Lutein: A Comprehensive Review of Its Pharmacological and Therapeutic Potential

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***Abstract*—Lutein is a naturally occurring xanthophyll carotenoid widely present in green leafy vegetables, fruits, and egg yolk. It is a lipid-soluble bioactive compound recognized for its significant pharmaceutical and nutraceutical importance, particularly in the prevention and management of ocular disorders. Lutein selectively accumulates in the macula and lens of the human eye, where it acts as a natural antioxidant and blue-light filter, thereby protecting retinal tissues from oxidative stress and photochemical damage. Numerous clinical and epidemiological studies have demonstrated its beneficial role in reducing the risk of age-related macular degeneration, cataracts, and other vision-related disorders. In addition to ocular health, lutein exhibits anti-inflammatory, neuroprotective, and cardioprotective properties, highlighting its broader therapeutic potential. Since lutein cannot be synthesized by the human body, adequate dietary intake and supplementation are essential. However, its poor water solubility and low bioavailability present formulation challenges, leading to the development of advanced pharmaceutical and nutraceutical delivery systems. This review focuses on the chemical nature, sources, pharmacological activities, therapeutic applications, and formulation strategies of lutein, emphasizing its growing role as a functional nutraceutical and preventive therapeutic agent.**

***Index Terms*—Lutein; Xanthophyll carotenoid; Antioxidant activity; Ocular health; Age-related macular degeneration; Nutraceuticals; Pharmaceutical applications; Bioavailability**

I. INTRODUCTION

In recent years, growing interest in naturally derived bioactive compounds has significantly influenced pharmaceutical and nutraceutical research. Among these compounds, lutein, a xanthophyll carotenoid, has emerged as an important molecule due to its wide range of therapeutic and preventive health benefits. Lutein is predominantly found in green leafy vegetables such as spinach, kale, and broccoli, as well as in egg yolk and maize. As humans are unable to synthesize lutein endogenously, sufficient dietary intake or supplementation is essential to maintain optimal physiological levels.

Pharmaceutically, lutein is well recognized for its protective role in ocular health. It selectively accumulates in the macular region of the retina and in the lens, where it contributes to macular pigment formation. Lutein acts as a potent antioxidant and a natural blue-light filter, protecting ocular tissues from oxidative stress and photochemical damage. These properties are particularly important in reducing the risk of age-related macular degeneration, cataracts, and other retinal disorders, which represent major public health concerns worldwide.

Beyond its ocular benefits, lutein demonstrates significant nutraceutical value owing to its antioxidant, anti-inflammatory, neuroprotective, and cardioprotective activities. Emerging studies suggest that lutein may play a role in improving cognitive function and reducing the progression of chronic diseases associated with oxidative damage and inflammation. Consequently, lutein has been widely incorporated into dietary supplements, functional foods, and fortified pharmaceutical formulations.

Despite its promising therapeutic profile, the clinical efficacy of lutein is limited by factors such as poor water solubility, low chemical stability, and limited oral bioavailability. These challenges have stimulated the development of advanced pharmaceutical and

nutraceutical delivery systems aimed at enhancing lutein absorption and therapeutic effectiveness. Therefore, this review focuses on the pharmaceutical and nutraceutical significance of lutein, highlighting its sources, pharmacological activities, therapeutic applications, and formulation strategies, thereby emphasizing its potential as a valuable bioactive compound in preventive and therapeutic healthcare.

Beneficial effects of lutein on neurodegenerative disease

Microglia, the principal immunological effector cells in the central nervous system (CNS), have been linked to the preservation of brain homeostasis and control of neuronal surveillance [1,2]. By secreting IL-10, which has anti-inflammatory and neuroprotective qualities, these cells control the homeostasis of the central nervous system [3, 4]. Microglia hyperactivation has been associated with neurodegenerative disorders, and in vitro experiments have shown that IL-10 inhibits the production of proinflammatory cytokines by microglia and other glia [5]. When IL-10 binds to the receptor, the JAK-STAT pathway is triggered, which inhibits the production of cytokine genes and the capacity to deliver antigens [6].

Pap et al. found that lutein has anti-inflammatory and antioxidant qualities in BV-2 microglia when H2O2 was present [7]. According to their findings, lutein suppresses the production of ROS and lowers inflammation by increasing IL-10 and reducing the release of proinflammatory TNF-α. Low levels of proinflammatory TNF-α and anti-inflammatory IL-10 cytokines were released by BV-2 cells in the control group. In response to stress stimuli brought on by H2O2, the cells produced more TNF-α and less IL-10. They also demonstrated that lutein, either by itself or in conjunction with H2O2 therapy, may raise IL-10 levels in BV-2 cells without upregulating proinflammatory molecules. The lutein and H2O2-treated cells displayed a time-dependent declining trend in TNF-α cytokine levels as compared to cells that received H2O2 alone. The increase of IL-10 in response to lutein treatment is believed to represent the primary anti-inflammatory, inhibitory, or self-regulating activity of the cytokine through autocrine and paracrine mechanisms [8].

By inhibiting inflammatory signalling pathways, such as NF-κB, and controlling the production of IL-1β, COX-2, iNOS, and TNF-α, lutein decreased neuroinflammation in LPS-activated microglia. Lutein may cause Kelch-like ECH-associated protein 1 (Keap1) to separate from the Nrf2/Keap1 complex and activate extracellular signal-regulated kinase (ERK), a mitogen-activated protein kinase. Phosphorylated Nrf2 forms a heterodimer with small Maf proteins (sMaf) in the nucleus. Antioxidant enzymes like NAD(P)H quinone oxidoreductase 1 (NQO1) and HO-1 are expressed when this complex binds to the antioxidant response element (ARE), a regulatory region of DNA. Thus, lutein offers defence against neurodegenerative disorders linked to inflammation [9,10]. Unlike nonpolar carotenoids, lutein and zeaxanthin have polar groups at both ends of their molecules, giving them a membrane-spanning conformation in membrane lipid bilayers. In these circumstances, it is believed that these groups adopt a perpendicular or semi perpendicular orientation. This characteristic can have a substantial impact on membrane characteristics including fluidity, ion exchange, oxygen transport, and membrane stability when combined with their high solubility in membranes [11,12]. By affecting gap junctions, it might also affect inter-neuronal transmission [13, 14]. Evidence suggests that lutein localises to membrane domains rich in polyunsaturated fatty acids (PUFAs), such as docosahexaenoic acid (DHA), and may be positioned in membranes to avoid the oxidation of these sensitive brain lipids [15,16]. In addition to maintaining membrane fluidity and structure, suppression of DHA oxidation keeps DHA accessible for cleavage and the subsequent synthesis of anti-inflammatory chemicals [17,18]. Severe traumatic brain injury (STBI) is associated with oxidative stress-induced inflammation and apoptosis [15]. By suppressing the expression of IL-1β, IL-6, and monocyte chemoattractant protein-1 (MCP-1) and lowering serum ROS levels, lutein avoided severe brain damage in rats [19].

Lutein protects against ischemia-reperfusion injury by lowering oxidative stress, inflammation, and the expression of COX-2 and NF-κB, according to earlier studies by Cheng et al. [20]. During cerebral ischemia-reperfusion, NF-κB is essential for regulating the release of inflammatory mediators. Numerous investigations have shown that NF-κB activation is triggered by cerebral ischemia-reperfusion [21]. Lutein treatment significantly reduced NF-κB protein

synthesis in STBI rat models [19]. [Figure 1] show how lutein prevents oxidative stress-induced inflammatory reactions in neurodegenerative disorders [7,9,10,13,20].

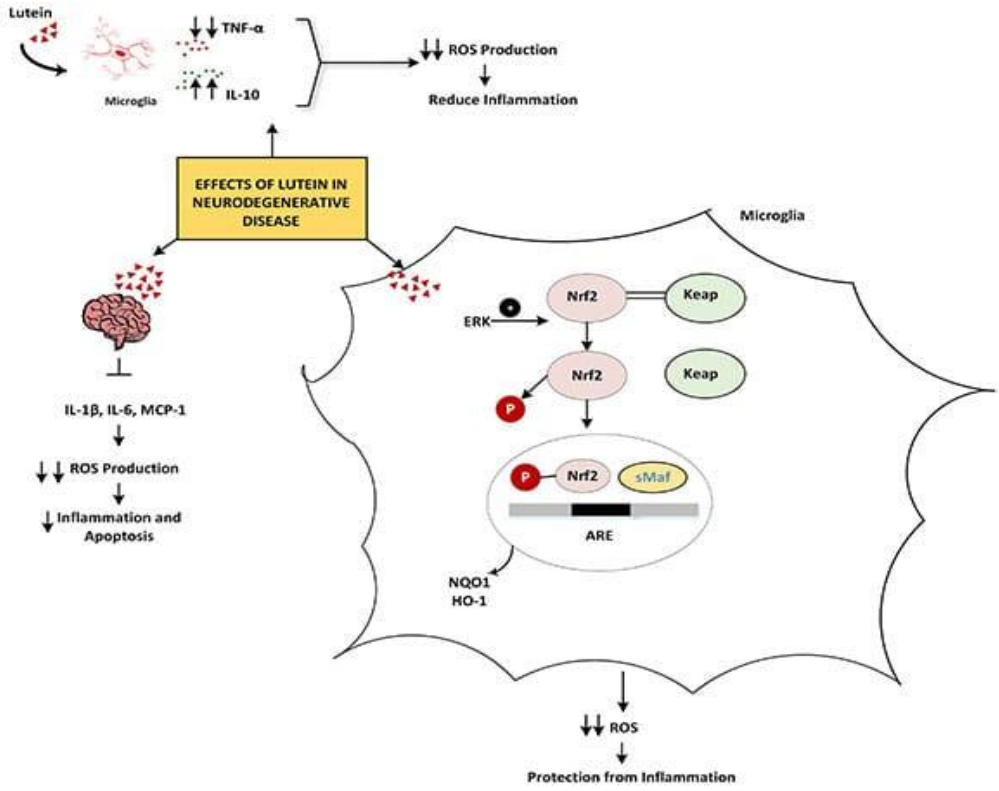

Figure 1. The mechanism by which lutein inhibits oxidative stress-induced inflammatory responses in neurodegenerative diseases. ↑: increasing; ↓: decreasing. TNF-α: tumour necrosis factor-α; IL-10: interleukin-10; ROS: reactive oxygen species; Nrf2: nuclear factor erythroid 2-related factor 2; ARE: antioxidant response element; HO-1: heme oxygenase-1; NQO1: NAD(P)H quinone oxidoreductase 1; MCP-1: monocyte chemoattractant protein-1; ERK: extracellular signal-regulated kinase; Keap: Kelch-like ECH-associated protein; sMaf: small Maf proteins

II. LUTEIN AS A CARDIOPROTECTIVE AGENT

Lutein is well-known for its advantages for cardiovascular health, possibly lowering the risk of coronary artery disease because of its anti-inflammatory and antioxidant qualities. Ex vivo research on lutein has anti-inflammatory effects on human peripheral blood mononuclear cells (PBMCs), according to Chung et al. [22]. Lutein accumulates intracellularly and inhibits NF-κB signalling when added to PBMCs at concentrations between 10 and 20 μM. Lastly, inhibits the adhesion of leukocytes and the generation of inflammatory genes like TNF, IL-6, and IL-1β [22]. Lutein supplementation has been shown to prevent the formation of atherosclerotic lesions in animal models [23–25]. Both anti-inflammatory and antioxidant qualities may offer atheroprotective advantages. It is well known that lutein can prevent cell lipid oxidation and oxidative cell damage [26]. Lutein supplementation decreased the inflammatory response of monocytes to oxidised LDL in atherosclerosis-prone mice, according to Dwyer et al. [23]. In guinea pig models, a diet high in lutein protected atherosclerosis and decreased oxidised LDL concentrations, MDA, and cytokine production in aortic tissue [24].

Those with a history of atherosclerosis had higher blood levels of complement factors C3 and C3a. C3 creates a membrane assault complex that can kill pathogens or host cells by creating a hole or pore in the membrane through a separate complement route.

Lutein has been shown to reduce plasma complement factor levels, including membrane attack complex. Therefore, by inhibiting or minimising tissue oxidation and preventing the activation of the blood's dangerous complement factors, lutein may support atheroprotection and cardiometabolic health [27]. Carotenes boost the bioavailability of NO by significantly reducing ROS and nitrotyrosine (an ONOO–) index.

Concurrently, it inhibits the interaction between monocytes and human umbilical vein endothelial cells (HUVECs) as well as the synthesis of adhesion molecules that rely on NF-κB (Figure 2). [28].

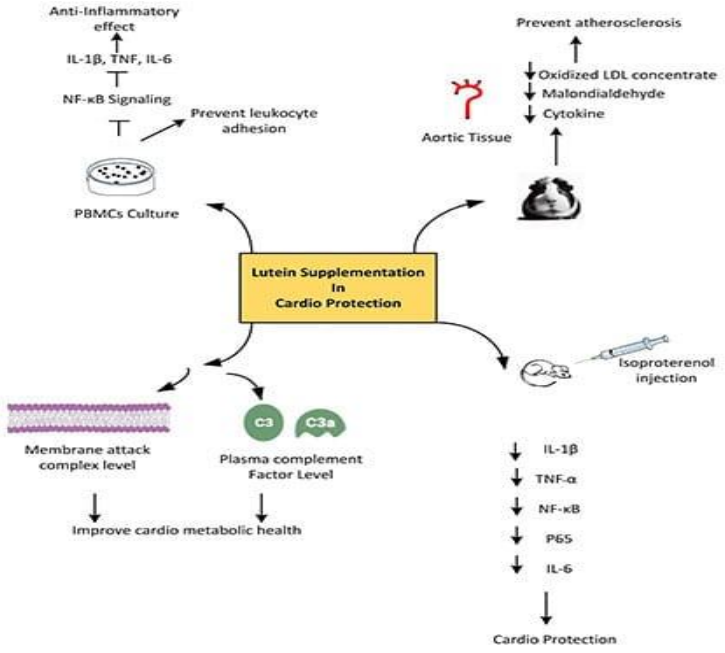

Figure 2. The overall mechanism of action of lutein as a cardioprotective agent. ↓: decreasing. IL-1β: interleukin-1β; TNF: tumour necrosis factor; NF-κB: nuclear factor kappa B; PBMCs: peripheral blood mononuclear cells; LDL: low-density lipoprotein

III. HEPATOPROTECTIVE EFFECTS OF LUTEIN

By regulating the Nrf2/HO-1 signalling pathway, lutein exhibits anti-oxidative and anti-inflammatory properties that prevent alcohol-induced liver damage. Alcohol-induced decreases in SOD and GPx levels were mitigated by high-dose lutein, which enhanced the production of the antioxidant enzyme HO-1. The "total antioxidant capacity (T-AOC)" was also increased. Lutein administration decreased levels of triglycerides (TG) and MDA as well as the alcohol-induced rise of cytochrome P450 2E1 (CYP2E1), indicating that its antioxidant actions may help shield the liver from harm.

Furthermore, via modifying the NF-κB signalling system, lutein has been shown to lessen inflammation, reverse the effects of alcohol on inflammatory protein levels, and partially enhance liver health. By controlling the feedback between Nrf2 and aldehyde dehydrogenase 2 (ALDH2), antioxidants such as lutein may promote alcohol metabolism and reduce alcohol-related liver damage. This further illustrates how high-dose lutein raised the mRNA expression of ALDH2, which is connected to the liver's metabolism of alcohol [29, 30].Administering lutein (40 mg/kg body weight) 30 min before ethanol exposure lowered levels of inflammatory proteins (NF-κB, COX-2, iNOS), inflammatory cytokines (TNF-α, MCP-1, IL-1β, IL-6), liver enzymes (aspartate aminotransferase, alanine aminotransferase, LDH), and oxidative stress markers (ROS, lipid peroxidation, protein carbonyls, and sulfhydryl's) in rats. Additionally, lutein boosted Nrf2 levels and increased the activity of antioxidant enzymes (catalase, GPx, GSH, and GST) [31]. In guinea pigs fed a high-cholesterol diet, lutein (0.1 g

per 100 g) therapy prevents degenerative diseases in the liver by lowering hepatic free cholesterol, lipid peroxidation, and attenuating the inflammatory responses known to be involved in the development of non-alcoholic fatty liver disease (NAFLD) [32]. Additionally, data suggest that the reduced NF-κB, p65 DNA binding activity was the cause of the attenuated inflammatory response with lutein therapy. Lutein directly reduces the activation of NF-κB and inhibits the levels of mRNA and protein of TNF-α, IL-1β, and COX-2. Carotenoids given before hatching and in their diet after hatching help lower inflammation markers in the liver as suggested by some studies conducted in slow-growing egg-type chicks. Changes in liver weight during inflammation and IL-6 mRNA levels in the spleen were reduced. This effect may be mediated by the peroxisome proliferator-activated receptor gamma (PPARγ)/retinoid X receptor (RXR) pathway, which directly affects gene expression, or by reducing oxidative stress and modifying the inhibitor of kappa B (I-κB)/NF-κB pathway [33]. Gündoğdu et al. [34] reported that in cytokine-related liver ischemia-reperfusion injury in rats, lutein administration decreases oxidant markers like MDA and levels of proinflammatory cytokine mediators including TNF-α, NF-κB, and IL-1β. The values observed were similar to those in the group of good health. Again, in the lutein-administered group, we observed mild sinusoidal dilation in the parenchyma and portal regions, together with a histological look similar to normal liver cells, where inflammation accompanied with hepatic congestion was retreated. Lutein can protect against tissue damage induced by excess NF-κB and TNF-α. Its hepatoprotective action is attributed to its ability to inhibit the creation of ROS and the synthesis of proinflammatory cytokines (Figure 3).

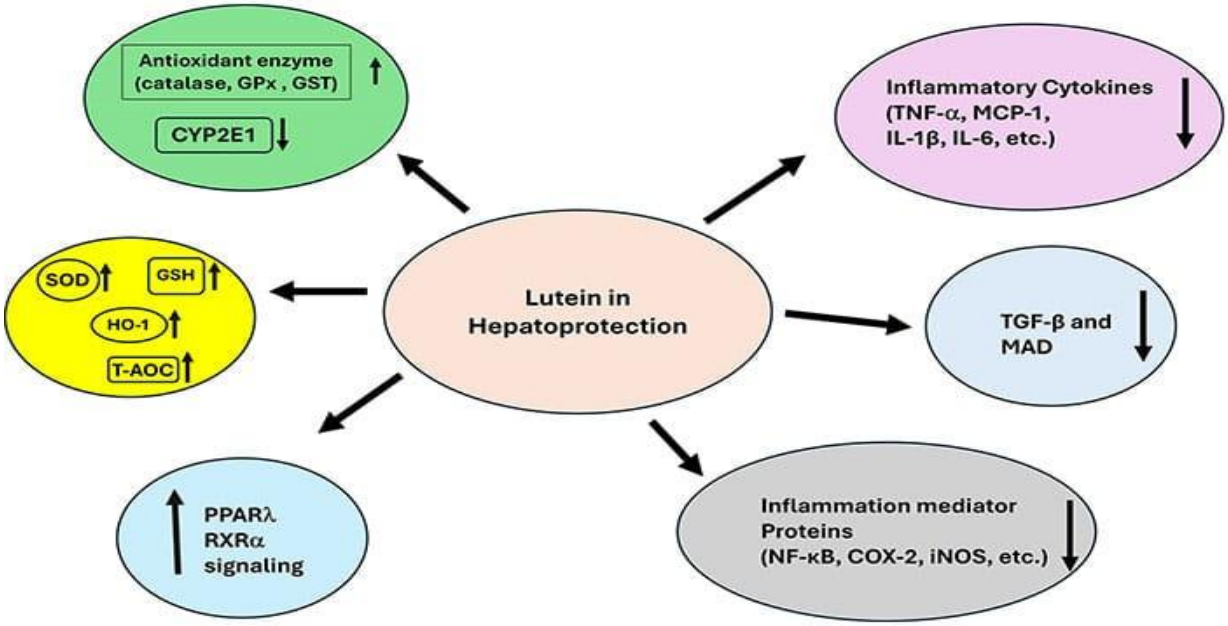

Figure 3. The overall mechanism of action of lutein as a hepatoprotective agent. ↑: increasing; ↓: decreasing. GPx: glutathione peroxidase; GST: glutathione S-transferase; SOD: superoxide dismutase; GSH: glutathione; HO-1: heme oxygenase-1; T-AOC: total antioxidant capacity; PPARλ: peroxisome proliferator-activated receptor λ; RXRα: retinoid X receptor α; TNF-α: tumor necrosis factor-α; IL-1β: interleukin-1β; NF-κB: nuclear factor kappa B; COX-2: cyclooxygenase-2; iNOS: inducible nitric oxide synthase; CYP2E1: cytochrome P450 2E1; MCP-1: monocyte chemoattractant protein-1

Strong protective effects of lutein are seen against hepatic and pulmonary toxicities brought on by cyclophosphamide (CP). Its capacity to reduce lipid peroxidation, prevent oxidative and nitrosative stress, and restore antioxidant enzyme activity is what gives it this protective action. Lutein's strong antioxidant action was successful in blocking NF-κB/p38-MAPK activation, which in turn prevented the release of

cytokines. Consequently, lutein may be clinically significant if paired with CP following additional experimental and clinical validation research [35].

In slow-growing egg-type chicks, carotenoid exposure in Ovo and in the food after hatch reduces markers of inflammation in the liver (e.g., change in liver weight during acute phase response) and spleen (e.g., IL-6 mRNA abundance). These outcomes are most likely mediated by the PPARγ/RXR pathway directly influencing gene expression, or by impacts on oxidative stress and the ensuing modifications in the I-κB/NF-κB pathway. The mechanism is as follows, RXR binding and heterodimerization with PPARγ bound to fatty acids, eicosanoids, and several synthetic ligands, carotenoids influence immunological responses [36]. To influence transcription processes, PPARγ-RXR dimers bind response elements and co-activators in DNA. Specifically, these dimers inhibit the transcription factor NF-κB, which in turn controls the expression of genes related to inflammation and immunity, such as iNOS [29–31, 33, 35–37].

IV. LUTEIN IN PREVENTING EYE DISEASE

Lutein inhibits STAT3 activation in the retinal cells in addition to its well-known impact on rhodopsin preservation [38]. STAT3 is activated by inflammatory cytokines including IL-6, and STAT3 controls IL-6. As a result, once STAT3 activity surpasses a certain threshold, the IL-6-STAT3 pathway starts a vicious cycle that exacerbates the pathogenic condition. But lutein prevents STAT3 activity, ending this vicious cycle and protecting the eye from tissue damage. Lutein may block the direct pathway of ROS-induced STAT3 phosphorylation and activation. Lutein's decrease of ROS may inhibit JAK and STAT3's quick activation, effectively preserving rhodopsin protein. Because oxidative stress and inflammation are related and lutein can regulate them, lutein has an anti-inflammatory effect [39]. Vision is hampered by oxidative stress, fast cytokine transmission in the retinal neural cells, and related inflammatory reactions. Lutein therapy successfully reduced ROS, which made it easier to lower rhodopsin levels and increase the expression of glial fibrillary acidic protein (GFAP), preventing visual damage during inflammation. Neuroprotection against retinal inflammatory diseases may also be provided by lutein treatment [38].

The inactivation of proteasomes is another mechanism that connects oxidative stress to altered gene expression linked to inflammation. When lutein or zeaxanthin was given to the retinal pigment epithelium (RPE), the proteasome was protected from inactivation and the changes in the expression of these inflammation-related genes were lessened. This may be one of the ways that eating foods high in lutein and zeaxanthin reduces the incidence of AMD and affects ocular and systemic inflammation [40].

In the serum and retina of LPS-induced lethal dosage (LD) mice, studies employing lutein encapsulated in poly(lactic-co-glycolic acid) (PLGA)-phospholipid nano-carrier showed enhanced anti-inflammatory effect. Additionally, they suppressed COX-2 and iNOS expression and decreased NF-κB p65 activity. Lutein-loaded nanoparticles successfully improved lutein's solubility, stability, and bioavailability, hence boosting its bio efficacy. These results will support the use of lutein-PLGA neural crest cells (NCs) (+PL) (PLGA nanocarrier with phospholipid) against oxidative stress and ocular inflammatory effects in addition to target delivery to the retina [41].

Karakurt et al. [42] reported that isoniazid (50 mg/kg, p.o., 14 days) and ethambutol (50 mg/kg, p.o., 14 days) were found to cause toxic ocular neuropathy, which was significantly reduced by lutein treatment for two weeks (0.5 mg/kg). MDA, IL-1β, and TNF-α levels were considerably lower in blood samples and tissues from the rats given lutein. Additionally, the group that received lutein had significantly higher levels of total GSH in their tissue and serum, indicating that lutein is important in preventing damage to the optic nerve.

The anti-cataract effect of lutein treatment is believed to be aided by increased levels of DHA and eicosapentaenoic acid. Lutein's antioxidant properties and the inflammatory mediators of fatty acid eicosanoids work together to prevent cataract development. The results show that when combined, lutein and omega-3 fatty acids can effectively reduce oxidative stress and inflammation to prevent cataracts. The PGE2-mediated inflammatory response was decreased by the lutein administration, underscoring the importance of fatty acids, especially those in the omega-3 family, and the necessity of preventing inflammation. Numerous genes involved in the inflammatory response, including COX-2 and iNOS2, are regulated by NF-κB. Additionally, lutein

supplementation lowers the incidence of cataracts by inhibiting the expression of these genes [43].The continuous administration of lutein (12 mg) for 16 weeks as a formulation, taking into account its bio-accessibility, increased macular pigment optical density (MPOD), improved contrast sensitivity, and prevented decreases in visual function caused by a glare from light in a randomised double-blind placebo controlled parallel group comparison trial [38, 39, 41–44].

V. LUTEIN IN PREVENTING AND CURING BONE DISEASE

In osteoblast cultures, lutein encouraged the formation of mineralised bone nodules. On the other hand, vitamin D3 bone resorption produced by 1α, 25-dihydroxyvitamin was clearly reduced by lutein. In co-cultures of osteoblasts and bone marrow cells, lutein prevented 1α, 25-dihydroxyvitamin D3 from producing osteoclasts. Additionally, lutein inhibits soluble receptor activator of NF-κB ligand (RANKL), which causes bone marrow macrophage cultures to produce more osteoclasts. Using dual X-ray absorptiometry and micro-computed tomography (μCT) scans to quantify bone mineral density, five-week-old male mice were administered lutein orally for four weeks. This resulted in a considerable increase in femoral bone mass, especially in cortical bone. Lutein mainly affects macrophages and osteoclast precursor cells by preventing RANKL-dependent osteoclast formation. Furthermore, lutein suppresses osteoblast RANKL expression, which in turn suppresses osteoclast differentiation. This action is explained by lutein's capacity to lower RANKL mRNA expression in osteoblasts, which is normally brought on by bone-resorbing agents. Lutein successfully boosts bone mass in growing mice by reducing bone resorption and encouraging bone growth. Therefore, lutein may be a naturally occurring material that promotes bone turnover and is beneficial to human bone health [45].

While preventing osteoclastic bone resorption, lutein encourages the formation of new bone. Since NF-κB activation is necessary for both IL-1-induced RANKL synthesis by osteoblasts and RANK-dependent differentiation into osteoclasts in macrophages, it appears likely that NF-κB is one of the molecular targets of lutein in bone resorption. Osteocytes and osteoblasts may be key players in the negative regulator of bone formation, which includes sclerostin, a product of the sclerosteosis (SOST) gene. Therefore, the lowering of sclerostin expression may be necessary for lutein to increase bone formation by blocking canonical wingless-related integration site (Wnt)/β-catenin signalling. To determine if lutein directly affects the level of sclerostin, more research on this possible relationship is required [46]. Because lutein can activate Nrf2, treating chondrocyte cells with it showed a significant protective effect against oxidative stress events caused by monosodium iodoacetate (MIA). By upregulating ARE, the transcription factor Nrf2, often referred to as nuclear factor erythroid 2-related factor 2, is an essential regulator of redox imbalance. In response to oxidative stress, Nrf2 offers cytoprotective action; nevertheless, excessive redox conditions lead to Nrf2 downregulation, which encourages changes to normal cellular functioning. The administration of lutein showed increased expression levels of downstream genes HO-1 and NQO-1 in addition to a significant increase in Nrf2. By boosting Nrf2 and the cytoprotective antioxidant system, lutein reduced oxidative stress. When lutein was administered, proinflammatory cytokines were produced and inflammatory proteins (NF-κB and COX-2) were significantly downregulated. By scavenging superoxide and H2O2 as well as the NF-κB-regulated inflammatory genes, iNOS, TNF-α, IL-1β, and COX-2, lutein decreased intracellular H2O2 production in LPS-stimulated macrophages. Lutein reduced LPS-induced NF-κB activation in a strong association with its inhibitory effect on I-κB kinase (IKK) activity, I-κB degradation, nuclear translocation of NF-κB, and binding of NF-κB to the κB motif of the iNOS promoter. In PI3K activity, phosphatase and tensin homolog (PTEN) inactivation, NF-κB-inducing kinase (NIK), and Akt phosphorylation, this compound inhibited the increase of IKK activation brought on by LPS and H2O2 [47, 48].

Lutein treatment significantly reduced MIA-induced caspase-3 activation and membrane potential loss, preventing chondrocyte cell death. Lutein prevents osteoarthritis by regulating oxidative stress and apoptosis through the production of Nrf2 and NF-κB [49]. It was discovered for the first time that lutein inhibits the growth and activation of dendritic cells (DCs). Lutein first significantly and dose-dependently

decreased the expressions of three maturation-associated surface markers in LPS-stimulated DCs: CD40, co-stimulatory molecule CD86, and major histocompatibility complex (MHC) class II molecule. CD86 expression was the phenotypic alteration most strongly affected by lutein exposure. Additionally, as DCs develop, they release a large number of inflammatory cytokines, which are believed to be functional markers of DC maturation. Following lutein injection, the proinflammatory cytokines IL-12 p40 and IL-6 produced by LPS-stimulated DCs were significantly reduced [50]. Suppressing IL-6 expression [51] and IL-6 receptors[44, 46, 50, 52] can also be used therapeutically to reduce inflammation and alter immunological responses.

VI. ANTI-DIABETES EFFECTS OF LUTEIN

Lutein absorption and biological activity are supported by elevated blood levels of HDL-cholesterol (HDL-C). The primary lutein carrier in the circulatory circulation is HDL-C. Serum lutein levels have been found to be negatively linked with inflammatory markers such as leukocyte count and C-reactive protein (CRP) [53]. When lutein was given to diabetic rats, proinflammatory cytokines like TNF-α and IL-1β were significantly reduced in the testicles [54]. It has previously been shown to have anti-inflammatory properties [55]. By protecting the proteasome from oxidative stress-induced inactivation, lutein is thought to have reduced the inflammatory response [41]. Lutein inhibits the activation of microglia in Ins2Akita/+ mice. This outcome is consistent with an in vitro investigation that found lutein decreased ROS production, TNF-α and IL-1β release, and microglial activation [11]. Lutein may protect the diabetic retina from inflammatory damage due to its capacity to scavenge ROS. Therefore, long-term lutein therapy protected the retinal vasculature, reduced retinal inflammation, and preserved retinal function in Ins2Akita/+ mice. According to these results, patients with early-stage diabetic retinopathy may benefit from lutein as a long-term therapeutic intervention to prevent inflammation and retinal degeneration [56].

The raised levels of Thio barbituric acid reactive substances (TBARS), caspase-3, TNF-α, IL-1β, and IL-6 in the cerebral cortex (CCT) caused by diabetes were significantly decreased by a lutein-rich dietary supplement. The inhibition of non-protein sulfhydryl groups (NP-SH), DNA, and RNA levels was significantly decreased when rats fed a conventional diet were given lutein as a dietary supplement at three different doses (40 mg/kg, 80 mg/kg, and 160 mg/kg). This impact was demonstrated in a dose-dependent manner. The diabetic animal's diabetes-induced downregulation of insulin-like growth factor (IGF), nerve growth factor (NGF), and brain-derived neurotrophic factor (BDNF) was lessened after five weeks of lutein food supplementation [57]. These elements are necessary for axon development and neuronal survival. By secreting enzymes like GSH and SOD, they reduce oxidative stress and shield neurones from myelin and neuronal damage [58–60]. In addition to its well-known advantages including antioxidant and anti-inflammatory qualities, the findings of earlier research did in fact demonstrate that lutein is neuroprotective. Additionally, it concentrated corneal thickness linked to diabetes [9, 40, 54, 56, 57].

VII. LUTEIN SUPPRESSED SKIN INFLAMMATION

Research has demonstrated that lutein efficiently reduced the synthesis of IL-6, COX-2, and matrix metalloproteinase-9 (MMP-9) in UV-irradiated keratinocytes, IFN-γ/TNF-α-stimulated human keratinocyte cell line cells, and LPS-treated macrophages. By inhibiting neutrophil accumulation, which is brought on by the activation of the transient receptor potential ankyrin 1, lutein also reduces cutaneous inflammation [62]. Lutein can prevent the activation of the redox-sensitive AP-1 pathway, according to additional research on nuclear transcription factor levels and intracellular signalling pathways. The antioxidant activity of lutein, which involves scavenging free radicals and ROS, is responsible for its AP-1-targeted anti-inflammatory action. Because of its anti-oxidative qualities, lutein is therefore suggested as a possible anti-inflammatory and cosmetic agent for treating inflammatory skin diseases [61, 62].

VIII. CONCLUSION

Lutein is a naturally occurring carotenoid found mainly in fruits and vegetables, and it plays an important role in maintaining overall health. This review highlights the wide range of biological

activities of lutein, especially its strong antioxidant and anti-inflammatory properties. Lutein is particularly beneficial for eye health, as it helps protect retinal cells from oxidative damage and supports visual function. In addition, studies suggest that lutein may reduce the risk of chronic diseases such as cardiovascular disorders, certain cancers, and age-related cognitive decline. Its ability to neutralize free radicals and regulate inflammatory pathways makes it a valuable compound in both pharmaceutical and nutraceutical applications. Although existing research shows promising health benefits, further clinical studies are needed to better understand its mechanisms of action, optimal dosage, and long-term safety. Overall, lutein emerges as a beneficial dietary component with significant potential in disease prevention and health promotion.

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