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Long-Term Health Effects of Artificially Colored Foods in Adults and Children: A Review of Scientific Literature on Attention Deficits, Carcinogenicity, and Allergy Risks

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ABSTRACT

The widespread use of artificial food colorants in processed foods has raised concerns regarding their long-term health effects, particularly in sensitive populations like children. This review evaluates current scientific literature on the potential health risks associated with synthetic food colorants, including attention deficits, carcinogenicity, and allergenic responses. Synthetic dyes, such as tartrazine (E102) and Brilliant Blue FCF (E133), are highly valued for their stability and vibrancy but have been linked to neurobehavioral and allergenic effects. Evidence suggests that azo dyes may induce hyperactivity, learning impairments, and allergic reactions, particularly in children and those with a genetic predisposition to sensitivities. In contrast, natural pigments like curcumin (E100), chlorophyllin (E140), and anthocyanins (E163) exhibit anti-inflammatory and antioxidant properties, supporting cardiovascular, cognitive, and cancer-preventive health benefits, though their stability in food applications presents a challenge. The review also highlights regulatory responses, such as the European Union's mandatory labeling requirements, which aim to reduce synthetic dye exposure in high-risk groups. Given the adverse effects associated with synthetic colorants, there is an increasing shift toward natural alternatives. However, enhancing the bioavailability and stability of these natural compounds is essential for their broader adoption. This comprehensive analysis underscores the need for balanced, evidence-based regulation and consumer education to promote safer food colorant choices and supports ongoing research into functional food colorants that offer both aesthetic appeal and health benefits.

Keywords

artificial colorants, diet, food coloring, synthetic colorants, food dyes, concentration deficit, concentration disorder, cancerogenesis, cancerous food additives

INTRODUCTION: Classification of Food Colorants by Chemical Composition and Source

Food colorants serve a dual purpose in the food industry by enhancing visual appeal and indicating product quality. In the European Union, these additives are classified by "E" numbers, which denote specific regulatory standards to ensure consumer safety[^22][^40]. Broadly, food colorants can be classified by their chemical structure and source, distinguishing between natural and synthetic options, each of which offers unique stability and application profiles across food products[^40][^74]. For instance, curcumin (E100) is a natural polyphenolic pigment derived from turmeric, notable for its antioxidant and anti-inflammatory properties despite limited bioavailability, which restricts its absorption and efficacy in foods without specific formulations[^55][^61]. Tartrazine (E102), a synthetic yellow azo dye, is chemically stable and widely used in long-shelf-life products, but its azo linkage has been implicated in potential neurobehavioral and allergic reactions, especially in sensitive individuals and children[^1][^3][^5]. Brilliant Blue FCF (E133), another synthetic dye, offers high structural stability across processing conditions; however, concerns over its neurodevelopmental effects have led to cautious regulatory assessments[^12][^27]. Chlorophyllin (E140), derived from chlorophyll, is stabilized with copper to enhance water solubility and is valued for its antioxidant and chemopreventive properties, which may mitigate oxidative damage linked to cancer risk[^64][^10][^65]. Carotenoids (E160a-f) and anthocyanins (E163) not only offer vibrant aesthetic qualities but also provide health benefits, including antioxidative support, making them valuable in functional foods[^74][^46][^52]. This classification framework, grounded in chemical structure and source, clarifies the diverse health implications of food colorants, spanning risks and functional health advantages, which is essential for balanced use in food processing and regulation.

Table 1. Overview of most commonly used food colorants

colorant	**symbol (EU)**	**color**	**source**	**general impact on health**	**solu--bility**	**chemical properties**
curcumin	E100	yellow	rhizome of *Curcuma longa*	anti-inflammatory, antioxidant, neuroprotective, anticancer, gut health [61, 57]	lipids	polyphenol, diarylhep--tanoid
tartrazine	E102	yellow	synthetic	may cause allergies, hyperactivity concerns [1, 3, 5, 7]	water	azo dye
carminic acid	E120	red	insects of *Sternorrhyncha* suborder	antioxidant, anti-inflammatory, supports kidney health; allergy risk, gastrointestinal distress [17, 18, 19]	water	glycosylated anthraquinone

brilliant blue FCF	E133	blue	synthetic	anti-inflammatory, neuroprotective, ADHD symptom concerns; potential allergen, kidney stress in high doses [12, 16, 27]	water	triarylmethane dye
chloro--phyllin	E141	green	semi-synthetic (modified chlorophyll from green vegetables)	antioxidant, anti-cancer, gut health [10, 11, 66]	water	porphyrin derivative
sulfite ammonia caramel	E150d	dark brown	synthetic	potential toxicity, immune impacts [22, 20, 23]	water	product of ammonia--sucrose reaction
caro--tenoids	E160	orange / red	orange / red vegetables, mainly carrots	vit. A precursors, eye health, antioxidant, cardiovascular support [74, 75, 82]	lipids	tetraterpenes derivatives
betanins	E162	red / / pink	beetroots and other members of *Caryophyllales* order	antioxidant, anti-inflammatory, liver health support [68, 72, 73]	water	glycosylated tyrosine derivatives

antho- -cyanins	E163	purple / red (pH- - dependent)	purple fruits & vegetables, mainly black carrot	cardiovascular health, antioxidant, cognitive support [44, 46, 50]	water	polymethines, flavonoids

Differential Health Impacts of Food Colorants: Identification of Harmful, Neutral, and Health-Promoting Compounds

The health impacts of food colorants range from potentially harmful to beneficial, depending on their chemical nature and usage patterns[^1][^22]. Synthetic colorants, particularly azo dyes like tartrazine (E102), are valued for their stability and vibrant color but have been linked to adverse effects, such as allergic reactions, neurotoxicity, and possible genotoxicity due to aromatic amine byproducts formed during metabolism[^1][^3][^6]. Studies on azo dyes indicate that such compounds may impair learning and memory and increase hyperactivity in children, resulting in regulatory guidelines recommending limited exposure in vulnerable populations[^5][^15][^27]. Similarly, Brilliant Blue FCF (E133) and Allura Red (E129) are associated with neurobehavioral risks, particularly for children frequently exposed through processed foods, raising public health concerns[^27][^30][^16]. On the contrary, certain natural pigments, such as curcumin (E100) and chlorophyllin (E140), present potential health benefits[^10][^61]. Curcumin is recognized for its anti-inflammatory and neuroprotective effects, though it requires enhanced formulations to increase bioavailability in foods[^55][^56]. Chlorophyllin, which mitigates oxidative stress, exhibits chemopreventive qualities that may contribute to lower cancer risk[^10][^64][^65]. Anthocyanins (E163), found in dark-hued fruits like berries, support cardiovascular and cognitive health due to their anti-inflammatory effects, making them popular for both aesthetic and functional roles in foods[^44][^46][^48]. This differentiation emphasizes the need for thoughtful selection of colorants in food processing, with an emphasis on those that pose minimal health risks or provide added health benefits.

Distinction Between Synthetic Food Colorants and Artificial Color Enhancement Techniques

Synthetic colorants such as tartrazine (E102) and Brilliant Blue FCF (E133) are chemically designed to deliver consistent and vivid hues in processed foods; their stability and cost-effectiveness, however, are often balanced by potential health trade-offs, including allergenicity and neurotoxicity in susceptible individuals[^5][^27]. In contrast, artificial color enhancement through natural pigments resonates with health-conscious consumers seeking “clean-label” options[^36][^67]. For instance, black carrot and beetroot extracts provide vibrant hues from anthocyanins and betalains, respectively[^44][^68][^71]. These natural pigments, however, are sensitive to heat and light exposure, which can limit their application in processed foods, presenting formulation challenges for manufacturers[^73][^72]. This trend reflects consumer preference for natural additives, despite production complexities and higher costs, as well as the regulatory efforts that prioritize food safety[^40][^18]. Analytical advancements in detecting and quantifying these compounds play a pivotal role in regulatory strategies for both synthetic and natural colorants, ensuring safer use across the food industry[^12][^20][^40].

Endogenous Pigment Sources in Whole Foods: Natural Occurrence and Types

Whole foods inherently provide a wide array of bioactive pigments, each contributing specific health benefits beyond color[^74][^46]. Carotenoids, such as beta-carotene and lycopene found in carrots, tomatoes, and other red-orange fruits, are known for their antioxidative properties and potential to reduce cardiovascular risk, and they also play a role in supporting vision health[^81][^82]. Astaxanthin, a potent carotenoid in marine foods like shrimp and salmon, exhibits anti-inflammatory effects that support skin and eye health, underscoring the diverse applications of carotenoids in both nutrition and cosmetics[^79][^77]. Chlorophyll, responsible for the green color in leafy vegetables, aids in detoxification and is associated with reduced cancer risk due to its ability to bind carcinogens and facilitate their excretion[^64][^65][^66]. Anthocyanins, present in berries and purple vegetables, offer strong antioxidative and anti-inflammatory properties, supporting cardiovascular and cognitive function[^45][^48]. Betalains, sourced from beetroot and prickly pear, have shown promise in cancer prevention and vascular health by modulating oxidative stress[^71][^72][^70]. These natural pigments collectively highlight the health benefits of whole foods, supporting a dietary preference for naturally colored produce.

Industrial Food Categories Incorporating Exogenous Colorants During Processing

The food industry incorporates exogenous colorants to standardize appearance, enhance visual appeal, and restore color lost during processing[^36][^40]. Synthetic dyes like tartrazine (E102) and Brilliant Blue FCF (E133) are extensively used in candies, beverages, and snack foods due to their stability and cost-effectiveness; however, studies linking these dyes to allergenic and neurobehavioral effects, especially in children, have raised concerns[^1][^2][^15]. For example, Brilliant Blue FCF and Allura Red have been associated with attention deficits and hyperactivity, leading some regions to impose strict regulatory limits on their use in children's products[^27][^29]. Natural colorants, like chlorophyllin (E140) and beetroot betalains, are increasingly utilized in "clean-label" products because of their safer profile and health-promoting properties, although they are less stable under certain processing conditions[^10][^71][^73]. The industry's balance between color stability and safety continues to shape innovations in food colorant use, reflecting growing consumer demand for minimally processed and health-conscious food products.

Quantitative Analysis of Food Colorant Consumption Across Dietary Patterns

Food colorant consumption varies significantly by age, diet, and geographic region, with children generally consuming higher quantities due to their preference for bright, processed foods[^14][^15]. For instance, tartrazine (E102) is commonly found in snacks and beverages aimed at children, and studies link high intake of synthetic dyes with allergic reactions and behavioral changes[^3][^7]. Geographic analyses further show that Western dietary patterns, rich in processed foods, correlate with higher synthetic dye intake, highlighting the global spread of these additives[^25][^33]. Conversely, individuals adhering to whole-food diets consume fewer artificial dyes, prioritizing naturally colored foods that offer additional health benefits[^26][^70]. These patterns underline the need for dietary guidance and regulatory attention to minimize synthetic dye exposure, especially for vulnerable populations.

Health-Promoting Effects of Bioactive Pigments in Color-Rich Dietary Sources

Bioactive pigments found in colorful fruits and vegetables contribute to health through antioxidant, anti-inflammatory, and neuroprotective properties[^63][^64]. Anthocyanins, which give berries their red, purple, and blue hues, have been linked to cardiovascular and cognitive benefits by neutralizing oxidative damage and reducing inflammation[^44][^45]. These effects are particularly relevant for mitigating age-related diseases, as seen in research on blueberry anthocyanins[^47][^49]. Carotenoids, such as beta-carotene and lutein found in carrots and leafy greens, are essential for eye health, protecting retinal cells from blue light and reducing the risk of macular degeneration[^81][^82]. Marine-derived carotenoids like astaxanthin offer anti-aging benefits by protecting cells from lipid peroxidation, which supports mitochondrial function and overall cellular health[^77][^83]. Betalains, prominent in beetroot and prickly pear, exhibit anti-cancer properties by modulating oxidative pathways, enhancing nitric oxide production, and supporting vascular health[^68][^71][^72]. Chlorophyllin also offers detoxifying effects and DNA protection, providing a dietary defense against carcinogens[^10][^64][^65]. These pigments, in contrast to synthetic dyes, exemplify the health-supporting potential of natural compounds, aligning with the broader concept of food as medicine.

Clinical Manifestations of Adverse Effects from High Intake of Harmful Food Colorants

Clinical consequences of high intake of synthetic food colorants include allergic reactions, neurobehavioral changes, and genotoxicity[^1][^2][^3]. Sensitive individuals, particularly those exposed to tartrazine (E102), may experience asthma, urticaria, and angioedema, with studies showing that tartrazine exacerbates asthma symptoms in atopic individuals[^4][^5]. Neurobehavioral impacts, especially in children, are associated with synthetic dyes like tartrazine and Brilliant Blue FCF, which have been shown to impair learning, increase hyperactivity, and disrupt memory, potentially via oxidative and inflammatory pathways[^27][^29]. Genotoxic studies on synthetic dyes suggest DNA-binding properties that could lead to genomic instability and increase cancer risk, while caramel colors containing 4-MEI add an additional layer of carcinogenic risk due to toxic byproducts formed during their production[^6][^21][^22]. This highlights the importance of stringent intake regulations to minimize these risks.

Populations with Increased Risk of Adverse Effects Due to High Colorant Consumption

Certain populations face increased susceptibility to adverse effects from synthetic food colorants, particularly children, individuals with allergic predispositions, and those with genetic differences affecting colorant metabolism[^1][^14]. Children, due to their lower body weight and dietary habits, are exposed to higher relative amounts of synthetic colorants, such as tartrazine (E102), which is prevalent in snacks and beverages aimed at younger audiences. This exposure is associated with behavioral changes and cognitive impairments, underscoring the need for caution in products marketed toward children[^5][^27][^3]. Individuals with a history of atopy or dye sensitivities are also at risk; for example, tartrazine can trigger hypersensitivity reactions, including urticaria, asthma exacerbations, and angioedema[^2][^4][^16]. Furthermore, genetic polymorphisms in metabolic enzymes, such as those that process azo dyes, can lead to variability in toxicity levels. Individuals with certain genetic profiles may metabolize these additives into toxic intermediates more efficiently, raising risks for organ toxicity and oxidative damage[^8][^9]. Those with compromised liver or kidney function may also experience heightened adverse effects due to reduced detoxification capacity, making them more vulnerable to organ-related toxicity from dyes like carmoisine and Brilliant Blue FCF[^13][^12][^26]. This recognition of risk differences emphasizes the need for targeted dietary guidelines and potential regulatory adjustments to limit artificial dye exposure in these vulnerable groups.

Dietary and Regulatory Interventions to Minimize Intake of Potentially Harmful Food Colorants

Minimizing synthetic food colorant intake requires an integrated approach, combining consumer education, industry shifts toward safer alternatives, and stricter regulatory oversight[^25][^35]. Public education campaigns are essential for raising awareness of the adverse health effects associated with synthetic colorants, such as tartrazine and Allura Red, which have been linked to allergic reactions and potential neurotoxicity[^5][^27][^3]. Educating consumers on reading labels empowers them to make informed choices, particularly for children, who are at higher risk due to their dietary exposure to brightly colored foods[^29][^15]. Many companies are responding to the demand for clean-label products by reformulating their offerings to include natural colorants, such as chlorophyllin and curcumin, which provide added antioxidant benefits and align with consumer preferences for health-conscious ingredients[^67][^61][^58]. Regulatory bodies can further support these efforts by mandating stricter limits on synthetic dye concentrations and requiring comprehensive risk assessments[^10][^20][^40]. For example, the European Union's precautionary labeling approach, which mandates warnings on products containing certain synthetic dyes, has encouraged manufacturers to reduce the use of these additives[^22][^18]. Investing in research to enhance the extraction and stability of natural pigments can further facilitate their use as synthetic dye replacements, enabling safer, health-promoting food colorants that meet industrial demands[^11][^63][^18]. Altogether, these strategies create a proactive framework for reducing synthetic dye exposure and protecting public health, while supporting the industry's shift towards safer, functional alternatives.

Discussion

The findings from this review highlight the contrasting health implications associated with synthetic versus natural food colorants[^15][^18]. Synthetic colorants, particularly azo dyes like tartrazine (E102) and Brilliant Blue FCF (E133), demonstrate remarkable stability and vibrant color properties, making them indispensable in processed foods and beverages[^1][^6]. However, their chemical structures, especially the azo bond in tartrazine, introduce risks, including neurobehavioral and allergic reactions, particularly in children and sensitive populations[^3][^5]. Studies indicate that the breakdown of azo dyes can yield aromatic amines, which may exhibit genotoxic properties[^7][^6]. Additionally, emerging research suggests potential links between synthetic dyes and neurobehavioral changes, such as increased hyperactivity and attention deficits in children, raising public health concerns[^27][^29][^30]. Conversely, natural pigments like curcumin (E100) and chlorophyllin (E140) not only enhance color but also offer significant antioxidant and anti-inflammatory benefits[^55][^64]. These natural compounds support cellular health and may provide chemopreventive effects by reducing oxidative stress, as seen with chlorophyllin in preclinical studies[^64][^65]. Anthocyanins and carotenoids also demonstrate substantial health benefits, particularly in cardiovascular and eye health, which makes them attractive as dual-purpose functional ingredients[^74][^83]. Nonetheless, natural colorants face limitations in stability and may require advanced processing to maintain their effectiveness in food applications[^67][^63]. Regulatory efforts, such as the European Union's labeling requirements, reflect a trend toward transparency and safer consumption, especially for children[^10][^11]. The potential for natural colorants to replace synthetic ones in specific applications aligns with growing consumer demand for minimally processed, health-conscious foods[^18][^11].

Conclusions

This review underscores the importance of choosing food colorants based on a balance between safety, stability, and health benefits[^26][^25]. Synthetic colorants, despite their functional appeal in food production, are increasingly scrutinized for their potential to elicit adverse health effects, particularly in children[^14][^3]. Continued research into the long-term effects of synthetic dyes, especially in neurodevelopmental and genotoxic contexts, is crucial[^29][^22]. On the other hand, natural pigments like curcumin, chlorophyllin, and anthocyanins present safer alternatives that not only contribute color but also deliver health-promoting properties[^55][^64][^52]. While natural colorants may require formulation enhancements to overcome stability challenges, their integration into food systems aligns with modern dietary shifts toward clean-label products[^73][^58]. Effective regulatory frameworks that limit the use of synthetic dyes and promote transparent labeling could support public health initiatives by reducing synthetic dye exposure in high-risk populations[^18][^10]. Future studies should focus on optimizing the stability and bioavailability of natural colorants to facilitate their broader application as viable alternatives to synthetic additives[^72][^63]. These findings reinforce the potential for food colorants to serve functional roles in supporting health, providing both aesthetic and physiological benefits[^67][^26].

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