International Journal for Vitamin and Nutrition Research

Int. J. Vitam. Nutr. Res. **2026**; 96(4): 50575
https://doi.org/10.31083/IJVNR50575

Review

Nutritional Benefits of Dietary Lutein, Zeaxanthin, and Meso-Zeaxanthin in Canine, Feline, and Equine Companion Animals: A Narrative Review

Nicole T. Stringham[1,*]

[1]Northern Arizona University, Flagstaff, AZ 86011, USA
*Correspondence: ntstringham@gmail.com (Nicole T. Stringham)
Academic Editor: Torsten Bohn
Submitted: 1 February 2026 Revised: 22 May 2026 Accepted: 15 June 2026 Published: 6 August 2026

Abstract

The macular xanthophyll carotenoids lutein, zeaxanthin, and meso-zeaxanthin have well-established roles in oxidative regulation, inflammation, and visual function in humans. Collectively, these carotenoids are perhaps best known for their ability to reduce the risk of development and progression of age-related macular degeneration in humans—a condition that resembles *senile retinal atrophy* in older dogs and cats, although the relevance of macular xanthophylls to companion animal health remains incompletely defined. This review synthesizes the available literature on the absorption, target tissue deposition, mechanistic pathways, and physiological effects of these carotenoids in dogs, cats, and horses. Evidence indicates that lutein and zeaxanthin, are absorbed and systemically distributed in companion animals, with the most robust functional data currently available in dogs, particularly regarding immune modulation and retinal electrophysiological stability. Carotenoid transport mechanisms, including high-density lipoproteins, binding proteins, such as scavenger receptor BI (SR-BI), transmembrane glycoprotein CD36, START-domain lipid-binding protein 3 (StARD3), and glutathione S-transferase pi 1 (GSTP1), and metabolic enzymes, including the carotenoid cleavage enzymes beta-carotene oxygenase 1 and 2 (BCO1 and BCO2), are conserved across mammalian species and provide a mechanistic framework for tissue- and system-specific activity in the visual, immune, nervous, integumentary, and cardiovascular systems among. Histologic confirmation remains limited, however, especially in cats and horses. Collectively, existing data suggest an important biological role for these xanthophyll carotenoids in companion animals, but substantial knowledge gaps remain regarding species-specific bioavailability, tissue deposition, and clinical outcomes. The biological benefits of lutein, zeaxanthin and meso-zeaxanthin in humans, along with the central similarities in mammalian physiology, support the potential of these dietary and supplemental compounds to enhance the health of companion animals. Future supplementation studies, however, are needed to characterize dose–response relationships in these species and clarify the potential functional benefits of these nutrients in companion animal nutrition.

Keywords: lutein; zeaxanthin; meso-zeaxanthin; omega fatty acids; dog; cat; horse; dietary xanthophylls

1. Introduction

Dietary carotenoids, particularly the macular xanthophylls lutein (L), zeaxanthin (Z), and meso-zeaxanthin (MZ), play critical roles in oxidative balance, cellular signaling, and tissue-specific photoprotection across a wide range of vertebrate species [1,2,3,4]. In humans, these compounds are best known for their selective accumulation in the macula, where they contribute to visual performance and protect the retina against oxidative and inflammatory damage. Carotenoids are absorbed by different species and utilized by physiologic systems to varying degrees; increasing evidence suggests that similar biological mechanisms may be conserved in dogs, cats, and horses—companion animals—wherein visual function, immune competence, cognitive health, and systemic oxidative stress are recognized as key determinants of animal health and aging [5,6,7,8]. Despite the growing incorporation of carotenoids into commercial pet and equine feeds [9], the scientific literature evaluating their absorption, tissue distribution, physiological effects, and clinical relevance remains limited. L, Z, and MZ have been shown to have a wide variety of benefits in human health, including cardiovascular and metabolic health, immune modulation, cognitive health and performance, antioxidant and anti-inflammatory capacity, skin health, and visual system benefits [10,11,12,13]. These same physiologic benefits could potentially extend into companion animal health. The basic framework for this idea is outlined in Fig. 1.

Pets are of increasing importance given their integral role as human companions and service animals. As interest grows in the use of nutrition to support health beyond basic dietary needs, L, Z, and MZ appear to have great potential as functional and supplemental ingredients for companion animals. Bioactive ingredients intended to modulate physiological processes, extend lifespan, reduce disease risk, or support targeted health outcomes are common in commercial pet and equine diets, and reflect advances in both nutritional science and pet owner expectations [14]. Within this context, L has received particular attention for its role in

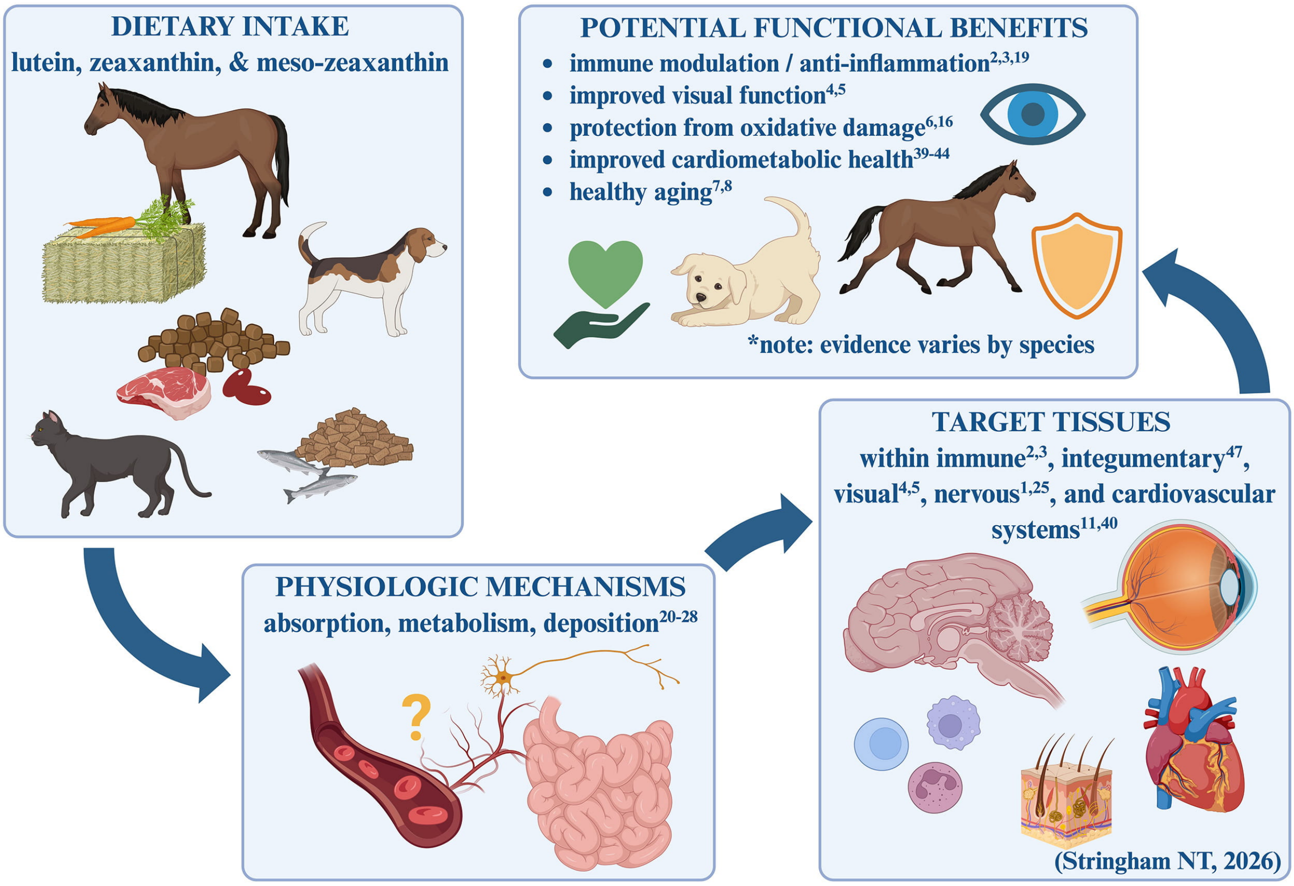

Fig. 1. Basic framework for potential physiologic benefits of dietary lutein, zeaxanthin, and meso-zeaxanthin in companion animals. This framework outlines the potential functional benefits of these nutrients in companion animals, while highlighting the need for future studies to understand the physiologic mechanisms leading to tissue deposition and utilization in these species.

mitigating oxidative stress and inflammation in ocular and extra-ocular tissues, roles which are shared with the commonly co-ingested stereoisomer zeaxanthin [15,16]. Meso-zeaxanthin is widely incorporated into human eye-health supplements but has a more limited evidence base in animal species. All three of these dietary xanthophylls have "Generally Recognized As Safe" status from the U.S. FDA and the Joint FAO/WHO Expert Committee on Food Additives and European Food Safety Authority have designated acceptable daily intakes ranging from 0–2 mg/kg, with no adverse effects reported at much higher doses [17,18]. Taken together, the established safety profile and potential benefits to the health and well-being of pets reinforce the need for a species-specific evaluation of the existing literature and potential for future research. The following review outlines our current understanding of the absorption, deposition, and potential functional benefits of xanthophyll carotenoids in tissues of the integumentary, immune, nervous, visual, and cardiovascular systems of canine, feline, and equine companion animals.

2. Absorption and Deposition

Absorption and deposition of L, Z, and MZ are primary considerations when extrapolating human and lab-based (e.g., murine) findings to companion animals such as dogs, cats, and horses. Table 1 summarizes the available data on the presence of L, Z, and MZ in specific tissues of five mammalian species (further discussed throughout this review). There are a few studies that show that dietary L and Z are absorbed into blood plasma in dogs, thus confirming intestinal uptake and bioavailability [3,19]. In beagles, L was absorbed into plasma, increasing in a dose-dependent manner after supplementation. More generally, carotenoids are lipid soluble and have been shown in canine studies of antioxidant supplementation to systemically distribute to the liver, adipose, and plasma lipoproteins [19]. Although dogs lack a true macula, L and Z have been shown to influence retinal function by demonstration of improved electroretinographic stability following supplementation [5]. Given that several carotenoid transport proteins and enzymes are conserved [20,21,22,23,24], the potential for antioxidant activity within the canine retina is likely but has not been histologically demonstrated. Additionally, whereas L and Z have been identified in human and primate brain tissue [12,25], no studies have characterized carotenoid transport or binding mechanisms in the brains of dogs, cats, or horses. As mentioned above, however, xanthophyll transport and binding proteins (e.g., scavenger receptor BI (SR-BI), transmembrane glycoprotein CD36, START-domain lipid-binding protein 3 (StARD3), glutathione S-transferase pi 1 (GSTP1)) are conserved and expressed across mammalian nervous tissues, including the brain and retina [21,23,26,27] and may play a central role in the systemic immune and cardiovascular benefits of L, Z, and MZ as well.

Table 1. Tissue presence of lutein, zeaxanthin, and meso-zeaxanthin by species.

	Humans	Dogs	Cats	Horses	Rodents
Skin/integument	+	?*	?	?	+
Plasma/blood	+	+	+	+	+
Adipose	+	+	+	+	+
Liver	+	+	+	+	+
Retina	+	+	?*	?*	+
Brain	+	?*	?	?	+
Milk	+	?*	?*	+	+

(+) ≥1 present; (-) not present; (?) information/studies not available, represents a gap in the literature; (*) increased likelihood based on similar deposition pathway (e.g., transport enzyme conservation) or molecule (e.g., beta-carotene).

In domestic cats, studies of dietary carotenoid uptake have shown that β-carotene is absorbed into plasma and leukocytes in a dose-dependent manner but is not efficiently converted to vitamin A [28]. While this is not specific to the xanthophyll carotenoids, it demonstrates that the feline gut can absorb carotenoid molecules from the diet. Almost all uptake studies in cats have focused on β-carotene; however, as mentioned above, lipid-soluble pigments such as astaxanthin (a xanthophyll carotenoid similar to L, Z, and MZ) are absorbed and transported via lipoproteins, which is a likely lipophilic pathway in felines. The absorption and uptake of other carotenoids such as L, Z, and MZ into the feline tissues remains an empirical question, but the similarities of the xanthophyll carotenoids to β-carotene in terms of enzymatic transport and deposition provides a rationale for potential utilization in tissues. Future detailed studies are needed to determine specific physiologic mechanisms in cats.

Even more elusive is the study of absorption and deposition in equines. A study of carotenoids and fat-soluble vitamins in horse tissues found measurable levels of these compounds in plasma, milk, adipose, and liver of horses fed typical diets [29]. This study also showed that horses exhibit distinct profiles of carotenoid tissue distribution compared to cows, with horses preferentially storing carotenoids in the liver, and cattle in adipose. This difference suggests that mechanisms of carotenoid absorption and tissue storage in horses differ from bovines, and that this may underlie differential utilization/function of carotenoids in these species, respectively. In this same study, pasture-fed mares were found to only have trace amounts of L detected in plasma despite the relatively high amount measured in their diet, suggesting that either absorption is not biologically prioritized, or higher amounts are needed to increase L concentration within the blood.

3. Immune System

L, Z, and MZ have well-established antioxidant effects within the immune system and have been shown to reduce pro-inflammatory cytokines (e.g., interleukin 1 beta (IL-1β) and tumor necrosis factor alpha (TNF-α)) and increase serum antioxidant capacity within systemic circulation of humans [10,11]. Similarly, early foundational work in animals established analogous antioxidant and immune system activity in response to carotenoids (particularly β-carotene) [19]. Subsequent work showed that non-provitamin A carotenoids (e.g., L) were equally, if not more effective, as provitamin A carotenoids (e.g., β-carotene) in enhancing humoral immune responses; a finding that is particularly important for species such as the domestic cat, that is notoriously inefficient at converting carotenoids to vitamin A [30]. In cats, dietary studies indicate that L is absorbed and can influence immune parameters, with evidence suggesting potential synergistic effects when administered alongside other lipid-based nutrients such as fish oil, reflecting the importance of dietary context for carotenoid bioactivity in this obligate carnivore species [2,31]. In dogs, supplementation studies have demonstrated that dietary L enhances both humoral and cell-mediated immune responses, including increased lymphocyte proliferation and antibody production, providing some of the strongest species-specific evidence for immunomodulatory effects of xanthophylls in companion animals [3]. These findings are consistent with more recent reviews of canine immune modulators, which identify carotenoids as capable of influencing immune signaling pathways and inflammatory balance [32]. Collectively, these animal studies support the hypothesis that L, Z, and MZ act systemically to modulate inflammatory signaling via mechanisms that involve oxidative stress attenuation. While the magnitude and clinical relevance of these effects likely differ by species, the existing literature supports a conserved biological role for dietary xanthophylls in immune processes across these mammalian species.

Unfortunately, there are currently no peer-reviewed studies demonstrating immune system effects derived from xanthophyll supplementation in horses. Nutritional immunology research in equines has instead focused on vitamins, minerals, and fatty acids and has typically been extrapolated from positive outcomes observed in other species. Several nutrients have been implicated in immunological health of horses and have been associated with positive outcomes; these include vitamins E and C, minerals (zinc and selenium) and arginine, as well as omega-3 and -6 fatty acids [33]. Given that other antioxidants (e.g., vitamin E) have shown immunomodulatory effects in horses, there is potential for L, Z, and MZ to have beneficial effects, particularly given their roles as robust antioxidants. Oxidative stress and the excess generation of free radicals are known to cause damage to the equine health [34]. Sport horses, in particular, experience extra systemic and immune stress given the high demand of competition and the associated travel/exposure to new environmental elements. Wild ungulates do not appear to accumulate carotenoids in serum with simple dietary intake [35]. Supplementation with xanthophyll carotenoids in racing horses, however, resulted in increased antioxidant status and decreased training-related oxidative stress in this species [36], suggesting that xanthophyll absorption and activity is indeed possible and potentially beneficial in equines.

4. Visual System/Retina

A wide gap in the literature exists between human and animal companion data with regard to visual health and performance. L, Z, and MZ are probably best known to improve eye health and reduce the risk of developing/limit the progression of age-related macular degeneration in humans [37]. These nutrients are also increasingly recognized for their potential to support retinal health and visual function in companion animals, but direct evidence has been limited. In dogs, supplementation studies with antioxidants including L and Z have demonstrated improved retinal function (as measured by electroretinography) and decreased age-related changes in refractive error; these results are suggestive of functional benefits for both retinal health and visual acuity [5]. These findings, although preliminary, are consistent with mechanistic data from other vertebrates that indicate xanthophylls are integral to photoprotection and maintenance of central vision, supporting the plausibility of meaningful visual outcomes in dogs and, potentially, in other companion species.

The mechanistic link for potential roles of L, Z, and MZ within the canine, feline, and equine retina involves the carotenoid transport and conversion enzymes—and their evolutionary conservation across species. For example, StARD3 has been implicated in L binding in the human retina and is conserved across mammalian species [23]; annotated orthologs are listed for dogs, cats, and horses [22]. Similarly, GSTP1, which has been identified as a high-affinity zeaxanthin-binding protein in the human retina [21], also demonstrates orthologs [20], thus supporting the possibility of similar carotenoid-binding mechanisms for both L and Z across these species. Finally, the enzyme RPE65 is highly conserved across vertebrates, including humans, mice, and horses and is essential for the visual cycle as well as conversion of L to MZ in the human retina [24]. RPE65 deficiency causes severe inherited blindness by blocking the vitamin A cycle; it is strongly expressed in native retinal pigment epithelium in horses, as well as dogs and cats, and genetic mutations are associated with retinal dystrophy in these species [38]. RPE65 also functions as an isomerase converting dietary L into MZ, one of the three macular carotenoids critical for protecting the central retina from blue light and oxidative damage [24]. This dual role highlights how L and Z intake may contribute not only to traditional retinal metabolic pathways but also to the local production of macular pigments that are protective against phototoxicity and oxidative stress. Evolutionarily conserved proteins suggest that similar mechanisms could operate in companion animals, but species-specific studies examining xanthophyll deposition, retinal metabolism, and functional outcomes in these animals are lacking, which illustrates a clear gap in our understanding of these pathways and application to veterinary nutrition. It is promising, however, that (as mentioned above), L and Z were able to influence retinal function in dogs following supplementation and retinal stability was positively influenced even in the absence of a true macula [5]; this seems to indicate that positive outcomes and improved performance in the retina of animals whose physiology doesn't necessarily favor central vision and acuity is possible. Supplementation studies addressing retinal health and visual function, particularly in aging animals, are needed to determine the clinical potential of xanthophyll-based interventions across companion species.

5. Cardiovascular/Metabolic

Recent research suggests that the physiological effects of L, Z, and MZ may include benefits to metabolic and cardiometabolic health and may be relevant to obesity in both humans and animals. In an insulin-resistant rodent model fed a high-fat diet, MZ supplementation attenuated hepatic lipid accumulation, improved liver function, and reduced markers of cardiometabolic risk. Outcomes included improved modulation of insulin-signaling pathways and key transcription factors such as PPAR-γ, Nrf2, and NF-κB, suggesting a potential protective role against fatty liver and associated metabolic dysfunction [39]. Mechanistic investigations have further elucidated how L interacts with oxidative and inflammatory pathways to inhibit NF-κB and provide antioxidant protection. These findings provide a biochemical basis for L's systemic effects on lipid metabolism and inflammation within the cardiovascular system [40]. Additionally, in a recent human supplementation study, L, Z, and MZ resulted in significant decreases in the pro-inflammatory cytokines IL-1β and TNF-α, and oxidized low-density lipoprotein [11]. These findings demonstrate potential for these antioxidant molecules to aid in prevention of obesity and oxidative processes (e.g., atherosclerosis) within the cardiovascular system. It has been shown that dogs fed a human-like diet, including table scraps, exhibit signs of accelerated aging and experience the deleterious health effects associated with consuming a standard Western diet. Specifically, feeding dogs high-fat and energy-dense processed foods can cause insulin resistance, dyslipidemia, increased adiposity, and changes in inherent metabolism—all changes seen with the aging process. In as few as 17 weeks, beagles given a high-fat diet showed increased body fat and adipocyte size, dysregulated insulin release, elevation in serum lipids (cholesterol, triglycerides, free fatty acids) and leptin [41]. Similar to features that are associated with human metabolic syndrome, obese dogs can exhibit dysregulated lipid metabolism, hyperinsulinemia and insulin resistance, increased cholesterol, and mild hypertension [42]. High-fat diets alter the gut microbiome and integrity of the intestinal barrier; these outcomes that have been implicated in metabolic diseases in both humans and dogs [43]. Although the metabolic pathways are similar, the clinical outcomes differ in dogs, as they rarely progress to type 2 diabetes or atherosclerosis [44]. Nevertheless, high-fat diets and obesity in canines and felines lead to deleterious effects including higher oxidative stress, chronic inflammation, dysregulated lipid and glucose metabolism—all of which are drivers of general pathophysiology and premature aging. To our knowledge, no experimental work focusing on cardiovascular benefits of L, Z, and MZ in canine or feline companion animals has been reported; this gap in the literature represents an area for future study with a plausible rationale for empirical rationale. The aforementioned results seen in humans and lab animals warrant application and a focused examination of dietary xanthophylls within the context of animal obesity and metabolic syndrome, particularly in dogs and cats that may be prone to overeating due to their human proximity.

Research on dietary supplementation for equine cardiovascular benefits has focused largely on vitamins E, C, and β-carotene, rather than L, Z, and MZ [34]. However, given the oxidative stress associated with exercise in horses, it is another area that would benefit from future research.

6. Future Research Directions

Macular xanthophyll research in companion animals is generally lacking and for some organ systems (e.g., “skin/integument” and “nervous system”) there are no data. Based on research in humans and other animals, however, there is significant potential for these nutrients to benefit system-specific health in dogs, cats, and horses. Structures and physiologic connections that comprise the skin, integument, and nervous systems specifically represent logical directions for future research and are outlined below.

6.1 Skin/Integument

Carotenoids such as L and Z are absorbed into circulation after dietary intake in dogs and cats and plasma levels increase with supplementation [3], but there are no data that document deposition into the skin of these species. In humans and laboratory animals (i.e., rodents), L and Z are present in skin and have been studied for their potential to protect against UV damage [13,16]. Species-specific differences in carotenoid metabolism and tissue uptake exist, however, and utilization across physiologic systems likely vary by species. There is rationale for local deposition and antioxidant activity within the skin and integument of dogs, cats, and horses. The relatively high turnover rate of cells within these systems, coupled with the direct exposure of these superficial tissues to environmental stressors suggests that these tissues would benefit significantly from the protective benefits of L, Z, and MZ. L, Z, and MZ are lipophilic antioxidants that quench reactive oxygen species, particularly in lipid membranes. The lipophilic outermost layers of skin, i.e., stratum corneum, in humans has been shown to contain deposits of xanthophyll carotenoids that directly correlate to plasma concentrations [45]. Moreover, omega-3 and omega-6 fatty acids are plentiful in the cell membranes of keratinocytes, hair follicles, nail beds, and hooves and are essential to the health and protection of integumentary tissues [46,47,48,49]. Co-localization of the polyunsaturated fatty acids with L, Z, and MZ may, therefore, provide dual protection for these tissues, thus decreasing oxidative stress, reducing inflammation, and promoting healthy coats and integumentary appendages.

Nails, hooves, and hair follicles are sites of high metabolic activity, particularly during growth and keratinization, making them susceptible to oxidative stress. Reactive oxygen species and associated oxidative stress interfere with hair follicle development and growth [47]; therefore, if L, Z, and MZ were locally deposited at these tissue development sites, it may limit oxidative damage and protect structural proteins and lipids needed for healthy skin and appendages. Equine hooves are highly vascularized and require adequate nutrient and antioxidant supply for strength and proper keratinization, while the fur quality and nail integrity in dogs and cats rely on follicular and nail matrix cell health; both of which may benefit from the antioxidant and anti-inflammatory support of L, Z, & MZ.

6.2 Nervous System

L and Z accumulate selectively in neural tissues. In human and primate models, L is the predominant carotenoid in neural tissue, particularly in brain areas with high metabolic demand and potential for increased oxidative stress. Studies in humans have shown that higher levels of retinal (and therefore brain) L and Z correlate with improved cognitive processing, memory, and reaction time [12,50]. Additionally, L, Z, and MZ supplementation has been associated with increased serum antioxidant capacity and brain-derived neurotrophic factor, a marker of neural plasticity [30]. While direct analogs of these human findings are limited in companion animal species, there is a mechanistic basis to explore similar cognitive effects dogs, cats, and horses, particularly when provided alongside omega-3 polyunsaturated fatty acids (i.e., docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA)).

Again, given the across-species conservation and neural expression of SR-BI, CD36, StARD3, and GSTP1 (as noted in the "Visual System/Retina" section), it is plausible that mechanisms involving xanthophyll carotenoids in the brain tissue of dogs, cats, and horses are similar to those described in humans and non-human primates. More research is needed to determine species-specific mechanisms and activity within the central nervous system in order to properly translate effects into canine, feline, and equine populations.

7. Conclusion

Collectively, the available literature supports the conclusion that the xanthophyll carotenoids L, Z, and MZ are absorbed and systemically distributed in companion animals, with dogs demonstrating the most consistent evidence of bioavailability and positive functional outcomes. Oxidative stress is implicated in the aging process in canines, so it is reasonable to assume that incorporation of antioxidants may lead to improvement in aging/age-related disease processes. Older animals have increased susceptibility to tissue damage from reactive oxygen species, which can cause accelerated aging and contribute to the development of cognitive impairment, disrupted physiology, chronic disease, and a reduced quality of life. Moreover, with a higher prevalence of canine and feline obesity, as well as high-fat diets, it is important to consider the potential for antioxidant and anti-inflammatory properties of L, Z, and MZ to counteract the pernicious effects of these conditions.

The evolutionary conservation of carotenoid transporters, binding proteins, and enzymes across species provides a mechanistic basis for tissue-specific activity of L, Z, and MZ within immune, visual, nervous, integumentary, and cardiovascular systems. Functional outcomes associated with xanthophyll intake, such as immunomodulatory effects and improvements in retinal electrophysiological stability have been demonstrated in canine models; however, in cats and horses, there is a significant gap in the research. Taken together, these data indicate that L, Z, and MZ meaningfully contribute to oxidative and inflammatory regulation across multiple physiological systems in companion animals, albeit with species-specific differences in magnitude and expression.

Real-world application of the effects of xanthophyll supplementation in companion animals is limited by important knowledge gaps. While carotenoids are increasingly incorporated into commercial pet and equine diets, studies directly linking intake to tissue deposition, mechanistic activity, and clinically relevant outcomes are few. Future investigations should aim to examine species-specific dose-response relationships, quantify tissue distribution in body systems, and ideally define the functional effects within the retina, central nervous system, immune tissues, and cardiovascular system. It would also be prudent to examine potential interactions/synergy with dietary lipids (i.e., omega-3 and -6 fatty acids) and investigate applications to specific populations within species (e.g., aging, obese, sport/exercise) in order to determine the specific benefits of dietary and supplemental L, Z, and MZ in veterinary nutrition and companion animal health.

Author Contributions

NTS was responsible for the conception of ideas presented, writing, and the entire preparation of this manuscript.

Ethics Approval and Consent to Participate

Not applicable.

Acknowledgment

Not applicable.

Funding

This research was funded by Industrial Organica S.A.

Conflicts of Interest

The author has consulted for Industrial Organica, a supplier of supplemental dietary xanthophylls. The author declares no conflicts of interest.

References

[1] Mohn ES, Erdman JW, Jr, Kuchan MJ, Neuringer M, Johnson EJ. Lutein accumulates in subcellular membranes of brain regions in adult rhesus macaques: Relationship to DHA oxidation products. PLoS ONE. 2017; 12: e0186767. https://doi.org/10.1371/journal.pone.0186767

[2] Kim HW, Chew BP, Wong TS, Park JS, Weng BB, Byrne KM, et al. Modulation of humoral and cell-mediated immune responses by dietary lutein in cats. Veterinary Immunology and Immunopathology. 2000; 73: 331–341. https://doi.org/10.1016/s0165-2427(00)00152-5

[3] Kim HW, Chew BP, Wong TS, Park JS, Weng BB, Byrne KM, et al. Dietary lutein stimulates immune response in the canine. Veterinary Immunology and Immunopathology. 2000; 74: 315–327. https://doi.org/10.1016/s0165-2427(00)00180-x

[4] Bernstein PS, Li B, Vachali PP, Gorusupudi A, Shyam R, Henriksen BS, et al. Lutein, zeaxanthin, and meso-zeaxanthin: The basic and clinical science underlying carotenoid-based nutritional interventions against ocular disease. Progress in Retinal and Eye Research. 2016; 50: 34–66. https://doi.org/10.1016/j.preteyeres.2015.10.003

[5] Wang W, Hernandez J, Moore C, Jackson J, Narfström K. Antioxidant supplementation increases retinal responses and decreases refractive error changes in dogs. Journal of Nutritional Science. 2016; 5: e18. https://doi.org/10.1017/jns.2016.5

[6] Muršec A, Poljšak B, Nemec Svete A, Erjavec V. Antioxidant Strategies for Age-Related Oxidative Damage in Dogs. Veterinary Sciences. 2025; 12: 962. https://doi.org/10.3390/vetsci12100962

[7] McKenzie BA. Immunosenescence and Inflammaging in Dogs and Cats: A Narrative Review. Journal of Veterinary Internal Medicine. 2025; 39: e70159. https://doi.org/10.1111/jvim.70159

[8] Blanchard T, Eppe J, Mugnier A, Delfour F, Meynadier A. Enhancing cognitive functions in aged dogs and cats: a systematic

review of enriched diets and nutraceuticals. GeroScience. 2025; 47: 2925–2947. https://doi.org/10.1007/s11357-025-01521-z
[9] Baritugo KA, Bakhsh A, Kim B, Park S. Perspectives on functional foods for improvement of canine health and treatment of diseases. Journal of Functional Foods. 2023; 109: 105744. https://doi.org/10.1016/j.jff.2023.105744
[10] Stringham NT, Holmes PV, Stringham JM. Effects of macular xanthophyll supplementation on brain-derived neurotrophic factor, pro-inflammatory cytokines, and cognitive performance. Physiology & Behavior. 2019; 211: 112650. https://doi.org/10.1016/j.physbeh.2019.112650
[11] Stringham NT, Green M, Roche W, Prado-Cabrero A, Mulcahy R, Nolan J. Lutein, zeaxanthin, and meso-zeaxanthin supplementation attenuates inflammatory cytokines and markers of oxidative cardiovascular processes in humans. Nutrition, Metabolism, and Cardiovascular Diseases: NMCD. 2024; 34: 1976–1983. https://doi.org/10.1016/j.numecd.2024.05.009
[12] Johnson EJ. Role of lutein and zeaxanthin in visual and cognitive function throughout the lifespan. Nutrition Reviews. 2014; 72: 605–612. https://doi.org/10.1111/nure.12133
[13] Roberts RL, Green J, Lewis B. Lutein and zeaxanthin in eye and skin health. Clinics in Dermatology. 2009; 27: 195–201. https://doi.org/10.1016/j.clindermatol.2008.01.011
[14] Shoveller AK, Bosch G, Trevizan L, Wakshlag JJ, Columbus DA. Editorial: Nutrition and Management of Animals We Keep as Companions. Frontiers in Veterinary Science. 2021; 8: 748776. https://doi.org/10.3389/fvets.2021.748776
[15] Akkewar AS, Mishra KA, Kamble MG, Kumar S, Dey J, Sethi KK. A mechanistic review on growing multiple therapeutic applications of lutein and its global market research. Phytotherapy Research: PTR. 2024; 38: 3190–3217. https://doi.org/10.1002/ptr.8197
[16] Murillo AG, Hu S, Fernandez ML. Zeaxanthin: Metabolism, Properties, and Antioxidant Protection of Eyes, Heart, Liver, and Skin. Antioxidants (Basel, Switzerland). 2019; 8: 390. https://doi.org/10.3390/antiox8090390
[17] Council for Responsible Nutrition. Lutein, Zeaxanthin, and Meso-Zeaxanthin. In: Vitamin and Mineral Safety: 4th Edition. Council for Responsible Nutrition. 2025. Available at: https://www.crnusa.org/sites/default/files/CRNVMS4-Lutein%20Zeaxanthin%20Meso_30Sept2025.pdf (Accessed: 20 January 2026).
[18] Xu X, Zhang L, Shao B, Sun X, Ho CT, Li S. Safety evaluation of meso-zeaxanthin. Food Control. 2013; 32: 678–86. https://doi.org/10.1016/j.foodcont.2013.02.007
[19] Chew BP. Importance of antioxidant vitamins in immunity and health in animals. Animal Feed Science and Technology. 1996; 59: 103–14. https://doi.org/10.1016/0377-8401(95)00891-8
[20] National Center for Biotechnology Information. GSTP1 – glutathione S-transferase pi 1. NCBI Gene. 2026. Available at: https://www.ncbi.nlm.nih.gov/datasets/gene/2950/#orthologs (Accessed: 16 January 2026).
[21] Bhosale P, Larson AJ, Frederick JM, Southwick K, Thulin CD, Bernstein PS. Identification and characterization of a Pi isoform of glutathione S-transferase (GSTP1) as a zeaxanthin-binding protein in the macula of the human eye. The Journal of Biological Chemistry. 2004; 279: 49447–49454. https://doi.org/10.1074/jbc.M405334200
[22] National Center for Biotechnology Information. STARD3 (StAR related lipid transfer domain containing 3). NCBI Gene. 2026. Available at: https://www.ncbi.nlm.nih.gov/datasets/gene/10948/#orthologs (Accessed: 16 January 2026).
[23] Li B, Vachali P, Frederick JM, Bernstein PS. Identification of StARD3 as a lutein-binding protein in the macula of the primate retina. Biochemistry. 2011; 50: 2541–2549. https://doi.org/10.1021/bi101906y
[24] Shyam R, Gorusupudi A, Nelson K, Horvath MP, Bernstein PS. RPE65 has an additional function as the lutein to *meso*-zeaxanthin isomerase in the vertebrate eye. Proceedings of the National Academy of Sciences of the United States of America. 2017; 114: 10882–10887. https://doi.org/10.1073/pnas.1706332114
[25] Vishwanathan R, Neuringer M, Snodderly DM, Schalch W, Johnson EJ. Macular lutein and zeaxanthin are related to brain lutein and zeaxanthin in primates. Nutritional Neuroscience. 2013; 16: 21–29. https://doi.org/10.1179/1476830512Y.0000000024
[26] Silverstein RL, Febbraio M. CD36, a scavenger receptor involved in immunity, metabolism, angiogenesis, and behavior. Science Signaling. 2009; 2: re3. https://doi.org/10.1126/scisignal.272re3
[27] Acton S, Rigotti A, Landschulz KT, Xu S, Hobbs HH, Krieger M. Identification of scavenger receptor SR-BI as a high density lipoprotein receptor. Science (New York, N.Y.). 1996; 271: 518–520. https://doi.org/10.1126/science.271.5248.518
[28] Chew BP, Park JS, Weng BC, Wong TS, Hayek MG, Reinhart GA. Dietary beta-carotene absorption by blood plasma and leukocytes in domestic cats. The Journal of Nutrition. 2000; 130: 2322–2325. https://doi.org/10.1093/jn/130.9.2322
[29] Álvarez R, Meléndez-Martínez AJ, Vicario IM, Alcalde MJ. Carotenoids and fat-soluble vitamins in horse tissues: a comparison with cattle. Animal: an International Journal of Animal Bioscience. 2015; 9: 1230–1238. https://doi.org/10.1017/S1751731115000415
[30] Chew BP, Park JS. Functions and actions of retinoids and carotenoids: building on the vision of James Allen Olson. Journal of Nutrition. 2004; 134: 257–261.
[31] Park HJ, Park JS, Hayek MG, Reinhart GA, Chew BP. Dietary fish oil and flaxseed oil suppress inflammation and immunity in cats. Veterinary Immunology and Immunopathology. 2011; 141: 301–306. https://doi.org/10.1016/j.vetimm.2011.02.024
[32] Barroso C, Fonseca AJM, Cabrita ARJ. Vitamins, Minerals and Phytonutrients as Modulators of Canine Immune Function: A Literature Review. Veterinary Sciences. 2024; 11: 655. https://doi.org/10.3390/vetsci11120655
[33] Warren LK. 0817 Optimizing nutrition to improve immune function in horses. Journal of Animal Science. 2016; 94: 392–393. https://doi.org/10.2527/jam2016-0817
[34] Garcia EIC, Elghandour MMMY, Khusro A, Alcala-Canto Y, Tirado-González DN, Barbabosa-Pliego A, et al. Dietary Supplements of Vitamins E, C, and β-Carotene to Reduce Oxidative Stress in Horses: An Overview. Journal of Equine Veterinary Science. 2022; 110: 103863. https://doi.org/10.1016/j.jevs.2022.103863
[35] Slifka KA, Bowen PE, Stacewicz-Sapuntzakis M, Crissey SD. A survey of serum and dietary carotenoids in captive wild animals. The Journal of Nutrition. 1999; 129: 380–390. https://doi.org/10.1093/jn/129.2.380
[36] Giercuszkiewicz-Hecold B, Kulka M, Czopowicz M, Wilczak J, Szarska E, Strzelec K, et al. The effect of long term astaxanthin supplementation on the antioxidant status of racing Arabian horses - preliminary study. Scientific Reports. 2024; 14: 27991. https://doi.org/10.1038/s41598-024-77732-9
[37] Mares J. Lutein and Zeaxanthin Isomers in Eye Health and Disease. Annual Review of Nutrition. 2016; 36: 571–602. https://doi.org/10.1146/annurev-nutr-071715-051110
[38] Winkler PA, Occelli LM, Petersen-Jones SM. Large Animal Models of Inherited Retinal Degenerations: A Review. Cells. 2020; 9: 882. https://doi.org/10.3390/cells9040882
[39] Sahin K, Orhan C, Akdemir F, Tuzcu M, Sahin N, Yilmaz I, et al. Mesozeaxanthin protects the liver and reduces cardio-metabolic risk factors in an insulin resistant rodent model. Food & Nu-

trition Research. 2017; 61: 1353360. https://doi.org/10.1080/16546628.2017.1353360
[40] Hajizadeh-Sharafabad F, Ghoreishi Z, Maleki V, Tarighat-Esfanjani A. Mechanistic insights into the effect of lutein on atherosclerosis, vascular dysfunction, and related risk factors: A systematic review of in vivo, ex vivo and in vitro studies. Pharmacological Research. 2019; 149: 104477. https://doi.org/10.1016/j.phrs.2019.104477
[41] McKenzie B, Peloquin M, Tovar A, Graves JL, Ratcliff E, Tucker K, et al. Feeding dogs a high-fat diet induces metabolic changes similar to natural aging, including dyslipidemia, hyperinsulinemia, and peripheral insulin resistance. American Journal of Veterinary Research. 2024; 85: ajvr.23.11.0253. https://doi.org/10.2460/ajvr.23.11.0253
[42] Tvarijonaviciute A, Ceron JJ, Holden SL, Cuthbertson DJ, Biourge V, Morris PJ, et al. Obesity-related metabolic dysfunction in dogs: a comparison with human metabolic syndrome. BMC Veterinary Research. 2012; 8: 147. https://doi.org/10.1186/1746-6148-8-147
[43] Moinard A, Payen C, Ouguerram K, André A, Hernandez J, Drut A, et al. Effects of High-Fat Diet at Two Energetic Levels on Fecal Microbiota, Colonic Barrier, and Metabolic Parameters in Dogs. Frontiers in Veterinary Science. 2020; 7: 566282. https://doi.org/10.3389/fvets.2020.566282
[44] Verkest KR. Is the metabolic syndrome a useful clinical concept in dogs? A review of the evidence. The Veterinary Journal (London, England: 1997). 2014; 199: 24–30. https://doi.org/10.1016/j.tvjl.2013.09.057
[45] Jahns L, Johnson LK, Conrad Z, Bukowski M, Raatz SK, Jilcott Pitts S, et al. Concurrent validity of skin carotenoid status as a concentration biomarker of vegetable and fruit intake compared to multiple 24-h recalls and plasma carotenoid concentrations across one year: a cohort study. Nutrition Journal. 2019; 18: 78. https://doi.org/10.1186/s12937-019-0500-0
[46] Harauma A, Enomoto Y, Endo S, Hariya H, Moriguchi T. Omega-3 fatty acids mitigate skin damage caused by ultraviolet-B radiation. Prostaglandins, Leukotrienes, and Essential Fatty Acids. 2024; 203: 102641. https://doi.org/10.1016/j.plefa.2024.102641
[47] Du F, Li J, Zhang S, Zeng X, Nie J, Li Z. Oxidative stress in hair follicle development and hair growth: Signalling pathways, intervening mechanisms and potential of natural antioxidants. Journal of Cellular and Molecular Medicine. 2024; 28: e18486. https://doi.org/10.1111/jcmm.18486
[48] McHaney AM, Welti R, Roth MR, Dinnetz JM, Furtney SR, Pendergraft JS, et al. Omega-3 Fatty Acid Supplementation Affects Selected Phospholipids in Peripheral White Blood Cells and in Plasma of Full-Sized and Miniature Mares. Journal of Equine Veterinary Science. 2013; 33: 779–786. https://doi.org/10.1016/j.jevs.2012.12.008
[49] Kar P, Rajesh JB, Behera SK, Konwar B, Samanta AK, Prasad H, et al. Omega Fatty Acids and Its Role in Amelioration of Canine Dermatological Disorders. Journal of Scientific Research and Reports. 2024; 30: 910–921. https://doi.org/10.9734/jsrr/2024/v30i112618
[50] Lindbergh CA, Mewborn CM, Hammond BR, Renzi-Hammond LM, Curran-Celentano JM, Miller LS. Relationship of Lutein and Zeaxanthin Levels to Neurocognitive Functioning: An fMRI Study of Older Adults. Journal of the International Neuropsychological Society: JINS. 2017; 23: 11–22. https://doi.org/10.1017/S1355617716000850