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Review

Phytochemical Deposition in Pasture-Raised Eggs: Insights from Production System and Forage Access

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Abstract

Eggs are a widely consumed and nutritionally valuable food, increasingly recognized for their potential to deliver not only essential nutrients but also health-promoting phytochemicals such as carotenoids and polyphenols. However, the presence and variability of these compounds in eggs remains poorly understood, particularly in pasture-raised systems where hens have access to fresh forage. This review explores the current state of knowledge regarding the transfer of phytochemicals from forage to eggs, highlighting the factors that influence their deposition and the implications for egg nutrient quality, hen health, and consumer health. Forage composition, which varies by plant species, season, and management practices, plays an important role in determining phytochemical intake of the hen, and consequently the egg content. While evidence suggests pasture access enhances yolk carotenoid levels and may contribute to polyphenol deposition, little is known about farm-to-farm variation and the degree of nutrient transfer. As pasture-based egg systems continue to gain popularity, understanding and optimizing phytochemical transfer from diet to egg could improve the consistency and nutritional value of eggs while supporting sustainable food production goals.

Keywords: hen nutrition; production systems; sustainable agriculture; phytochemicals; pasture-raising system

1. Introduction

Eggs are among the most widely consumed animal-source foods globally, valued for their dense and highly bioavailable nutritional profile [1,2]. Their nutritional value, however, is not fixed; yolk composition can shift meaningfully depending on what the hen eats, particularly with respect to phytochemicals, the plant-derived compounds with antioxidant and anti-inflammatory properties that hens transfer from diet to egg. This diet-dependent variability has made production system a growing focus of interest. Pasture-raised hens, with access to fresh forage, are hypothesized to produce eggs with distinct phytochemical profiles compared to conventionally raised eggs.

Consumer interest in pasture-raised eggs continues to increase, driven by concerns about animal welfare, environmental sustainability, and nutritional quality; trends are reflected in the doubling of U.S. backyard flock-keeping households between 2018 and 2024 [3,4]. Pasture-raised eggs already carry a significant retail price premium, yet the scientific evidence needed to back up nutritional claims remains thin. Research on grass-fed beef has shown that fresh forage intake can alter the nutritional profile in ways that matter to consumers, but the egg literature has not kept pace with that kind of systematic

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investigation [5,6]. While studies of eggs have reported seasonal and geographic variation in yolk fatty acid composition, suggesting that environmental and dietary factors can influence egg nutrient profiles, the phytochemical composition of pasture-raised eggs remains comparatively understudied [7,8].

Common pasture species including alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), chicory (*Cichorium intybus* L.), and ryegrass (*Lolium perenne* L.) contain appreciable concentrations of polyphenols and carotenoids that can transfer from feed into the egg yolk [9,10]. Controlled dietary supplementation trials have established this transfer across multiple compound classes, including red clover isoflavones, rosemary-derived carnosic acid, and carotenoid-rich dietary additives that enrich yolk pigmentation while reducing lipid peroxidation [11–14]. Understanding the transfer of phytochemicals from forage to egg yolk is important because these compounds may provide nutritional benefits to consumers. Egg yolk carotenoids, particularly lutein and zeaxanthin, are more bioavailable than plant-source equivalents, and clinical trials confirm that consuming carotenoid-enriched eggs improves macular pigment optical density and plasma lutein levels [15].

Supplementation studies establish that phytochemicals can move from diet to egg, but they do not capture the complexity of pasture-based production, where hens graze a diverse, seasonally changing mix of plants rather than a controlled dose of a single compound. The handful of studies that have examined pasture-raised eggs directly suggest that forage access can substantially elevate yolk carotenoid concentrations compared to confinement systems, with some evidence of seasonal variation [9,10]. However, these studies are few, methodologically inconsistent, and almost entirely focused on carotenoids. Polyphenol transfer from grazed forage into eggs has limited systematic attention, and there are few studies that have profiled both carotenoid and polyphenol content across a full grazing season under well-characterized pasture conditions. As a result, the extent to which pasture management, and its seasonal variation, shapes the full phytochemical profile of eggs remains poorly described.

This review synthesizes the available evidence on phytochemical enrichment of eggs, drawing on controlled supplementation studies to establish the biological basis for diet-to-egg transfer and on the limited pasture literature to identify what is known about how forage diversity and seasonal variation may influence phytochemical levels. In doing so, it maps the current knowledge and makes the case for systematic, season-long profiling of pasture-raised eggs as a necessary next step for translating biological potential into evidence-based guidance for producers, consumers, and policymakers.

2. Methodology

This scoping review was conducted in accordance with the PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist and explanation and Chapter 11 of the Joanna Briggs Institute Reviewers' Manual [16,17].

3. Dietary Phytochemicals

Defining and classifying dietary phytochemicals provides necessary context for understanding their potential presence in pasture-raised eggs. The term 'phytochemicals,' as used in this review, refers to plant-derived secondary metabolites: non-nutritive compounds not required for fundamental plant life processes, but which play roles in plant defense, signaling, and adaptation, and which may confer biological activity relevant to animal and human health [18]. Phytochemicals are often produced to adapt and defend in response to stressors including drought, extreme heat, plant pathogens, and grazing [19].

Phytochemicals are grouped into four major groups: terpenes, phenolics, alkaloids, and sulfur-containing compounds, as shown in Figure 1 [20].

Terpenes include volatile aroma compounds and non-volatile lipophilic pigments such as carotenoids, valued for their antioxidant properties and role in pigmentation; in eggs, carotenoids are tetraterpenoids (C40) responsible for yolk coloration and are classified into xanthophylls and carotenes, whose lipophilic nature enables efficient deposition into the yolk via the hen's diet [21,22]. Terpenes are unsaturated 5-carbon cyclic or acyclic compounds that are made of isoprene monomeric units and can be classified by their number of isoprene units [23].

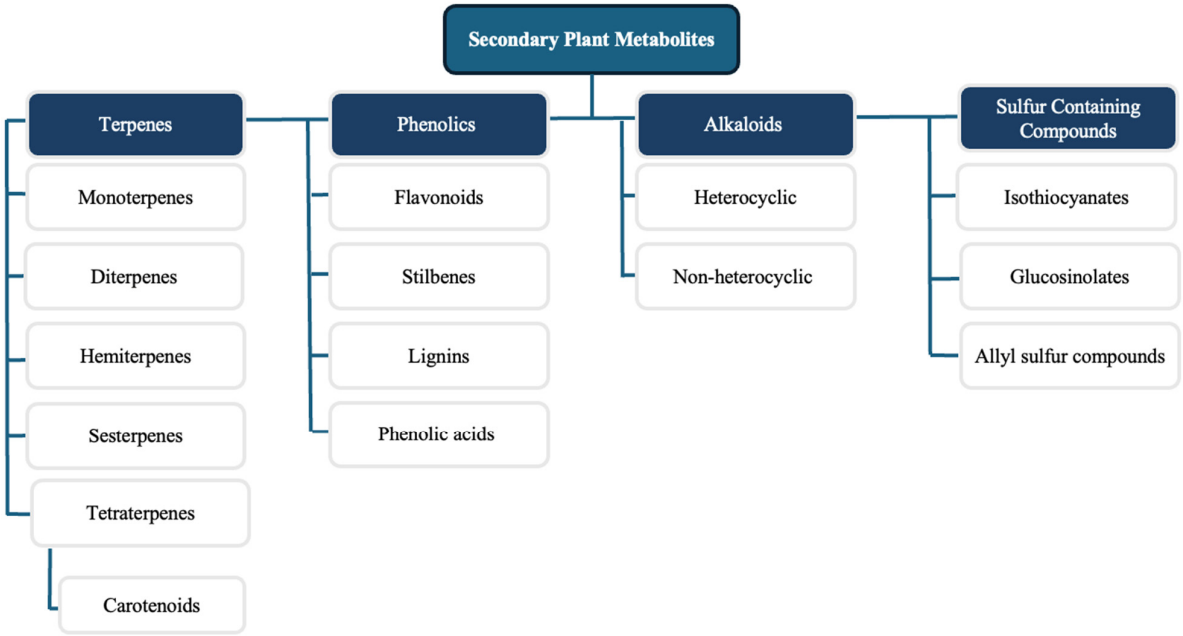


Figure 1. Classification of secondary plant metabolites. Metabolites are grouped into four major classifications: terpenes, phenolics, alkaloids, and sulfur-containing compounds.

Polyphenols are the most structurally diverse and abundant class, acting as reducing agents that protect against oxidative stress, with absorption and activity shaped by chemical structure; they include flavonoids, stilbenes, lignans, and phenolic acids, and long-term human consumption is linked to reduced risk of cardiovascular disease, diabetes, and certain cancers, while in poultry they have been shown to improve hen health and productivity [24–28]. Polyphenols comprise a hydroxyl group (-OH) bound to an aromatic hydrocarbon group. The majority of naturally occurring phenols occur as glycosides, or sugar residues, bound to an aglycone [24].

Alkaloids primarily defend plants against herbivores; their effects in poultry are less studied than those of carotenoids and polyphenols, though evidence suggests they may influence immunity, gut health, and microbiota, while toxic pyrrolizidine alkaloids have been linked to liver injury in broilers [29–34]. Alkaloids are a class of nitrogen-containing compounds; their name comes from the word alkaline and they are typically organic bases derived from amino acids [29].

Sulfur-containing phytochemicals, abundant in cruciferous vegetables, contribute to plant defense and antioxidant activity by releasing metabolites such as hydrogen sulfide; in poultry, sulfur supplementation can acidify hen feces and limit microbial ammonia production, helping prevent growth inhibition and footpad lesions caused by excess ammonia in litter [35–40]. The structure of sulfur-containing compounds is based on how sulfur atoms bind to carbon atoms within a chain or cyclic structure [30].

4. Phytochemicals in Layer Hen Diets: Supplementation and Forage-Derived Sources

Phytochemicals are gaining interest for their wide range of uses in the layer hen industry. Phytochemicals are being explored as potential alternatives to antibiotics. Antibiotics are used in the layer hen industry to reduce inflammation, prevent disease and serve as growth promoters; however, overuse can lead to antibiotic resistance, thereby reducing effectiveness in disease prevention and infection treatment [41]. Highly resistant bacteria isolates of penicillin, sulfisoxazole, streptomycin, tetracycline and quinolones have been isolated from poultry samples; these resistant bacteria can be transferred through the food chain and into the environment, posing a public health risk of antibiotic resistance [42]. Emerging evidence indicates that phytochemicals can serve as antibiotic alternatives by enhancing immune function, improving gut health, and reducing disease pressure in layer hens.

A wide range of plant products and byproducts have been studied as potential alternatives to antibiotics and growth promotors [43]. Certain phytochemicals have demonstrated antioxidant effects by scavenging free radicals which reduces oxidative stress [44]. Some phytochemicals exhibit antimicrobial activity by increasing the permeability of bacterial cell membranes, causing degradation and cell death [45,46]. Furthermore, polyphenols influence immune function by promoting immune cell proliferation, upregulating cytokine expression, and increasing antibody titers [47–49]. Phytochemicals can enhance beneficial gut microflora by supporting favorable microbes, allowing them to outcompete pathogens. Lastly, phytochemicals exhibit anti-inflammatory properties by improving intestinal epithelial integrity through tight junction protein enhancement which lowers the risk of leaky gut and systemic infections. Phytochemicals may support intestinal integrity by maintaining the mucosal barrier and enhancing nutrient absorption through increased villus height [50]. It is also important to consider that phytochemicals do not act in isolation; synergistic or antagonistic interactions among co-occurring compounds may influence their absorption, metabolism, and overall biological effect, though this remains an understudied area in layer hen nutrition [51]. For example, carvacrol and thymol, two monoterpenes in oregano, have synergistic effects in reducing antibiotic resistance for poultry-borne pathogens [52]. Phytochemicals can enter the hen diet through forage, feed, and supplementation. The following subsections examine the documented effects of phytochemicals on the health of hens and their delivery into the hen diet through forage and supplementation.

4.1. Essential Oils, Herbs and Spices

Controlled supplementation studies provide the strongest mechanistic evidence for phytochemical efficacy in layer hens, as they allow dose standardization and isolation of specific bioactive compounds. Cinnamon (*Cinnamomum verum* J.S. Presl) has been extensively studied as a potential antibiotic alternative for its beneficial impacts on nutrient digestibility, blood biochemical profile, immunomodulation, hypocholesterolemia properties, and gene expression. Further, cinnamon in the hen diet can help reduce heat stress by maintaining proper electrolytic balance [53]. Cinnamon consists of many bioactive compounds that may be responsible for these properties: cinnamaldehyde, cinnamate, and cinnamic acid [53]. Thyme (*Thymus vulgaris* L.) supplementation can enhance layer hen productivity and egg quality. Thyme, when administered over an eight-week period, significantly enhanced egg weight, egg mass, yolk color and shell thickness ($p < 0.05$) [54]. Black cumin (*Nigella sativa* L.) in the hen diet has demonstrated similar beneficial impact on egg quality, improving both egg quality and egg production over an extended period [55]. Adding oregano oil (*Origanum vulgare* L.) to the hen diet significantly increases the villus height and villus height/depth ratio in the small intestine; a larger surface area promotes

the absorption of nutrients. The most prominent phytochemicals in oregano are thymol and carvacrol [56]. The bioactive compounds in rosemary (*Rosmarinus officinalis* L.), an herb widely used as a natural antioxidant food additive, are primarily phenolics, including carnosic acid and carnosol, key contributors to its antioxidative activity. Carnosic acid is the predominant compound and exhibits particularly strong antioxidant activity. Rosemary supplementation also demonstrated a deposition of these beneficial bioactive compounds into the hen yolk, particularly carnosic acid, which was detected at concentrations of approximately 20 ng/g of egg yolk, highlighting its bioavailability in hen diets [11].

4.2. Polyphenol Supplementation in Layer Hens

Grape pomace (*Vitis vinifera* L.), a polyphenol-rich byproduct of winemaking, has been studied for its role in improving yolk lipid profile and oxidative stability [57]. Garlic (*Allium sativum* L.), another commonly used phytochemically rich food product, contains various polyphenolic compounds including gallic acid, rutin, and protocatechuic acid. These compounds give garlic its antibacterial and antiparasitic activities [58]. Dietary peppermint (*Mentha* × *piperita* L.) extracts effectively increased serum IgG in hens, an immunoglobulin that regulates the immune system, indicating its enhancement in immunity. Peppermint also improves fatty acid profile, antioxidant status, microbial richness, and egg quality parameters [59]. Yucca (*Yucca schidigera* Roezl ex Ortgies) and Quillaja (*Quillaja saponaria* Molina) supplementation improve eggshell and cuticle quality [60]. Higher cuticle quality prevents entry of pathogenic bacteria including *Salmonella* and *Escherichia coli*. Yucca also reduces nitrogen extraction, a factor that contributes to ammonia formation, thus improving litter quality and hen welfare [60]. Green tea (*Camellia sinensis* (L.) Kuntze) polyphenol epigallocatechin-3-gallate (EGCG), an abundant catechin in green tea, has demonstrated antioxidant effects in layer hens by activating the mitogen-activated protein kinase and nuclear factor erythroid 2-related 2 signaling pathways in the liver, upregulating antioxidant enzymes and reducing plasma malondialdehyde [61]. EGCG supplementation at 165 mg kg^{-1} over eight weeks increased total antioxidant capacity, reducing power, and oxygen radical capacity in both egg white and yolk, while also increasing yolk carotenoid content and egg white tryptophan [61].

Polyphenols can reduce heat stress in hens; hot periods can slow hen growth, impair immune function and cause intestinal dysfunction. Wormwood (*Artemisia annua* L.), olive (*Olea europaea* L.), milk thistle (*Silybum marianum* L. Gaertn), fennel (Foeniculum vulgare Mill.), rosemary (*Rosmarinus officinalis* L.) and thyme (*Thymus vulgaris* L.) are medicinal plants rich in polyphenols that can reduce the effects of heat stress in layer hens [62]. Phenolic compounds disrupt microbial cell membranes and can slow the growth of spoilage-causing microbes including *Salmonella*. The antioxidant abilities of phytochemicals may also chelate iron ions, starving bacteria of iron and inhibiting proliferation. Polyphenols from grape and apple waste slow lipid oxidation and prolong freshness [63]. Commonly supplemented plant products and their effects in layer hens are shown in Table 1.

4.3. Carotenoid Supplementation and Yolk Enrichment

Carotenoids are of particular interest in the layer hen industry; their lipophilic properties allow them to be efficiently deposited in egg yolks. Dietary additives high in carotenoids can also enhance yolk color. Turmeric powder (*Curcuma longa* L.), tomato (*Solanum lycopersicum* L.), carrots (*Daucus carota* L.), red pepper (*Capsicum annuum* L.), paprika (*Capsicum* L.) and marigold (*Tagetes erecta* L.) extract not only improve the yolk color by enhancing dark yellow and red hues, but improve egg quality and yolk cholesterol levels as well [55,64–66]. β-Carotene may be the carotenoid responsible for driving these changes [13,67]. Lycopene, a carotenoid typically supplemented from tomato byproducts, effectively lowers egg choles-

terol and lipid peroxidation while darkening egg yolks [14,68,69]. Currently, the European Union, Canada and the United States regulate the addition of synthetic xanthophylls in the hen diet for the purpose of darkening yolks [22]. However, instead of using synthetic xanthophylls, producers may implement naturally occurring xanthophylls like those in red pepper, marigold, tomatoes and other carotenoid-rich food products to darken egg yolks.

4.4. Forage-Derived Phytochemicals

While supplementation in the hen's diet establishes phytochemical efficacy in hens, fresh forage can serve as a complex, seasonally variable mixture available through natural foraging behavior rather than as isolated or standardized preparations. Fresh forage is a source of diverse phytochemicals, including polyphenols and carotenoids, providing a range of benefits to the hen and enhancing yolk nutrient composition. A study evaluating the influence of husbandry systems on the nutrient composition of eggs in Ancona hens demonstrated the transfer of pasture-derived phytochemicals to hen eggs [70]. Three groups of hens were compared: a control group (caged), an ecological group with standard pasture access (4 m^2 per hen), and an ecological-plus group with expanded pasture access (10 m^2 per hen). Across the grazing season, hens with larger pasture access (ecological-plus) showed higher forage intake and significantly greater deposition of carotenoids and polyphenols into the yolk compared with the control and standard ecological hens. Total carotenoid concentration more than doubled in the ecological-plus system (1597.8 μg/100 g yolk) compared to both the control (721.5 μg/100 g) and standard ecological hens (758.5 μg/100 g). This increase was largely driven by lutein, which reached 1386 μg/100 g in ecological-plus eggs compared to 568.5 and 552.8 μg/100 g in control and ecological systems, respectively. Zeaxanthin concentrations were also elevated in ecological-plus hens (136.5 μg/100 g) relative to control (94.3 μg/100 g) and ecological hens (91.3 μg/100 g). Flavonoid concentrations also showed dramatic differences, increasing from 14,000 μg/100 g in both the control and ecological systems to 44,500 μg/100 g in the ecological-plus system. The effect was most pronounced in spring, coinciding with peak forage availability and diversity [70]. Similarly, in another study, hens with access to permanent grassland produced eggs with significantly higher concentrations of lutein (+260 μg), zeaxanthin (+174 μg), and α-tocopherol (+270 μg) compared to a control group with access to rangeland without grass, alongside improved yolk color [71].

The influence of husbandry systems on yolk xanthophyll profiles has been further characterized across commercial production systems. A study analyzing xanthophyll concentrations in commercial egg yolks grouped samples into four husbandry classes: ecological (class 0), free-range (class 1), barn (class 2), and caged (class 3). Lutein and zeaxanthin, the two xanthophylls most directly reflective of forage intake, were highest in ecological eggs, with mean lutein concentrations of 1764.1 ± 430.0 μg/100 g and zeaxanthin concentrations of 1021.4 ± 199.5 μg/100 g, compared to markedly lower levels across the free-range, barn, and caged classes. Notably, canthaxanthin and β-apo-8′-carotenoic acid ethyl ester were absent from ecological yolks but present across the other three classes, reflecting their use as synthetic feed additives in conventional systems. β-cryptoxanthin was detected only in ecological and caged eggs, suggesting it may derive from both natural forage and certain conventional feed ingredients. These xanthophyll profiles collectively reinforce the conclusion that outdoor access and forage availability meaningfully shape the carotenoid composition of egg yolks, with ecological husbandry producing the most distinct and elevated xanthophyll concentrations [72].

Previous research demonstrating that nutrient levels vary with season, geography, and production system suggests that phytochemical content may follow a similar pattern [7,8]. The few studies examining phytochemical deposition in eggs from hens with pasture access,

including the studies referenced above, suggest that transfer is biologically meaningful, but the evidence base remains too limited to draw conclusions about dose, bioavailability, or the relative contribution of specific forage species. Expanding research in this area is necessary to fully characterize the nutritional value of pasture access and to inform evidence-based pasture management recommendations.

Many pasture-raised hens are also supplemented with grain-based feed, and these conventional feed ingredients are not devoid of phytochemicals themselves. Corn, wheat, and soybean meal each contribute their own compounds, generally at lower concentrations than pasture forage. Corn has the highest phenolic content among commonly consumed grains, with carotenoid concentrations reaching up to approximately 30 mg/kg dry weight, primarily as lutein and zeaxanthin [73–75]. Wheat also contains phytochemicals, including phenolic acids, flavonoids, and carotenoids, generally at lower concentrations than corn [76]. Soybean, commonly used as a protein source in poultry feed, contains phenolic compounds and flavonoids, with total phenolic content ranging from 1.15 to 1.77 mg gallic acid equivalents/g and flavonoid content ranging from 0.68 to 2.13 mg quercetin equivalents/g across different genotypes [77,78].

4.5. Challenges to Phytochemical Implementation in Layer Hens

Although phytochemicals can improve hen health, egg quality and nutrient composition of eggs, it is important to acknowledge barriers to implementation on a large scale in the layer hen industry [58,63,71,72,79]. The bioavailability of phytochemicals must be understood; interventions may have low absorption due to low solubility or inappropriate molecular size. Factors including extraction methods, form of product (powder, extract, oil), dosage variations, and low purity may influence effectiveness. Adulterations, low stability during storage and transportation, high volatility of bioactive compounds, and cost of production are all barriers to application in the industry [80].

Regarding phytochemicals present in forage, the concentration in forage may not be high enough to be an effective dose. There may also be potential synergisms between phytochemicals in forage that influence their overall efficacy. Further, breed of hen may influence efficiency of phytochemical deposition in eggs. For example, when ISA Brown and Hy-Line White hens were fed identical diets supplemented with carotenoids from marigold extract, ISA Brown hens demonstrated a notably greater ability to absorb and deposit dietary carotenoids into egg yolks compared to Hy-Line White hens [81]. Another study found carotenoid concentrations vary widely across nine different hen breeds, with lutein ranging from approximately 10 to 67 μg/g and zeaxanthin from 5 to 29 μg/g, highlighting the influence of genetic factors alongside diet on yolk composition [82]. Similar findings have been reported in organic production systems, where both hen genotype and forage source influenced yolk carotenoid composition. In a comparison of Lohmann Silver and New Hampshire hens fed diets supplemented with either maize silage and carrots or alfalfa silage, genotype significantly influenced yolk carotenoid concentrations. Moreover, hens receiving alfalfa silage produced eggs with darker yolks and higher concentrations of pigmenting carotenoids, demonstrating that both genetic background and forage composition contribute to variation in phytochemical deposition in eggs [83].

Consumer flavor preferences are another important consideration to adding phytochemicals into layer hen diets. When adding garlic to hen diets, there was a strong flavor transferred to the eggs that was not well accepted by consumers [84]. Further research is needed to determine consumer flavor preferences for eggs produced from various production types, including how fresh forage alters the overall sensory qualities of eggs. Overall, while phytochemicals offer promising avenues for optimizing layer hen production, there

are some notable challenges to overcome. To address these challenges, further research is needed to apply interventions to layer hens.

Table 1. Commonly supplemented plant products and their effects in layer hens.

Plant Supplementation	Effects	References
Cinnamon	Increased digestibility of nutrients, electrolyte balance, and blood biochemical profile	[53]
Thyme	Increased hen productivity and egg quality	[54]
Black cumin	Increased egg quality	[55]
Oregano oil	Increased absorption of nutrients	[56]
Rosemary	Improved lipid metabolism and antioxidant capacity	[85]
Grape pomace	Improved yolk lipid profile, oxidative stability, and antioxidant capacity; increased n-3 fatty acids	[57]
Garlic	Antibacterial and antiparasitic activity; lower cholesterol	[58]
Peppermint extract	Increased IgG, egg quality, antioxidant capacity, and fatty acid profile	[59]
Yucca	Improved eggshell quality and cuticle quality; reduced nitrogen extraction	[60]
Quillaja	Improved eggshell quality and cuticle quality	[60]
Fermented pine (*Pinus densiflora* Siebold & Zucc.)	Improved egg production, egg mass, yolk color, and eggshell color and strength; increased antioxidant capacity	[79]
Turmeric, paprika, red pepper, marigold extracts	Darker yolk color; increased egg quality and blood cholesterol	[55,64–66]

5. Phytochemicals Present in Forage and Grass

Hens raised on pasture exhibit variation in nutrient composition both seasonally and across geographic regions, likely influenced by the forage species available [7,8]. Access to fresh forage provides hens with health-promoting phytochemicals, which can impact hen health and be deposited into egg yolks, enhancing their nutrient profile. The species composition of pasture is a key determinant of phytochemical diversity and concentration. Diverse, multi-species pastures enhance the nutritional and phytochemical profile of foraging systems compared to monocultures [86]. Additionally, forage management practices such as rotational grazing, mowing height, and regrowth intervals can influence plant maturity and secondary metabolite content [87,88]. For example, rotational grazing can ensure hens access more tender, phytochemically rich plant tissues by preventing overgrazing and promoting regrowth.

While forage serves as a source of phytochemicals for pasture-raised hens, quantitative data on actual intake remain limited. Available evidence suggests considerable individual variation in grazing behavior, with grass consumption ranging from 13 to 130 g fresh weight per hen per day, equating to an average dry matter intake of approximately 14 g, representing around 7% of the daily energy requirement for a hen in full production [89]. More narrow estimates have also been reported, estimating an average of 10–30 g DM(dry matter) per day [90]. A separate analysis across multiple forage types found forage typically comprised less than 50% of total feed intake, and that intake exceeding approximately 50 g/hen/day was necessary to produce measurable effects on egg quality, including increased carotenoid content and darker yolk color [9]. The wide variation in forage consumed suggests that foraging has a meaningful but highly variable impact on hen diet.

5.1. Phytochemicals in Pasture Species

Pasture composition varies by region and landscape, but typical pastures contain a mix of legumes, grasses, and forbs, each contributing differently to phytochemical availability. Common legume species include alfalfa (*Medicago sativa*), clover (*Trifolium* spp.), trefoil (*Lotus corniculatus* L.), and vetches (*Vicia* spp.), while common grasses and forbs include ryegrass (*Lolium perenne* L.), Johnson grass (*Sorghum halepense* L. Pers.), chicory (*Cichorium intybus* L.), plantain (*Plantago major* L.), brassica (*Brassica oleracea* L.), and meadow grass (*Poa annua* L.) [91]. Polyphenols are abundant in many forage species, particularly perennial rye grass, chicory, plantain, brassica, red clover and alfalfa which contain high levels of flavonoids and phenolic acids [92,93]. Alfalfa, the most cultivated of the at least 83 *Medicago* species, contains approximately 1041 mg/kg DM total carotenoids and 18.6 g/kg DM total phenols, with lutein as its dominant carotenoid alongside neoxanthin and violaxanthin [94,95].

Clover, including white and red clover, is a particularly rich source of isoflavones [95–97]. Isoflavones can act as phytoestrogens, having mild estrogenic activity. Clover contains approximately 1044 mg/kg DM total carotenoids and 33,700 mg/kg DM total phenols, with characteristic compounds including antheraxanthin, lutein, neoxanthin, violaxanthin, flavonols, cinnamic acid derivatives, and flavanols [95]. Red clover contains high concentrations of the equol precursors formononetin and daidzein. Hens with access to fresh red clover pasture produced eggs containing biologically relevant levels of equol, approximately 11 μg per egg, which is comparable to levels achieved through isoflavone supplementation [12]. Isoflavones more broadly, including biochanin A, formononetin, genistein, and daidzein, are associated with improvements in age-related changes in reproductive capacity in some studies [97]. In aging hens, isoflavone supplementation improved the rate of egg laying and ovarian function [98].

In various trefoil species, flavonoids and saponins are highly abundant. Trefoil is also notably a source of condensed tannins, also known as proanthocyanidins [99]. Vetches are a potent source of flavones, coumarin, and triterpenoids, and contain approximately 1171 mg/kg DM total carotenoids and 22.9 g/kg DM total phenols [95,100].

Several additional forage and herb species, while less commonly studied in laying hens specifically, contribute to the broader phytochemical landscape of pasture systems. Stinging nettle (*Urtica dioica* L.), a common temperate-climate plant, contains substantial carotenoid concentrations: lutein at 366–525 mg/kg, β-carotene at 100–111 mg/kg, and zeaxanthin at 23–60 mg/kg of fresh plant material, with a total carotenoid content of approximately 50–75 mg/kg DM dominated by lutein, followed by violaxanthin, neoxanthin, and β-carotene [101,102]. These concentrations are broadly comparable to those found in grass and alfalfa [9]. Birdsfoot trefoil (*Lotus corniculatus*), a legume historically used in cattle feeding systems, contains high concentrations of β-carotene [103]. Marigold species (*Calendula officinalis* L. and *Tagetes erecta* L.) represent another carotenoid source, with flower petals containing lutein, lutein esters, zeaxanthin, lycopene, and β-carotene [104]. Kale (*Brassica oleracea* var. *sabellica* L.) represents another pasture species containing high total carotenoid (13.3 mg/100 g fresh weight) and polyphenol (27 mg/100 g fresh weight) concentrations [105]. Meadow grass and red clover are also particularly rich in carotenoids [106]. In a study examining nutrient availability in hen husbandry systems, grass and legume pastures, comprising ryegrass, trefoil, Johnson grass, and red clover, had high levels of violaxanthin, beta-carotene, and lutein [107]. Fresh forage contains relatively high carotenoid concentrations in many species, though levels vary considerably by plant type and maturity. The most common carotenoids in forage are beta-carotene and xanthophylls [108,109].

5.2. Seasonal Shifts in Forage Phytochemicals

The concentration of phytochemicals in forage is primarily dependent on many factors including season, climate, and plant characteristics. Carotenoid content is influenced by plant maturity, leaf to stem ratio, temperature and humidity [110]. Carotenoid content tends to be highest in humid climates and in less mature plants. Carotene, a type of carotenoid, is affected by species, light, nitrogen fertilization, and the interaction between light and nitrogen fertilization [111]. The bioavailability of carotene in forage was higher, on average, in warmer months. Bioavailability varies with factors including month, form of carotenoid, forage species and dry matter content; similar patterns may be observed in layer hens [112]. Furthermore, the highest amounts of phytochemicals were present in forage during spring months, when availability and diversity are at their peak [107]. Others have reported similar trends, observing polyphenol content in forage was at its highest in spring months [93,113]. These findings highlight the seasonal shifts and plant characteristics that may influence phytochemicals present in forage.

5.3. Soil Parameters Influence Forage Phytochemicals

While forage characteristics and composition determine the concentration of phytochemicals available to hens, the soil is an underlying component that further shapes phytochemical content. Nutrient availability and organic matter content present have the potential to influence the phytochemical profile of plants. Nutrient-rich soils may support phytochemical production by supplying necessary precursors, and some evidence associates higher soil nutrient availability with elevated phytochemical concentrations in plants [114]. Soils rich in organic matter typically have better soil structure and moisture retention, creating a more favorable environment for plant growth, leading to higher levels of phytochemicals. Soils lacking essential elements can detrimentally influence phytochemical content in forage; during periods of stress, resources are redirected away from secondary metabolite production towards primary metabolites. Conversely, plant stress, including lack of nutrient availability, heat stress, drought, and grazing can also stimulate the production of phytochemicals as an adaptive defense mechanism [115]. Both resource abundance and environmental stress can influence phytochemical content in forage.

5.4. Farm-to-Farm Variation in Phytochemical Availability

Concentrations of phenolics and carotenoids vary depending on the species available, leading to farm-to-farm variation in phytochemical content. While pasture management and composition influence the phytochemicals available, linking these factors to actual hen intake remains a challenge [6]. Factors such as selective foraging behavior, variability in pasture quality, and daily intake fluctuations contribute to inconsistency in quantification. Further, grazing animals exhibit a phenomenon referred to as 'nutritional wisdom'; the concept that animals can selectively forage and self-medicate based on post-ingestive feedback and physiological need [116]. Hens may preferentially select certain plant species containing specific phytochemicals in response to internal cues, further adding to the complexity of quantifying phytochemicals in the hen diet. Controlled feeding trials with known quantities of dried or encapsulated plant material are often used to establish baselines, but these do not fully demonstrate the complexity of hen foraging [117].

6. Deposition of Phytochemicals in Eggs

In pasture-based systems, hens may consume diverse plant materials rich in phytochemicals with the potential to influence egg antioxidant capacity and yolk pigmentation and exhibit human health benefits. However, for these compounds to be effectively deposited into the egg, they must first undergo digestion, be absorbed through the intestinal

tract, and then be incorporated into the yolk. The efficiency of these processes depends on both the chemical characteristics of the compounds and the physiology of the layer hen's digestive and metabolic systems. The digestion, absorption, metabolism, and deposition of phenols and carotenoids are shown in Figure 2.

6.1. Polyphenol Deposition Pathway

(Figure 2, P1) In the proventriculus, polyphenols in the food matrix may undergo initial chemical modification in acidic conditions. (Figure 2, P2) In the small intestine enzymatic hydrolysis converts glucosides into free aglycones, which may be absorbed across the intestinal wall into portal circulation [28]. (Figure 2, P3) However, approximately 90% of ingested polyphenols bypass small intestinal absorption and proceed to the large intestine where gut microbiota ferments them into smaller, more bioavailable phenolic metabolites via enzymatic hydrolysis and microbial action [118,119]. (Figure 2, P4) These metabolites are then transported to the liver, where they undergo phase II conjugation: glucuronidation, methylation, and sulfation, before entering systemic circulation [120]. (Figure 2, P5) Conjugated metabolites travel bound to albumin, lipoproteins (LDL and HDL), and red blood cells, with no free polyphenols present in circulation [121]. The predominant carrier varies by polyphenol class; phenolic acids associate primarily with albumin and HDL, anthocyanins preferentially bind to LDL, and catechins associate more readily with red blood cells [121]. Bound phenolics travel toward the ovary and oviduct (Figure 2, P6). In the ovary, albumin-bound metabolites may transfer to the egg yolk, though deposition occurs at relatively low levels [28,122]. Polyphenol bioavailability is further modulated by chemical structure, gut microbiota composition, intestinal transit time, and dietary fat content [119]. Polyphenol absorption and digestion in layer hens are complex processes dictated by compound properties and hen physiology. While the transfer of polyphenols into eggs is less documented than carotenoids, emerging analytical methods such as liquid chromatography–mass spectrometry (LC–MS) are beginning to detect and quantify polyphenolic metabolites in egg yolks from pasture-raised systems [123].

6.2. Carotenoid Deposition Pathway

Carotenoids are lipophilic, fat-soluble molecules that follow lipid transport pathways. Unlike polyphenols, which are hydrophilic and subject to extensive metabolic degradation, carotenoids are incorporated into lipid transport pathways during intestinal absorption, facilitating their high accumulation in the lipid-rich egg yolk. (Figure 2, C1) In the proventriculus, carotenoids enter the digestive tract bound within the food matrix. (Figure 2, C2) In the small intestine, digestive enzymes release carotenoids from the matrix, which are solubilized into mixed micelles and absorbed across the brush border via passive or active diffusion [22,124]. (Figure 2, C3) In the enterocytes, absorbed carotenoids are packaged into portomicrons and transported via the portal vein to (Figure 2, C4) the liver, where portomicrons are repackaged into very-low-density lipoproteins targeted to the yolk (VLDLy) [22]. (Figure 2, C5) Systemic circulation occurs when VLDLy particles pass through the theca and granulosa layers of the developing follicle; VLDLy particles in laying hens are approximately 30 nm in diameter and resistant to lipoprotein lipase hydrolysis, enabling them to pass through the granulosa basal lamina [125]. (Figure 2, C6) Once in the ovary, the VLDLy binds the LR8 (VLDL) receptor on the oocyte membrane and is internalized via receptor-mediated endocytosis, forming yolk granules [22]. Carotenoid deposition efficiency is strongly influenced by dietary fat levels, carotenoid type, and the SLAMENGHI factors: species, linkage, amount consumed, food matrix, effects of absorption, nutrient status, genetic factors, host-related factors, and interactions among these variables [126].

Xanthophylls such as lutein and zeaxanthin are generally deposited more efficiently in the yolk than β-carotene [127].

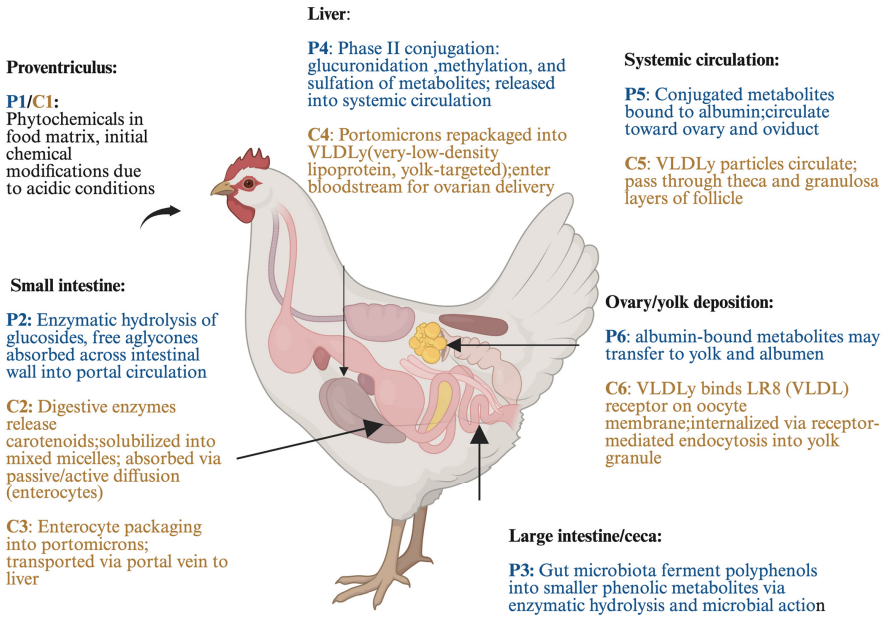


Figure 2. The figure demonstrates polyphenol (blue text) and carotenoid (yellow text) digestion, absorption, metabolism, and deposition in the laying hen. Polyphenols are partially absorbed in the small intestine, extensively metabolized by gut microbiota in the large intestine/ceca, and transported to the liver for conjugation (glucuronidation, methylation, sulfation) before circulation. Carotenoids are released from the food matrix, incorporated into micelles, absorbed by enterocytes, transported to the liver, packaged into VLDLy particles, and delivered to developing ovarian follicles for deposition into the egg yolk [22,120,122,124,128]. Created in BioRender (v2026). Adams, J. (2026) https://BioRender.com/h9g2ryg (accessed on 20 July 2026).

7. Significance of Phytochemicals in Eggs for Human Health

The healthfulness of eggs has historically been debated due to their cholesterol content, though more recent evidence indicates that dietary cholesterol from eggs has a limited effect on blood cholesterol levels in most individuals, and this perception is increasingly being reconsidered [129]. There is increasing evidence that eggs can be a source of bioactive compounds beneficial to human health, including polyphenols and carotenoids [130]. Dietary phytochemical intake has been associated with health-promoting effects and reduced oxidative stress in human studies [130]. Eggs are a potential source of both lutein and zeaxanthin; these xanthophylls are efficiently absorbed in humans from eggs [15]. Although one whole egg contains about 250 µg of lutein and zeaxanthin, less than other sources like raw spinach which contains 3659 µg per cup, the carotenoids in eggs are more bioavailable [131]. Lutein bioavailability from eggs is higher than other lutein-rich foods, likely due to components in egg yolk, like the fat emulsifier lecithin which enhances micelle formation and intestinal uptake [132]. Low lutein is a risk factor for age-related macular degeneration, the leading cause of vision loss in older populations, and consumption of lutein-enriched egg yolks was associated with improvements in visual acuity, macular pigment optical density, and plasma lutein concentration in elderly patients [133]. The level of antioxidant activity in the egg is influenced by cooking methods, storage, and gastrointestinal digestion. Carotenoids previously reported in eggs, including lutein, zeaxanthin, cryptoxanthin, and β-carotene, are summarized in Table 2. The values presented in Table 2 were sourced from food composition databases and represent baseline estimates of carotenoid and isoflavone concentrations reported in eggs. These data are included to demonstrate the potential

presence of phytochemicals in eggs rather than to reflect production system-specific concentrations. It is important to note that phytochemical content in eggs is likely to be influenced by factors such as production system, diet composition, and access to pasture or forage, as the dietary intake of laying hens is a primary determinant of yolk carotenoid and isoflavone deposition. However, comparative data across production systems (e.g., free-range, organic, conventional) remain scarce in the current literature, representing a notable gap in research.

Designer eggs are considered a category of functional food; that is, foods designed and enriched to provide health-promoting nutrients at levels exceeding those found in conventional counterparts. Consistent with concepts proposed by EFSA, FAO, and the FUFOSE initiative, these products represent an approach to designing foods for improved nutritional quality and potential health benefits. The high deposition of fat-soluble vitamins and beneficial fatty acids in the egg yolk from the hen diet makes eggs an effective vehicle for delivering these nutrients to humans [134–136]. The concept of designer eggs first started out of Alberta, Canada, where eggs were enriched with omega-3 fatty acids and antioxidants [134]. The ease with which egg nutrient composition can be altered makes them useful for providing essential nutrients to the population.

More recently, studies have emerged investigating eggs as a functional food vehicle for not only vitamins and fatty acids, but certain plant bioactive compounds. A study out of India coined the term 'Herbal Enriched Designer Eggs' (HEDE) in which eggs were enriched with plant compounds like allicin, betaine, eugenol, lumiflavin, lutein, sulforaphane and other bioactive phytochemicals [137]. This study was carried out by investigating seven hen diets: (1) a control diet with regular layer hen feed, (2) the standard 'designer egg' enriched diet, (3) a diet with garlic pearls, (4) fenugreek seeds, (5) bay/curry leaves, (6) basil leaves or (7) spirulina. This study found designer feeds improved hens' immunity and overall health. Eggs from the interventions had higher antioxidant properties, immunoglobulins, carotenoids, vitamin E, selenium, and omega-3 polyunsaturated fatty acids. Lastly, consumption of these 'Herbal Enriched Designer Eggs' produced beneficial changes in lipid profiles in human participants [84]. Although current evidence is insufficient to establish specific daily or weekly egg intake recommendations for achieving the health benefits associated with phytochemical-enriched eggs, future studies incorporating dose–response designs are needed to determine optimal consumption levels.

Table 2. Carotenoid and isoflavones previously reported in whole eggs and egg yolks, in raw and cooked eggs. Carotenoids include lutein, zeaxanthin, cryptoxanthin, and β-carotene. Isoflavones include daidzein and genistein. Data compiled from [138–143]. Data originally reported as per egg were converted to µg/100 g to provide consistency. Data was converted assuming an average egg weight of 50 g. Empty cells indicate no data reported [138–143].

	Whole Egg, Cooked	**Egg Yolk, Cooked**	**Whole Egg, Raw**	**Egg Yolk, Raw**	**Analytical Methods**	**References**
Lutein (trans + cis)	273 µg/100 g	744 µg/100 g	336 µg/100 g	917 µg/100 g	High-performance liquid chromatography (HPLC)	[138]
Zeaxanthin (trans + cis)	252 µg/100 g	686 µg/100 g	319 µg/100 g	870 µg/100 g	HPLC (AOAC 941.15)	[138]
Cryptoxanthin	546 µg/100 g	---	672 µg/100 g	---	HPLC (AOAC 941.15)	[139]
β-carotene	32 µg/100 g	---	0 µg/100 g	---	HPLC (AOAC 941.15)	[140]
Zeaxanthin + lutein	500 µg/100 g	---	504 µg/100 g	---	HPLC (AOAC 941.15)	[141]
Daidzein	---	---	20 µg/100 g	20 µg/100 g	HPLC methods adapted from Murphy et al. [142]	[143]
Genistein	---	---	20 µg/100 g	10 µg/100 g	HPLC methods adapted from Murphy et al. [142]	[143]
Total isoflavones	---	---	50 µg/100 g	50 µg/100 g	HPLC methods adapted from Murphy et al. [142]	[143]

8. Conclusions

Eggs are an established vehicle for dietary phytochemicals, with yolk composition directly reflecting the hen's diet. Pasture species commonly grazed by laying hens, including alfalfa, red clover, chicory, and ryegrass, provide distinct phytochemical classes including polyphenols and carotenoids, though concentrations vary substantially with season, plant maturity, and species composition. The evidence reviewed here supports the biological plausibility of phytochemical transfer from forage to egg: the lipophilic nature of carotenoids facilitates their efficient incorporation into the yolk via lipid transport pathways, and controlled supplementation trials have confirmed that specific compounds, including carotenoids, isoflavones, and phenolic acids such as carnosic acid, can be detected in egg yolk following dietary exposure. Pasture-specific studies, though limited in number, suggest that expanded forage access may substantially elevate yolk carotenoid concentrations, with effects most pronounced during spring when forage diversity and phytochemical content are at their peak.

Several critical knowledge gaps limit the translation of these findings into evidence-based recommendations. First, the evidence for polyphenol deposition from pasture forage specifically remains sparse. While supplementation studies demonstrate that certain polyphenols can be detected in egg yolk, the extent to which naturally consumed forage polyphenols, present at variable concentrations, are transferred to the egg under real production conditions is poorly understood. Second, the high degree of variability inherent to pasture systems, driven by forage species composition, season, geographic region, soil quality, management practices, insects, and hen breed, has not been systematically quantified, making it difficult to generalize findings across farms or production contexts. Third, the relative contributions of specific forage species to egg phytochemical profiles remain unknown, limiting the ability to design pasture composition or management strategies that reliably optimize egg quality.

For the human consumer, egg yolk carotenoids, particularly lutein and zeaxanthin, are more bioavailable than from plant sources, and clinical studies confirm that enriched eggs improve macular pigment optical density and plasma lutein. Systematic, standardized profiling of phytochemical concentrations across well-characterized pasture systems, seasons, and breeds remains the primary research need for translating this biological potential into evidence-based recommendations.

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