



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
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NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; 9(2): 408-412
Received: 18-11-2025
Accepted: 23-12-2025

Zainab Jassim Mohammed
Department of Biology, College of
Science, University of Misan,
Misan, Iraq

Marwah Ali Majeed
Department of Biology, College of
Science, University of Misan,
Misan, Iraq

Israa Ibrahim Lazim
Department of Biology, College of
Science, University of Misan,
Misan, Iraq

Corresponding Author:
Zainab Jassim Mohammed
Department of Biology, College of
Science, University of Misan,
Misan, Iraq

Insect-derived food colorants: Chemistry, applications, safety, and regulatory perspectives

Zainab Jassim Mohammed, Marwah Ali Majeed and Israa Ibrahim Lazim

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i2f.4888>

Abstract

Insect derived food colorants, especially carminic acid derived out of *Dactylopius coccus*, are one of the most thermally and photochemically stable natural red-pigments in modern food and cosmetic products. The growing popularity can be explained by the fact that consumers demand natural additives and the regulation discourages the use of synthetic dyes. The synthesis of historical, chemical, technological and regulatory information about insect-based food colorants is created, with their benefits and limitations highlighted in this review. Carminic acid has superiority compared to plant-based pigments like anthocyanins and chlorophylls due to its chemical stability at heat, light, and varying PH environments. The methods of extraction, such as aqueous extraction, precipitation and advanced purification, are always evolving, enhancing the level of pigment as well as eliminating any residues of allergens. Yet, the aspects of allergy, possible contamination in the process of importation and storage, and animal-based ingredient ethical aspects are a cause of concern. The review ends by noting that sustainable extraction, purification that is safer and high-stability plant, fungal or algal options that can rival carmine performance need to be developed.

Keywords: *Dactylopius coccus*, carmine, natural pigments, food colorants, EFSA, anthraquinones, food safety, FDA

1. Introduction

In food colorants, color is a necessary factor in food production, which aims at improving the aesthetical element of food but also the perception, acceptance and product identity by the consumer. In the last ten years, natural and clean-label colorants have gained more and more popularity due to the growing consumer interest in synthetic dyes and their toxicological impact (Dufresne, 2016) ^[2]. Insect-derived food colorants have seen a lot of interest because of their derived natural sources and their potential health benefits, making them a viable alternative to synthetic dyes. Due to consumers shifting more towards health-conscious and eco friendly products, the market of natural colorants will probably grow, and food producing companies will consider new ways of purification and extraction. Moreover, the biotechnological synthesis of carminic acid is a promising prospect of efficiency improvement in production and less environmental impact since the existing methods of its extraction may be labor-intensive and lead to inconsistent outcomes (Ferreira-Suarez *et al.*, 2023) ^[6]. Among natural pigments, insect colorants, particularly those of *Dactylopius coccus*, have seen a resurgence in scientific and industrial attention due to their superior stability and usefulness in a broad variety of processed foods (among natural pigments).

The primary cochineal dye pigment, carminic acid, has outstanding heat, light, and pH stability against most plant-based pigments, including anthocyanins, betanins, and chlorophyll derivatives (Rymbai *et al.*, 2011; Rodriguez-Saona and Wrolstad, 2001) ^[21, 20].

The reason behind this great stability is that the anthraquinone structure enhances resistance to thermal degradation and photodecomposition, thus is applicable in beverage coloration, confectionery, dairy products, and thermally processed foods (Chan *et al.*, 2017; Polak and Olsson, 2015). Its technological benefits have led to revival of natural red colourants in food production especially due to growing regulatory pressure of synthetic red pigments. Cochineal dye has been appreciated throughout the history. It was widely used in ancient Mesoamerican

civilizations, the Aztecs and the Mayans, as a textile, rituals and food (Callejas & Sillero, 2002; Graham, 2008) ^[1, 8]. Cochineal was brought to Europe by the Spanish after 16 th century and became a significant commodity since it has a rich hue and has better dyeing contents. Even though the demand dropped following the invention of synthetic dyes during the 19 th century, the contemporary resurgence of natural elements has made it applicable again in the contemporary food systems (Mattila and Roinioti, 2017) ^[13].

Although insect-derived colorants have been used long enough and are widely accepted, they raise a number of regulatory, ethical, and health-related issues. The FDA and European Food Safety Authority (EFSA) categorize carmine as a food additive that is not hazardous to consume but must be marked on the label since there are rare complications of allergic hypersensitivity reaction, such as urticaria and anaphylactic reactions (FDA, 2018; Jamil, 2012) ^[4, 12]. Besides, the production of insects, their extraction, and storage should adhere to high-quality standards to avoid microbial contamination, uptake of heavy-metals, and pigments degradation (FAO/WHO JECFA, 2019; Méndez-Gallegos *et al.*, 2021) ^[18, 19]. This is due to the fact that, with the rising global trend in the use of natural additives, the rising demand of sustainable sources of colorants, and the drive towards regulatory transparency, there is a need to have an in-depth review of insect-derived sources of food colorants. This is a review of recent advances in chemistry, extraction, stability, safety, and uses of insect-based pigments in comparison to plant and algae pigments. By combining history, science, and regulatory positions, this introduction will attempt to set a clear context on the current and future outlook of the use of insect-derived food colorants in the contemporary food systems.

2. Methods

The review made use of a systematic literature search and review methodology that facilitated the incorporation of high quality and scientifically relevant studies on insect-based food colorants especially carminic acid and cochineal extracts. There was a thorough search in the key scientific databases, such as Scopus, Web of Science, PubMed, and Google Scholar, with the range covering 2000-24. Keywords and Boolean combinations used included: “carminic acid,” “carmine,” “natural food colorants,” “cochineal extract,” “anthraquinone dyes,” “insect-derived pigments,” “food safety,” “color stability,” “E120 regulation,” and “natural dye extraction.”

Inclusion criteria focused on peer-reviewed articles, regulatory reports, and other official scientific reviews of the chemistry of insect-derived pigments, extraction methods, stability, toxicology, industrial applications, or status in regulatory affairs. Preference was also made to the popular publications, latest developments in the extraction and purification methods, and governmental safety evaluations conducted by the FDA (2018) ^[4], EFSA (2007), and JECFA (FAO/WHO, 2019) ^[18]. Historical and even chemical investigations were also incorporated, including early investigations of the composition and traditional applications of cochineal (Callejas and Sillero, 2002; Graham, 2008) ^[1, 8]. In order to capture the most topical scientific findings, research papers reporting experimental research of pigment stability to heat, light, and pH, including those by Rodriguez-Saona and Wrolstad (2001) ^[20], Sajjadi and Mansouri (2015) ^[15], and Chan *et al.* (2017) were given preference. Similarly, works addressing modern extraction techniques, purification, and control of contamination (Echeverria *et al.*, 2022; Méndez-Gallegos *et al.*, 2021) ^[19] were also comprised to show the current trends in the industry. The studies have been

filtered out by excluding those studies that were not peer-reviewed, those studies that did not contain sufficient methodological information, and those studies whose subjects were unrelated to this research (i.e., textile-only applications, synthetic colorants without comparing them to insect-derived pigments). All the information that was obtained in the literature was qualitatively synthesized, and it has been done by means of the traditional review methodologies widely applied to the natural product and food science study (Gazzola and Carlin, 2017; Mattila and Roinioti, 2017) ^[7, 13]. This method would mean that the current review would incorporate the current scientific and regulatory outlooks and technological innovations so as to give a comprehensive, evidence-based evaluation of insect-derived food colorants.

3. Results and Discussion

3.1 Historical Emergence and Industrial Revival

Mesoamerican civilizations, especially Aztecs and Mayans, were the pioneers of insect-based colorants, having cultivated the *Dactylopius coccus* as a source of crimson pigment (Callejas & Sillero, 2002; Graham, 2008) ^[1, 8]. A significant export of the Spanish colonial period was cochineal dye which was valued because of its bright color, mordanting capabilities, and resistance to fading. Its application in the 19th century was overtaken by synthetic colorants, but nowadays, due to concerns about synthetic dye toxicity and the preference of natural additives by consumers, carmine is in the spotlight once again (Dufresne, 2016; Mattila and Roinioti, 2017) ^[2, 13]. This revival is in line with current clean-label food trends and tighter regulatory requirements that encourage natural options.

3.2 Chemical Structure of Carminic Acid and Stability Advantages

The major chromophore in cochineal extract is carminic acid (C₂₂H₂₀O₁₃), which is an anthraquinone glycoside whose molecular structure explains its high stability in different environmental factors (Haug, 2010; Polak and Olsson, 2015) ^[9, 1]. It has conjugated structure which gives it resistance to:

- Thermal degradation throughout cooking and pasteurization
- Photodegradation under Visible or UV light
- pH-dependent discoloration, maintaining integrity in mildly acidic and neutral foods.

Compared studies indicate that carmine has higher stability, compared to natural pigments as show in figure 1 such as anthocyanins, chlorophylls and betalains, which have a high rate of loss of color when subjected to heat, or alkaline conditions (Rymbai *et al.*, 2011; Rodriguez-Saona and Wrolstad, 2001) ^[21, 20].

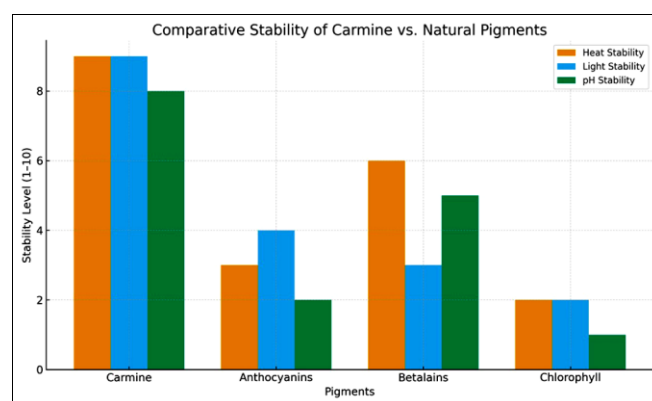


Fig 1: Comparative Stability of Carmine vs. Natural Pigments

Comparative studies indicate that compared to typical plant-based pigments like anthocyanin, chlorophylls, and betalains, which are unstable in the presence of heat, neutral pH or light, carmine has excellent thermal and photochemical stability (Rodriguez-Saona and Wrolstad, 2001; Rymbai *et al.*, 2011)^[20, 21]. Table 1 summarizes the differences in the stability characteristics of these pigments.

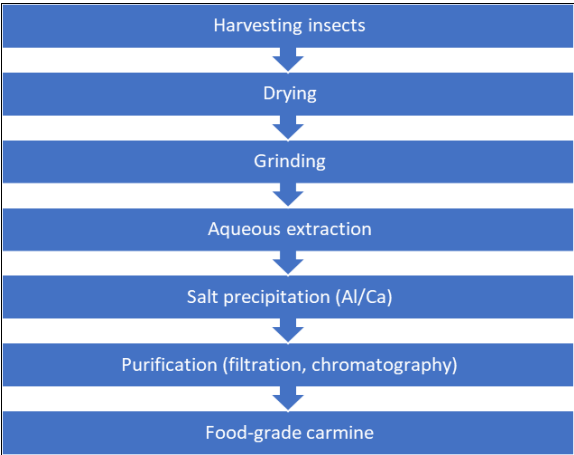
Table 1: Comparative Stability of Natural Red Pigments

Pigment	Source	Heat Stability	Light Stability	pH Stability	Reference
Carmine	<i>Dactylopius coccus</i>	Excellent	Excellent	Good	Haug (2010); Echeverría <i>et al.</i> (2022) ^[17]
Anthocyanins	Fruits	Poor	Moderate	Poor	Rodriguez-Saona & Wrolstad (2001) ^[20]
Betalains	Beetroot	Moderate	Poor	Moderate	Sajjadi & Mansouri (2015) ^[15]
Chlorophylls	Leafy greens	Poor	Poor	Poor	Rymbai <i>et al.</i> (2011) ^[21]

Table 1 indicates that carmine is more stable in a wide range of environmental settings, thus its popularity in the food industry as a heat-processing additive.

3.3 Extraction, Purification, and Processing Technologies

The current extraction of cochineal pigment uses a series of processes as illustrated in scheme 1; and they include drying, grinding, aqueous extraction, precipitation, and chromatographic purification (Echeverria *et al.*, 2022; Méndez-Gallegos *et al.*, 2021)^[19]. Precipitation using aluminum or calcium salts increases the yield of pigment and stability (FAO/WHO JECFA, 2019)^[18]. The pH and ionic strength during the extraction process are very important as carminic acid is stable at alkaline conditions and decomposes in highly acidic solutions (Rodriguez-Saona & Wrolstad, 2001)^[20].



Scheme 1: Extraction and Purification Workflow of Cochineal Pigment

The use of more advanced purification techniques like microfiltration and liquid chromatography enhances the purity of the pigment, eliminates allergenic protein contaminants, and improves thermal and optical stability (Méndez-Gallegos *et al.*, 2021)^[19]. Such technological advancement has played a critical role in addressing regulatory expectations and industrial need of natural dyes of high quality.

3.4 Industrial Applications in Food and Cosmetics

3.4.1 Food Sector

Carmine is also very popular in adding color to confections, juices, dairy products, baked goods, and processed meat because

of its high intensity of red color and resistance to the harsh processing environment (Graham, 2008)^[8]. It has a high affinity to proteins, lipids, and carbohydrates, which means that it provides even distribution of colors and is particularly useful in complex food matrices.

3.4.2 Cosmetics Sector

Carmine is still a high-end red dye in use in the cosmetics sector in lipsticks, blushes, foundations, and eyeshadows due to its ability to avoid bleeding and its compatibility with oils-based formulations (Martin and Ruiz, 2014; Rios and Peña, 2010)^[14]. Carmine has a better photostability and skin compatibility than synthetic counterparts.

3.5 Health, Safety, and Allergenicity Considerations

Despite carmine being deemed as safe by both FDA and EFSA, there are few allergic cases recorded such as contact dermatitis, urticaria, and in severe instances of allergic reactions, anaphylaxis (Jamil, 2012; EFSA, 2007)^[12, 1]. This has been blamed on the residuals of insect proteins that have not been fully eliminated in the extracts that are not thoroughly purified (Friedman, 2008)^[5].

3.5.1. Contamination Risks

Throughout storage and import, carmine could become contaminated by:

- Microorganisms under humid conditions (Echeverría *et al.*, 2022)^[17].
- Heavy metals leaching from packaging materials (FAO/WHO JECFA, 2019)^[18].
- Chemical residues accumulated during processing (Méndez-Gallegos *et al.*, 2021)^[19].

Strict manufacturing and storage procedures are, therefore, critical to pigment safety and stability.

3.5.2. Special Populations

The sensitivity children have to food colorants might be high because they consume greater amounts of them in comparison to body weight, and thus they need to be regulated carefully (Sivan and Chowdhury, 2019)^[16]. Despite the fact that regulatory authorities consider carmine as non-toxic, there are infrequent cases of allergic reactions and contamination especially when stored improperly or when not purified properly. These safety precautions are outlined in Table 2.

Table 2: Summary of Safety Issues Related to Carmine Use

Safety Aspect	Description	Evidence	Reference
Allergic Reactions	Hypersensitivity responses (urticaria, dermatitis, rare anaphylaxis)	Documented case reports	Jamil (2012) ^[12] ; EFSA (2007)
Microbial Contamination	Occurs during storage in humid environments	Moisture-dependent growth	Echeverría <i>et al.</i> (2022) ^[17]
Heavy Metals	Leaching from packaging during transport	Chemical contamination	FAO/WHO JECFA (2019) ^[18]
Sensitivity in Children	Higher intake relative to body mass	Increased exposure concerns	Sivan & Chowdhury (2019) ^[16]

As pointed out in Table 2, the general risk profile of carmine is not very high, but such aspects as allergenic proteins and microbial contamination require rigorous quality control measures.

3.6 Comparison with Natural Plant- and Algae-Based Alternatives

The increasing demand of veganism and environmentally friendly products have stimulated the research of plant pigments (e.g., beetroot, turmeric) and algal extracts. The alternatives have their limitations however:

- Anthocyanins lose color at neutral pH
- Betalains degrade under heat
- Phycocyanin from spirulina is unstable in acidic food systems (Sajjadi & Mansouri, 2015) [15].

None of them so far have matched the stability of heat and light of insect-derived carmine.

3.7 Regulatory Framework and International Guidelines

The regulatory authorities focus on transparency and consumer protection. Cochineal extract and carmine are considered to be allergens and should be labeled with a clear labeling by the FDA (FDA, 2018) [4]. Carmine is considered an additive (E120) by EFSA which requires declaration and warning statements (EFSA, 2007). The purity, acceptable daily intake and manufacturing practices are specified in global standards in the Codex Alimentarius and JECFA (FAO/WHO JECFA, 2019) [18]. Differentiation of international regulations shows the necessity of harmonization to enable international trade and consumer protection. There are regulatory agencies that do not have identical labeling requirements and safety assessments on carmine. The United States FDA requires labeling and EFSA names it as additive E120 and disclosures of allergens. Table 3 shows a comparison of the significant regulatory frameworks.

Table 3: International Regulations Governing Carmine

Regulatory Body	Requirements	Key Points	Reference
FDA (USA)	Mandatory labeling of “carmine” or “cochineal extract”	Allergen disclosure required	FDA (2018) [4]
EFSA (EU)	Additive E120; warning labels for allergies	Acceptable daily intake (ADI) established	EFSA (2007)
JECFA	Global purity and ADI specifications	International safety standards	FAO/WHO JECFA (2019) [18]
Codex Alimentarius	Harmonized labeling for international trade	Supports global uniformity	Gazzola & Carlin (2017) [7]

According to Table 3, carmine is recognized as safe by the majority of international bodies though transparency and clear labeling is given due to the rising consumer awareness on the risk of allergens.

- Color uniformity
- Texture and viscosity
- Gelation properties
- Emulsion stability

3.8 Interaction of Insect-Derived Pigments with Food Matrices

Carmine interacts intensively with proteins, starches and polysaccharides affecting (see figure 2):

Studies show that carmine-protein bonding enhances color retention but may influence food structure, especially in dairy and confectionery applications (Chan *et al.*, 2017; Rymbai *et al.*, 2011) [21].

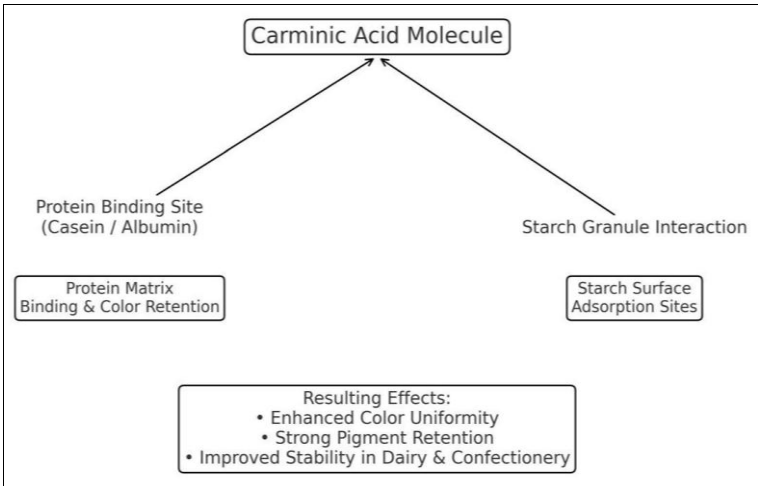


Fig 2: Interaction of Carminic Acid with Food Proteins and Starches

4. Conclusion

Carmine, one of the insect-derived colorants, cannot be replaced in the food and cosmetic industry because of its high stability, vibrant color and broad applicability. Although alternatives can be found, none of them are as thermally, photochemically, and pH-stable as carmine. However, such problems as allergenicity, ethical considerations, and the threat of contamination require further investigation. Future trends involve better purification technique, sustainable harvesting, and production of high stability plant or microbial pigments that can substitute carmine

without affecting performance.

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