutein with reduced graphene oxide nanocarriers and antioxidant protection against blue light. *Int J Nanomedicine*. 2021; 16:6843–6860. DOI: 10.2147/IJN.S320790
  24. Sunkireddy P, Jha SN, Kanwar JR, Yadav SC. Natural antioxidant biomolecules as future nanomedicine-based therapy for cataract. *Colloids Surf B Biointerfaces*. 2013; 112:554-562. DOI: 10.1016/j.colsurfb.2013.07.068
  25. Ganore JS, Adhav PS, Pagar CS, Kshirsagar SJ, Laddha UD. Herbal constituents combined with nanotechnology in diabetic retinopathy management: a review. *Next Nanotechnology*. 2026; 9:100409. DOI: 10.1016/j.nxnano.2026.100409
  26. Madaan T, Choudhary AN, Gyenwalee S, Thomas S, Mishra H, Tariq M, Vohora D, Talegaonkar S. Lutein: a versatile phyto-nutraceutical and recent advances in drug delivery. *PharmaNutrition*. 2017;5(2):64–75. DOI: 10.1016/j.phanu.2017.02.005
  27. Behl, T., Kaur, I. and Kotwani, A., 2016. Implication of oxidative stress in progression of diabetic retinopathy. *Survey of Ophthalmology*, 61(2), pp.187–196. <https://doi.org/10.1016/j.survophthal.2015.06.001>
  28. Calderon, G.D., Juarez, O.H., Hernandez, G.E., Punzo, S.M. and De la Cruz, Z.D., 2017. Oxidative stress and diabetic retinopathy: development and treatment. *Eye*, 31, pp.1122–1130. <https://doi.org/10.1038/eye.2017.134>
  29. Ferrington, D.A., Ebeling, M.C., Kapphahn, R.J., Terluk, M.R., Fisher, C.R., Polanco, J.R., Roehrich, H., Leary, M.M., Geng, Z., Dutton, J.R. and Montezuma, S.R., 2017. Altered bioenergetics and enhanced resistance to oxidative stress in human retinal pigment epithelial cells from donors with age-related macular degeneration. *Redox Biology*, 13, pp.255–265. <https://doi.org/10.1016/j.redox.2017.05.015>
  30. Hammes, H.P., 2018. Diabetic retinopathy: hyperglycaemia, oxidative stress and beyond. *Diabetologia*, 61, pp.29–38. <https://doi.org/10.1007/s00125-017-4435-8>
  31. Kimura, A., Namekata, K., Guo, X., Noro, T., Harada, C. and Harada, T., 2017. Targeting oxidative stress for treatment of glaucoma and optic neuritis. *Oxidative Medicine and Cellular Longevity*, 2017, Article ID 2817252. <https://doi.org/10.1155/2017/2817252>
  32. Kowluru, R.A. and Mishra, M., 2015. Oxidative stress, mitochondrial damage and diabetic retinopathy. *Biochimica et Biophysica Acta (BBA) - Molecular Basis of Disease*, 1852(11), pp.2474–2483. <https://doi.org/10.1016/j.bbadis.2015.08.001>
  33. Li, Y., Zhao, T., Li, J., Xia, M., Li, Y., Wang, X., Liu, C., Zheng, T., Chen, R., Kan, D., Xie, Y., Song, J., Feng, Y., Yu, T. and Sun, P., 2022. Oxidative stress and 4-hydroxy-2-nonenal (4-HNE): implications in the pathogenesis and treatment of aging-related diseases. *Journal of Immunology Research*, 2022, Article ID 2233906. <https://doi.org/10.1155/2022/2233906>
  34. Totsuka, K., Ueta, T., Uchida, T., Roggia, M.F., Nakagawa, S., Vavvas, D.G., Honjo, M. and Aihara, M., 2019. Oxidative stress induces ferroptotic cell death in retinal pigment epithelial cells. *Experimental Eye Research*, 181, pp.316–324. <https://doi.org/10.1016/j.exer.2018.08.019>
  35. Wu, M.Y., Yiang, G.T., Lai, T.T. and Li, C.J., 2018. The oxidative stress and mitochondrial dysfunction during the pathogenesis of diabetic retinopathy. *Oxidative Medicine and Cellular Longevity*, 2018, Article ID 3420187. <https://doi.org/10.1155/2018/3420187>

36. Xu, X., Pang, Y. and Fan, X., 2025. Mitochondria in oxidative stress, inflammation and aging: from mechanisms to therapeutic advances. *Signal Transduction and Targeted Therapy*, 10, Article 190. <https://doi.org/10.1038/s41392-025-02253-4>
37. Orhan, H., Marol, S., Hepşen, İ. F., & Şahin, G. (1999). Effects of some probable antioxidants on selenite-induced cataract formation and oxidative stress-related parameters in rats. *Toxicology*, 139(3), 219-232. [https://doi.org/10.1016/S0300-483X\(99\)00128-6](https://doi.org/10.1016/S0300-483X(99)00128-6)
38. Du, W., An, Y., He, X., Zhang, D., & He, W. (2018). Protection of kaempferol on oxidative stress-induced retinal pigment epithelial cell damage. *Oxidative Medicine and Cellular Longevity*, 2018, Article ID 1610751. <https://doi.org/10.1155/2018/1610751>
39. Gao, J., Tao, L., & Jiang, Z. (2023). Alleviate oxidative stress in diabetic retinopathy: Antioxidant therapeutic strategies. *Redox Report*, 28(1), 2272386. <https://doi.org/10.1080/13510002.2023.2272386>
40. Saviranta, N. M. M., Veeroos, L., Granlund, L. J., Hassinen, V. H., Kaarniranta, K., & Karjalainen, R. O. (2011). Plant flavonol quercetin and isoflavone biochanin A protect against oxidative stress in ARPE-19 cells. *Food Research International*, 44(1), 109–113. <https://doi.org/10.1016/j.foodres.2010.10.056>
41. Tiwari, M., & Kakkar, P. (2009). Plant-derived antioxidants protect against oxidative stress in macrophages. *Toxicology in Vitro*, 23(2), 295–301. <https://doi.org/10.1016/j.tiv.2008.12.014>
42. Gupta, S. K., Kalaiselvan, V., Srivastava, S., Saxena, R., & Agrawal, S. S. (2010). *Trigonella foenum-graecum* protects against selenite-induced oxidative stress in cataractogenesis. *Biological Trace Element Research*, 136, 258–268. <https://doi.org/10.1007/s12011-009-8540-5>
43. Huynh, T.-P., Mann, S. N., & Mandal, N. A. (2013). Botanical compounds: Effects on major eye diseases. *Evidence-Based Complementary and Alternative Medicine*, 2013, Article ID 549174. <https://doi.org/10.1155/2013/549174>
44. Vitiello, L., Capasso, L., Cembalo, G., De Pascale, I., Imperato, R., & De Bernardo, M. (2023). Herbal and natural treatments for the management of glaucoma: An update. *BioMed Research International*, 2023, Article ID 3105251. <https://doi.org/10.1155/2023/3105251>
45. Rooban, B. N., Sasikala, V., Gayathri Devi, V., Sahasranamam, V., & Abraham, A. (2012). Prevention of selenite-induced cataract by luteolin from *Vitex negundo*. *Chemico-Biological Interactions*, 196(1–2), 30–38. <https://doi.org/10.1016/j.cbi.2012.01.005>
46. Bigagli, E., Cinci, L., D'Ambrosio, M., & Luceri, C. (2017). Eye drops containing *Matricaria chamomilla* and *Euphrasia officinalis* protect against UVB-induced oxidative stress. *Journal of Photochemistry and Photobiology B: Biology*, 173, 618–625. <https://doi.org/10.1016/j.jphotobiol.2017.06.031>
47. Durgapal, S., Juyal, V., & Verma, A. (2021). In vitro antioxidant and anti-cataract activity of *Cineraria maritima*. *Future Journal of Pharmaceutical Sciences*, 7, 105. <https://doi.org/10.1186/s43094-021-00258-8>
48. Bungau, S., Abdel-Daim, M. M., Tit, D. M., et al. (2019). Health benefits of polyphenols and carotenoids in age-related eye diseases. *Oxidative Medicine and Cellular Longevity*, 2019, Article ID 9783429. <https://doi.org/10.1155/2019/9783429>
49. Pawlowska, E., Szczepanska, J., Koskela, A., Kaarniranta, K., & Blasiak, J. (2019). Dietary polyphenols in age-related macular degeneration. *Oxidative Medicine and Cellular Longevity*, 2019, Article ID 9682318. <https://doi.org/10.1155/2019/9682318>
50. Zhang, Y., An, Y., He, X., Zhang, D., & He, W. (2021). Esculetin protects corneal epithelial cells via Nrf2 pathway. *Experimental Eye Research*, 202, 108360. <https://doi.org/10.1016/j.exer.2020.108360>
51. Bulut, S., et al. (2026). Antioxidant activity of *Lavandula* × *intermedia* against UVB-induced corneal damage. *Experimental Eye Research*, 266, 110939. <https://doi.org/10.1016/j.exer.2026.110939>
52. Agarwal, R., Gupta, S. K., Srivastava, S., Agarwal, P., & Agrawal, S. S. (2009). Therapeutic potential of *Curcuma longa*, the golden spice of India, in drug discovery for ophthalmic diseases. *Expert Opinion on Drug Discovery*, 4(2), 147–158. <https://doi.org/10.1517/13543770802668117>
53. Kumar, R., Patel, D. K., Laloo, D., Sairam, K., & Hemalatha, S. (2011). Inhibitory effect of two Indian medicinal plants on aldose reductase of rat lens in vitro. *Asian Pacific Journal of Tropical Medicine*, 4, 694–697. DOI: 10.1016/S1995-7645(11)60178-7
54. Panghal, M., Arya, V., Yadav, S., Kumar, S., & Yadav, J. P. (2010). Indigenous knowledge of medicinal plants used by Saperas community of Khetawas, Jhajjar District, Haryana, India. *Journal of Ethnobiology and Ethnomedicine*, 6, 4. DOI: 10.1186/1746-4269-6-4
55. Sharma, A., Adhikari, D., & Wagh, V. V. (2024). An ethnobotanical investigation of medicinal plants used among rural communities in Northeastern Madhya Pradesh, India: A quantitative study. *Plant Biosystems*. <https://doi.org/10.1080/11263504.2024.2395845>
56. Ates, B., Trital, A., Mani, V. J., Xu, L., Lee, J. K., Ercal, N., & Yang, H. (2025). Engineered

- multifunctional drug-loaded dendrimer nanoparticles for glaucoma. *Biomacromolecules*. <https://doi.org/10.1021/acs.biomac.5c01704>
57. da Silva, S. B., Ferreira, D., Pintado, M., & Sarmiento, B. (2016). Chitosan-based nanoparticles for rosmarinic acid ocular delivery—In vitro tests. *International Journal of Biological Macromolecules*, 84, 112–120. <https://doi.org/10.1016/j.ijbiomac.2015.11.070>
  58. Grimaudo, M. A., Amato, G., Carbone, C., Diaz-Rodriguez, P., Musumeci, T., Concheiro, A., Alvarez-Lorenzo, C., & Puglisi, G. (2020). Micelle-nanogel platform for ferulic acid ocular delivery. *International Journal of Pharmaceutics*, 576, 118986. <https://doi.org/10.1016/j.ijpharm.2019.118986>
  59. Ibrahim, S. S., & Abd-allah, H. (2022). Spanlastic nanovesicles for enhanced ocular delivery of vanillic acid: Design, in vitro characterization, and in vivo evaluation. *International Journal of Pharmaceutics*, 625, 122068. <https://doi.org/10.1016/j.ijpharm.2022.122068>
  60. Krstic, L., Jarho, P., Ruponen, M., Urtti, A., González-García, M. J., & Diebold, Y. (2022). Improved ocular delivery of quercetin and resveratrol: A comparative study. *International Journal of Pharmaceutics*, 624, 122028. <https://doi.org/10.1016/j.ijpharm.2022.122028>
  61. Li, S., Chen, L., & Fu, Y. (2023). Nanotechnology-based ocular drug delivery systems: Recent advances and future prospects. *Journal of Nanobiotechnology*. <https://doi.org/10.1186/s12951-023-01992-2>
  62. Lima, B. S., Shanmugam, S., Quintans, J. S. S., Quintans-Júnior, L. J., & Araújo, A. A. S. (2019). Inclusion complex with cyclodextrins enhances the bioavailability of flavonoids: A review. *Phytochemistry Reviews*. <https://doi.org/10.1007/s11101-019-09650-y>
  63. Medoro, A., Davinelli, S., Scuderi, L., Scuderi, G., Scapagnini, G., & Fragiotta, S. (2025). Quercetin-based strategies for ocular diseases in older adults. *Clinical Interventions in Aging*. <https://doi.org/10.2147/CIA.S516946>
  64. Migone, C., Cerri, L., Ferreira, B., Fabiano, A., Parri, S., Mezzetta, A., Guazzelli, L., Piras, A. M., Zambito, Y., & Sarmiento, B. (2025). Olive leaf extract-based eye drop formulations for corneal wound healing. *Journal of Drug Delivery Science and Technology*, 110, 107026. <https://doi.org/10.1016/j.jddst.2025.107026>
  65. Olowosoke, C. B., Thrimawithana, T., & Huynh, T. (2026). Non-invasive pharmacological advances in early retinopathy treatment. *Pharmacological Reports*, 78, 123–172. <https://doi.org/10.1007/s43440-025-00778-7>
  66. Rahman, H. S., Othman, H. H., Ibrahim, N., Hammadi, N. I., Yeap, S. K., Amin, K. M., Samad, N. A., & Alitheen, N. B. (2020). Novel drug delivery systems for natural plant extracts. *International Journal of Nanomedicine*, 15, 2439–2483. <https://doi.org/10.2147/IJN.S227805>
  67. Sahoo, S. K., Dilnawaz, F., & Krishnakumar, S. (2008). Nanotechnology in ocular drug delivery. *Drug Discovery Today*, 13(3–4), 144–151. <https://doi.org/10.1016/j.drudis.2007.10.021>
  68. Tsai, C. Y., Woung, L. C., Yen, J. C., Tseng, P. C., Chiou, S. H., Sung, Y. J., Liu, K. T., & Cheng, Y. H. (2016). Thermosensitive chitosan-based hydrogels for sustained ocular delivery. *Carbohydrate Polymers*, 135, 308–315. <https://doi.org/10.1016/j.carbpol.2015.08.098>
  69. Xue, B., Lu, Y., Wang, S., Xiao, Q., Luo, X., Wang, Y., Yan, X., Yang, Z., & Jiang, B. (2024). Emerging role of nanozymes in ocular antioxidant therapy. *Nano Today*, 58, 102448. <https://doi.org/10.1016/j.nantod.2024.102448>
  70. Zhou, T., Li, S., Zhu, J., Zeng, G., Lv, Z., Zhang, M., Yao, K., & Han, H. (2025). Rosmarinic acid-grafted gelatin nanogels for ocular delivery. *Biomacromolecules*. <https://doi.org/10.1021/acs.biomac.5c01704>
  71. Kumari, S., Goyal, A., Khan, A. A., Garg, M., Sindhu, R. K., Fatima, S., & Mallick, S. (2025). Lipidic cubic phase zeaxanthin-loaded cubosomes: Formulation, characterization and antioxidant evaluation. *Biomass Conversion and Biorefinery*. Vol.15, pages 21261–21275.
  72. Tsai, C. Y., Woung, L. C., Yen, J. C., Tseng, P. C., Chiou, S. H., Sung, Y. J., Liu, K. T., & Cheng, Y. H. (2016). Thermosensitive chitosan-based hydrogels for sustained release of ferulic acid on corneal wound healing. *Carbohydrate Polymers*, 135, 308–315. <https://doi.org/10.1016/j.carbpol.2015.08.098>
  73. Zhou, T., Li, S., Zhu, J., Zeng, G., Lv, Z., Zhang, M., Yao, K., & Han, H. (2025). Rosmarinic acid-grafted gelatin nanogels for efficient ocular drug delivery in dry eye disease therapy. *Biomacromolecules*. <https://doi.org/10.1021/acs.biomac.5c01704>
  74. Sharma, D. S., Wadhwa, S., Gulati, M., et al. (2020). Recent advances in intraocular and novel drug delivery systems for diabetic retinopathy. *Expert Opinion on Drug Delivery*. <https://doi.org/10.1080/17425247.2021.1846518>
  75. Permatasari, H. K., Nurkolis, F., Iqhrammullah, M., et al. (2024). Lutein plant-based nanoencapsulation for ocular melanoma. *CyTA - Journal of Food*, 22(1), 2331070. <https://doi.org/10.1080/19476337.2024.2331070>

76. Lv, Y., Zhai, C., Sun, G., & He, Y. (2024). Chitosan-based nanocarriers for diabetic retinopathy. *Journal of Biological Engineering*. <https://doi.org/10.1186/s13036-024-00414-7>
77. Zhou, J., Zhao, D., Niu, S., et al. (2025). RGD-functionalized ginsenoside Rg3 liposomes for age-related macular degeneration. *International Journal of Nanomedicine*. <https://doi.org/10.2147/IJN.S520756>
78. Liu, Y., Dong, Y., Pu, X., & Yin, X. (2022). Curcumin-loaded ceria nanoclusters for cataract therapy. *Process Biochemistry*, 120, 239–249. <https://doi.org/10.1016/j.procbio.2022.05.008>
79. Tang, W., Huang, X., Yi, Y., et al. (2025). Hyaluronic acid-curcumin nanoparticles for uveitis via Keap1/Nrf2 pathway. *Small Structures*. <https://doi.org/10.1002/ssstr.202400484>
80. Chen, Y., Peng, D., Jiang, S., et al. (2026). Curcuma longa-derived vesicle-like nanoparticles in retinal neovascularization. *Journal of Nanobiotechnology*. <https://doi.org/10.1186/s12951-026-04303-7>
81. Song, K., Yan, M., Li, M., et al. (2020). Thymol-based nanomicelles for ocular delivery. *Colloids and Surfaces B*. <https://doi.org/10.1016/j.colsurfb.2020.111157>
82. Tsai, I. L., Tsai, C. Y., Kuo, L. L., et al. (2021). PLGA nanoparticles with Lingzhi extract for corneal protection. *Experimental Eye Research*. <https://doi.org/10.1016/j.exer.2021.108539>
83. Sohani, Z., Jamshidi, S., Koohi, M. K., et al. (2024). Curcumin nanoparticle hydrogels for keratitis. *Scientific Reports*. <https://doi.org/10.1038/s41598-024-74195-w>
84. Qiao, R., Yang, L., Zhang, S., et al. (2025). Copper-based nanozyme eye drops for oxidative stress. *ACS Omega*. <https://doi.org/10.1021/acsomega.5c00103>