REVIEW ARTICLE

Food Chemistry, Engineering, Processing and Packaging

Cyclodextrins for UV Protection in Food, Beverages, and Agricultural Products: A Comprehensive Review

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ABSTRACT

Background: Ultraviolet radiation (UVR) poses a significant threat to the stability and shelf-life of food, beverages, and agricultural products. This exposure leads to the degradation of sensitive compounds, resulting in reduced nutritional value, altered physical properties, and compromised products safety. Cyclodextrins (CDs), which possess a unique molecular structure with a hydrophobic cavity and a hydrophilic exterior, offer a promising solution by forming complexes with UVR absorbers. This inclusion complex formation enhances the stability, solubility, and bioavailability of sensitive compounds, thereby providing a protective mechanism against UVR-induced degradation.

Aims: This review comprehensively examines the applications of cyclodextrin-UVR absorber complexes for protecting food, beverages, and agricultural products from UVR-induced damage.

Methods: The methodology involved a comprehensive review of existing literature from scientific databases to analyze the efficacy of CD inclusion complex formation, their protective effects, and potential industrial applications.

Results: The findings indicate that these complexes significantly enhance the stability of UVR-sensitive compounds across all three sectors. In food, CDs protect essential nutrients including vitamins and antioxidants from degradation, prevent oxidation, and improve packaging technologies. For beverages, they stabilize color, flavor, and aroma compounds, preserving their quality over extended shelf-life periods. In agriculture, cyclodextrins mitigate the adverse effects of UVR exposure, protecting pigments and nutrients while improving crop yield and quality. Cyclodextrins protect bioactive molecules mainly by forming reversible inclusion complexes that hide sensitive parts of the molecule inside the CD cavity, lowering exposure to oxygen, light, metals, acids/bases, and volatilization. The effectiveness and the dominant protection pathway do depend on the food matrix (water, lipids, proteins, alcohol, sugar, pH, processing).

Conclusions: CDs-UVR absorber complexes represent an effective strategy for improving the stability and shelf-life of these products. Their ability to form inclusion complexes with UVR-sensitive compounds offers considerable advantages in preserving nutritional value, enhancing product quality, and promoting sustainability. Given the increasing consumer demand for healthier functional and high-quality products with extended shelf-life, cyclodextrin-based technologies are positioned as a vital component in future advancements within these industries. Further research and industrial-scale applications are essential to fully realize their potential.

Keywords: Cyclodextrin; UV-Radiation; Food stability; Agrochemicals; Bioavailability; Antioxidant.

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1 INTRODUCTION

Ultraviolet (UV) radiation, a component of sunlight, presents a significant threat to the stability, quality, and efficacy of various products across numerous industries. While pharmaceuticals, cosmetics, textiles, and plastics are all susceptible, food, beverages, and agricultural products are particularly vulnerable due to their direct impact on human health and global food security. UV exposure can lead to the degradation of sensitive compounds, resulting in reduced nutritional value, compromised sensory qualities, and shorter shelf life (Donsingha *et al.*, 2018; Kera *et al.*, 2024; Koutchma *et al.*, 2014). Among the various sectors impacted by UV radiation, food, beverages, and agricultural products are particularly critical due to their direct link to human health and nutritional well-being. The impact of UV radiation on these sectors is multifaceted, encompassing issues related to food security, safety, and nutritional value.

In agriculture, the effects of increased UV radiation are severe and can damage plant DNA, impair photosynthesis, and induce oxidative stress through the accumulation of reactive oxygen species (ROS). This leads to reduced crop yields and the degradation of vital nutrients such as carotenoids and vitamins (Dutta Gupta *et al.*, 2010). Paradoxically, while UV radiation is a known degradant, it is also used in the food industry for sterilization. However, excessive application can degrade essential nutrients like vitamins A, C, and E and antioxidants, while also initiating lipid oxidation in fats, leading to rancidity and off-flavors (Csapó *et al.*, 2019; Singh *et al.*, 2021).

In the food and beverage industry, UV radiation is commonly used as a sterilization and preservation method. However, its excessive application can lead to the degradation of essential nutrients, such as vitamins A, C, and E, as well as antioxidants like flavonoids and polyphenols. This degradation compromises the nutritional value of food products and may also affect their sensory properties, including taste, color, and texture. Studies have demonstrated that UV exposure can alter the chemical composition of food, leading to the formation of off-flavors and discoloration, which negatively impacts consumer acceptance (Singh *et al.*, 2021). Furthermore, UV radiation can initiate lipid oxidation in foods containing fats, resulting in rancidity and further deterioration of food quality (Csapó *et al.*, 2019).

To address the challenges posed by UV radiation in the food, beverage, and agricultural industries, innovative solutions are urgently needed. Cyclodextrins offer a promising approach. CDs are a family of cyclic oligosaccharides composed of glucose monomers linked by α-1,4 glycosidic bonds, forming a truncated cone-shaped structure with a hydrophobic interior and a hydrophilic exterior. This unique structure enables cyclodextrins to form inclusion complexes with a variety of hydrophobic molecules, making them valuable in numerous applications across pharmaceuticals, food, agriculture, and environmental fields (Csapó *et al.*, 2019; Singh *et al.*, 2021). In the food industry, cyclodextrins are utilized to improve the stability and shelf-life of food products by protecting sensitive ingredients from light, oxygen, and moisture (Gonzalez Pereira *et al.*, 2021). They can form inclusion complexes with volatile or unstable compounds such as flavors, vitamins, and colorants, thus preserving the sensory qualities and nutritional value of food and beverages. Cyclodextrins are also employed to mask undesirable tastes and odors, making them valuable in food formulation (Del Valle, 2004; Gonzalez Pereira *et al.*, 2021).

Cyclodextrins, non-reducing oligosaccharides composed of glucopyranose units, have gained significant attention due to their unique structural properties and applications. The most common cyclodextrins are α-, β-, and γ-cyclodextrins, containing 6, 7, and 8 units, respectively (Del Valle, 2004) (The fundamental unit of the CD is illustrated in Fig.1). Their distinctive structure, with a lipophilic inner cavity and a hydrophilic outer surface, enables them to form noncovalent inclusion complexes with a wide range of target molecules. The ability of cyclodextrins to modify the physicochemical properties of target molecules has led to their widespread use in various applications such as food, beverages and agriculture. Through formation of inclusion complexes, cyclodextrins can enhance solubility, stability, and bioavailability of poorly soluble compounds. Additionally, they can protect the products from degradation and improve their controlled release properties (Loftsson & Brewster, 1996).

The pervasive challenge of UV radiation in the food, beverage, and agricultural industries necessitates the development of innovative protective solutions. The integration of cyclodextrin-based UV absorbers presents a promising solution to mitigate the challenges posed by UV radiation in food, beverages, and agriculture. Cyclodextrins are a family of cyclic oligosaccharides with a unique ability to form inclusion complexes with various compounds, including UV absorbing molecules. When these complexes are applied to agricultural crops, they can provide a protective shield against harmful UV radiation, thereby preserving plant health, enhancing growth, and maintaining crop yields (Muñoz-Shugulí *et al.*, 2021). This protection is crucial in safeguarding crops from the detrimental effects of UV-induced oxidative stress, which can degrade both the nutritional quality and overall productivity of essential food crops. In the food and beverage industry, cyclodextrin-UV absorbers can be used to enhance the stability and shelf-life of products by preventing UV-induced degradation of sensitive nutrients, such as vitamins and antioxidants, as well as maintaining the sensory qualities of the products. These absorbers can be incorporated into packaging materials or directly into the products, offering a dual approach to UV protection. Overall, cyclodextrin-UVR absorber complexes offer a promising solution for food, agriculture and beverage products by mitigating the detrimental effects of UV radiation (Gonzalez Pereira *et al.*, 2021; Muñoz-Shugulí *et al.*, 2021).

This review provides a comprehensive analysis of cyclodextrin-UVR absorber complexes, focusing on their formation, properties, and applications in food, beverage, and agricultural industries. It explores factors influencing complex stability and their benefits for product quality, safety, and sustainability.

2 Physicochemical Properties of CDs

Among the various types of cyclodextrins, the natural α-, β-, and γ-cyclodextrins (Figure 1) are the most frequently studied and applied due to their unique physicochemical properties, which make them valuable in various applications (Szejtli, 1998; Zhou *et al.* 2022). Key physicochemical properties of the CDs are summarized in Table 1.

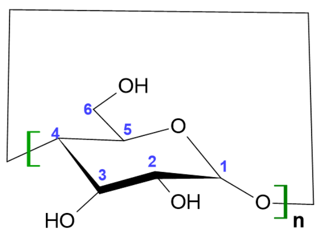

Figure 1. Basic Unit of Cyclodextrin; **n** is the number of glucose units (n = 6, 7, and 8 units for α-, β-, and γ-cyclodextrins respectively)

Table 1. Physicochemical properties of α-CD, β-CD and γ-CD (Adapted from Zhou *et al.*, 2022).

Type of Property	α-Cyclodextrin	β -Cyclodextrin	γ-Cyclodextrin	Reference
Number of Glucose Units	6	7	8	(Szejtli, 1998)
Molecular Weight	~972 Da	~1135 Da	~1297 Da	(Szejtli, 1998)
Cavity Diameter (nm)	0.47 – 0.53	0.60 – 0.65	0.75 – 0.83	(Szejtli, 1998)
Cavity Volume (nm^3)	0.174	0.262	0.427	(Del Valle, 2004)
Water Solubility at 25°C	~145 mg/mL	~18.5 mg/mL	~232 mg/mL	(Loftsson *et al.*, 1996)
Thermal Stability	Stable up to ~300°C	Stable up to ~300°C	Stable up to ~300°C	(Del Valle, 2004)
Hygroscopicity	Moderate	Low	High	(Del Valle, 2004)

2.1 α-Cyclodextrin

α-cyclodextrin (α-CD) is a cyclic oligosaccharide composed of six glucose units linked by α-1,4-glycosidic bonds with a molecular formula of $C_{36}H_{60}O_{30}$ and a molecular weight of 972.84 Da. Its compact structure and resistance to enzymatic degradation make α-CD adaptable for diverse applications, particularly in the food, agriculture, and beverage sectors (Mulargia *et al.,* 2022). In food, α-CD acts as an emulsifier and stabilizer, enhancing texture and shelf life by protecting flavors, vitamins, and pigments. In beverages, it improves solubility, masks undesirable tastes, and facilitates the controlled release of sweeteners. Furthermore, its use in agriculture helps to protect crop nutrients, such as carotenoids and vitamins from UV-induced degradation and improves the efficacy of agrochemicals (Chikamoto *et al.*, 2021; Mulargia *et al.,* 2022).

While α-CD is more soluble in water than β-CD, it is less soluble than γ-CD at 25 °C (Chikamoto *et al.*, 2021). All three natural cyclodextrins exhibit thermally stability and are resistant to alkaline or moderately acidic conditions (Mulargia *et al.,* 2022). Notably, α-CD is particularly resistant to hydrolysis in acidic solutions compared to both β-CD and γ-CD. Although it is unaffected by glucoamylase or β-amylase, α-CD can be hydrolyzed by certain α-amylases. The U.S. Food and Drug Administration (FDA) has classified α-CD as Generally Recognized As Safe (GRAS). However, its small cavity limits its ability to form inclusion complexes, and excessive consumption may lead to indigestion. To address these limitations, various chemical derivatives of α-CD have been developed through the modification of its hydroxyl groups. Despite its utility, the low yield and high cost associated with the enzymatic conversion of starch to α-CD limit its commercial use compared to β-CD (Wüpper *et al.* 2021).

2.2 β-Cyclodextrin

β-cyclodextrin (β-CD) is a cyclic oligosaccharide composed of seven glucose glucopyranose units, with a molecular formula is $C_{42}H_{70}O_{35}$ and the molecular weight of 1134.98 Da. This is due to the medium-sized cavity provides greater host guest stability and enables the formation of complexes with a wide range of substrate molecules, resulting in high yield and cost-effectiveness. β-CD exhibits the lowest water solubility among the three primary cyclodextrins, at approximately 1.85 g/100 mL at 25°C (Szejtli, 1998). Similar to other cyclodextrins, it is thermally stable above 200°C and resistant to alkaline and moderately acidic conditions, but it is more susceptible to hydrolysis in acidic environments compared to α-CD (Li *et al.,* 2014). Recognized as GRAS by the FDA (Kurkov *et al.,* 2013), β-CD may cause digestive discomfort when consumed in excessive quantities. Despite its lower solubility, β-CD is commercially preferred due to its balance of properties and the more efficient and cost-effective production process compared to α-CD. To enhance its functional versatility, various chemical derivatives of β-CD have been synthesized through modification of its hydroxyl groups, allowing for tailored applications in different industries (Li *et al.*, 2014).

2.3 γ-Cyclodextrin

γ-cyclodextrin (γ-CD) is a cyclic oligosaccharide composed of eight glucopyranose units, with a molecular formula of $C_{48}H_{80}O_{40}$ and a molecular weight of 1297.12 Da. Discovered in 1935, γ-CD was the earliest identified among the three natural cyclodextrins (Freudenberg *et al.*, 1935). It possesses the largest cavity, which facilitates the formation of inclusion complexes with larger and more diverse hydrophobic molecules (Loftsson *et al.*, 1996). This structural characteristic, combined with its hydrophobic interior and hydrophilic exterior, enhances its versatility in various applications.

γ-CD is particularly valued in the food, pharmaceutical, agriculture and cosmetic industries due to its superior solubility in water which is approximately 23 g/100 mL at 25°C, making it the most soluble of the cyclodextrins. It exhibits thermal stability above 200°C and, compared to the other cyclodextrins, is resistant to alkaline and moderately acidic conditions, although it is more susceptible to hydrolysis in strongly acidic environments. Despite its advantages, the high cost of enzyme production and purification, along with its lower yield, limit the large-scale manufacturing of γ-CD, driving researchers to optimize its preparation process. Nonetheless, its unique properties and wide ability to form inclusion complexes make γ-CD a valuable ingredient in specialized applications (Del Valle, 2004; Freudenberg *et al.*, 1935; Loftsson *et al.*, 1996). The structures of α-, β-, and γ-cyclodextrins (with n = 6, 7, and 8 units, respectively) are depicted in Figure 2.

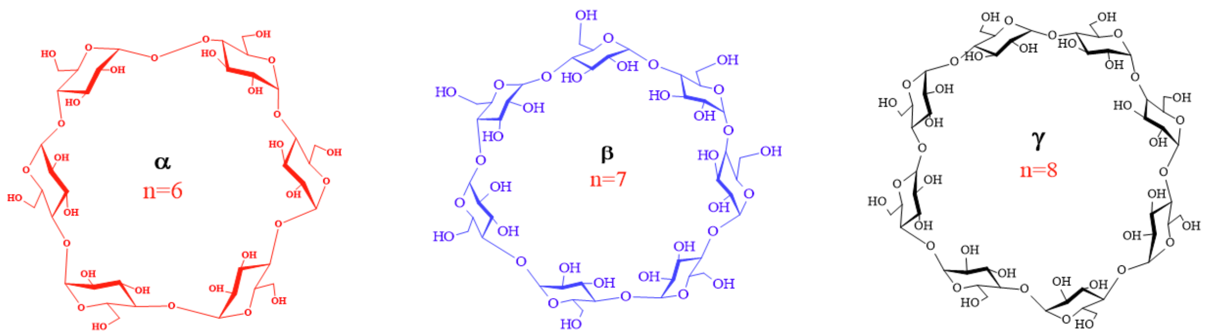

Figure 2. Structures of α-, β-, and γ-Cyclodextrins

Adapted from (Szejtli, 1998)

3 Inclusion Complexation of Cyclodextrins and UV Radiation Absorbers

Cyclodextrins possess a unique structure with a hydrophobic inner cavity and a hydrophilic outer surface. This allows them to form inclusion complexes with various targeted molecules, including UV absorbers. The formation of these complexes is of considerable interest due to the potential for enhancing the photostability and solubility of UV-absorbing agents. The stoichiometry of these inclusion complexes can vary; for instance, the complex between benzidine diammonium dipicrate and β-cyclodextrin was found to have a 1:2 guest-host stoichiometry (Hamdi *et al.*, 2009), while the complex of Orange II with β-cyclodextrin had a 1:1 ratio (Ping *et al.*, 2003). The formation constants of these complexes, determined through various spectroscopic methods, offer insights into their stability and inclusion efficiency.

Cyclodextrins have emerged as versatile host molecules in supramolecular chemistry, exhibiting their remarkable ability to form inclusion complexes with a wide range of targeted compounds, including UV radiation absorbers (Bates, 1994). This inclusion complex formation is primarily driven by host-guest interactions, wherein the hydrophobic cavity of cyclodextrins creates a stable environment for hydrophobic UVR absorbers, enhancing their solubility and stability in aqueous solutions (Bates, 1994; Noël *et al.*, 2021; Samperio *et al.*, 2010). The binding mechanism between cyclodextrins and UVR absorbers is governed by non-covalent interactions, such as van der Waals forces, hydrogen bonding, and hydrophobic effects (Bates, 1994; Purpura *et al.*, 2017; Samperio *et al.*, 2010). These interactions facilitate the formation of inclusion complexes, where the substrate molecules are effectively entrapped within cyclodextrin

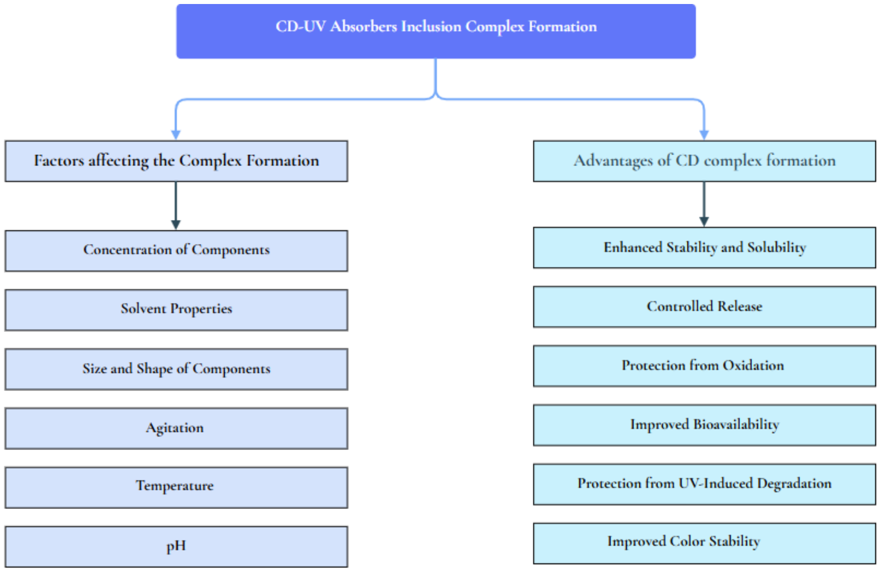

Figure 3. Parameters Affecting the CD-UVR Complex and Advantages of the Inclusion Complex Adapted from (Gonzalez Pereira *et al.*, 2021)

cavities. The inclusion complex formation allows for controlled release, improving the bioavailability and efficacy of poorly soluble UVR absorbers (Purpura *et al.*, 2017).

Several factors influence the stability of these inclusion complexes, including the size and shape compatibility between cyclodextrin and the substrate molecule, the degree of substitution on the cyclodextrin, the polarity of the solvent, and the presence of competing compounds (Bates, 1994; Noël *et al.*, 2021; Purpura *et al.*, 2017). Additionally, the use of larger cyclodextrins, such as γ-cyclodextrin, has been shown to enhance the inclusion complex formation efficiency of lipophilic compounds due to their larger cavity size, allowing for greater complexation. Various parameters affecting the inclusion complex, as well as major advancements of CD-UVR complexes, are summarized in Figure 3.

4 Applications of CD-UVR Absorbers in Food

The ability of cyclodextrins have the unique ability to form stable inclusion complexes with UV absorbers, which holds significant implications for their use in the food industry. By incorporating cyclodextrin-UV absorber complexes into food products, manufacturers can enhance the photostability and solubility of these UV-protective compounds, potentially increasing their efficacy in shielding against harmful ultraviolet radiation (Wang *et al.*, 2022). Cyclodextrins are widely employed in food manufacturing as additives for various functions, including improving sensory attributes, extending shelf life, and sequestering components. The various types of cyclodextrins (α, β, γ, and their derivatives) exhibit these positive effects, which can be achieved by combining small amounts of cyclodextrins with the material to be stabilized. This section discusses the diverse applications of cyclodextrins in food, including preservation of food color and texture, enhanced solubility, protection against UV-induced degradation of nutrients, development of functional food products with enhanced UV protection.

4.1 Preservation of Food Color and Texture

4.1.1 Protection of Pigments

Pigments such as carotenoids and anthocyanins are responsible for the vibrant colors found in fruits, vegetables, and beverages. However, these pigments are highly susceptible to degradation when exposed to UV radiation. This degradation leads to color fading, which can negatively impact the visual appeal and perceived freshness of food products. Cyclodextrin-UVR absorber complexes offer a promising solution to this issue by forming stable inclusion complexes with these sensitive pigments. Cyclodextrins, due to their hydrophobic interior and hydrophilic exterior, can encapsulate pigment molecules, shielding them from direct exposure to UV light. This protective mechanism helps to maintain the structural integrity of the pigments, thereby preserving the vibrant colors of the food products over extended periods. As an illustration, studies have shown that cyclodextrin complexes with carotenoids can significantly reduce UV-induced degradation, helping to maintain the color stability of food products like juices and dairy products

(Polyakov *et al.*, 2004; Wang *et al.*, 2022). Cyclodextrins protect pigments like carotenoids and anthocyanins by forming inclusion complexes, where the hydrophobic pigment molecules are encapsulated within the CD's hydrophobic cavity, shielding them from UV light and oxidative degradation through non-covalent interactions such as hydrophobic effects and van der Waals forces (Polyakov *et al.*, 2004; Wang *et al.*, 2022).

Additional studies have highlighted the benefits of CDs in improving the solubility and reducing the oxidation of natural pigments including curcumin and lycopene. CDs have also been demonstrated to stabilize chopped ginger root against enzymatic browning and maintain color and quality in apple and pear juices by preventing ascorbic acid oxidation. Approved by the FDA and the EU, α-, β-, and γ-CDs are commonly used in juice production to enhance color, reduce browning, and improve overall quality without significantly affecting aroma (Andreu-Sevilla *et al.*, 2011; Del Valle, 2004).

4.1.2 Prevention of Texture Changes

UVR is detrimental not only food color but can also induce structural changes in food components, leading to undesirable textural alterations. These changes can include the breakdown of proteins, the denaturation of enzymes, and the oxidation of lipids, which may result in a loss of firmness, increased softness, or the development of a rubbery texture in food products. Such textural changes can diminish the overall sensory experience and consumer acceptance of the product. Cyclodextrin-UVR absorber complexes can mitigate these adverse effects by protecting the structural integrity of food components. Through inclusion complex formation within the cyclodextrin cavity, these complexes reduce the likelihood of UV-induced reactions that lead to texture degradation (Cid-Samamed *et al.*, 2022; Zhou *et al.*, 2022). As a result, the original texture of the food product is better preserved, ensuring that consumers experience the intended sensory qualities. Research indicates that cyclodextrin complexes can help maintain the firmness and desirable mouthfeel of products like fresh-cut fruits and vegetables, as well as processed foods (Cid-Samamed *et al.*, 2022).

4.2 Enhanced Solubility

UV-absorbers, especially those with low water solubility, can form inclusion complexes with cyclodextrins, thereby improving their solubility and bioavailability in food products. This interaction significantly improves the water solubility of various food ingredients, particularly those that are poorly soluble in water. For example, when CDs form complexes with fat-soluble vitamins, pigments, or flavor compounds, they enhance the solubility and bioavailability of these components, making them more effective in food formulations. The end result is the formation of a water-soluble cyclodextrin-food component complex, which can enhance the stability, efficacy, and sensory qualities of food products (Saffarionpour *et al.*, 2024; Wüpper *et al.*, 2021). For instance, cyclodextrins can significantly improve the solubility of vitamins such as vitamin D and other fat-soluble vitamins, which are essential for fortification but often present solubility challenges in water-based food systems (Saffarionpour *et al.*, 2024). The enhanced solubility provided by cyclodextrins not only facilitates the formulation of more stable and effective food products but also ensures that the bioactive compounds are more readily absorbed by the body (Wüpper *et al.*, 2021).

4.3 Protection Against UV-Induced Degradation of Nutrients

4.3.1 Preservation of Vitamins

Vitamins are essential nutrients that play a critical role in maintaining overall health and well-being. However, many vitamins, such as vitamin C and B vitamins, are highly sensitive to UV light, which can cause significant degradation and loss of bioavailability. This degradation not only diminishes the nutritional value of food products but can also lead to the formation of harmful by-products. Cyclodextrin complexes offer a promising solution to protect these vitamins from UV-induced degradation. Cyclodextrins can encapsulate vitamin molecules within their hydrophobic cavity, shielding them from direct exposure to UV light (Dahabra *et al.*, 2021). This protective mechanism helps to maintain the stability and potency of the vitamins, ensuring that they remain bioavailable in food products. For instance, research has shown that cyclodextrin complexes with vitamin C can significantly reduce the rate of degradation when exposed to UV radiation, thereby preserving the vitamin's antioxidant properties and health benefits (Cid-Samamed *et al.*, 2022).

Cyclodextrins protect vitamins from UV degradation through the formation of inclusion complexes. The hydrophobic core of the CD encapsulates the vitamin molecule, shielding it from direct UV radiation, oxidation, and other degradation factors. For example, in aqueous beverages, CDs have been shown to improve the stability of vitamin C by physically blocking UV exposure and reducing its interaction with dissolved oxygen, thus preserving its antioxidant activity. However, in lipid-rich foods, the primary degradation pathway might be lipid peroxidation. Therefore, Vitamin E would be less degraded compared to vitamin C (Cid-Samamed *et al.*, 2022; Dahabra *et al.*, 2021).

4.3.2 Maintenance of Antioxidants

Antioxidants, such as flavonoids and phenolic compounds, are crucial in preventing oxidative damage in the body. They neutralize free radicals, reducing the risk of chronic diseases and contributing to overall health. However, antioxidants are also susceptible to degradation when exposed to UV light, leading to a reduction in their effectiveness. Cyclodextrin complexes can help maintain the stability and activity of antioxidants by protecting them from UV-induced degradation (Dahabra *et al.*, 2021). Inclusion complex formation with cyclodextrins shields antioxidants from direct UV radiation, thereby maintaining their structure and functionality. This not only enhances the overall antioxidant capacity of the food product but also extends its shelf life. Studies have demonstrated that cyclodextrin complexes can effectively protect antioxidants like flavonoids and phenolic compounds, ensuring their continued efficacy in combating oxidative stress (Suvarna *et al.*, 2022).

Antioxidants like flavonoids are vulnerable to UV-induced degradation. CDs form inclusion complexes with flavonoids, where van der Waals forces and hydrophobic interactions drive the flavonoid into the CD cavity. This complexation sterically hinders UV radiation from reaching the flavonoid's reactive sites. In fruit juices, CD complexation can prevent UV-induced oxidation of phenolic compounds, preserving the juice's color and antioxidant capacity. However, in high sugar content, the effectiveness could vary according to pH. For instance, in jams, the antioxidant activity would decrease due to low water activity (Suvarna *et al.*, 2022).

4.4 Development of Functional Food Products with Enhanced UV Protection

4.4.1 Fortified Beverages

The incorporation of cyclodextrin-UVR absorber complexes into functional beverages represents an innovative approach to enhancing the UV protection and nutritional value of these products. Fortified beverages, such as juices, sports drinks, and nutritional supplements, can benefit from the stability and solubility improvements provided by cyclodextrins. These complexes can encapsulate UV-sensitive nutrients and bioactive compounds, protecting them from degradation while ensuring that they remain effective throughout the product's shelf life (Crini *et al.*, 2018; Matencio *et al.*, 2020). For example, by fortifying beverages with cyclodextrin complexes containing vitamins, antioxidants, or other UV-sensitive compounds, manufacturers can create drinks that not only offer hydration and nutrition but also provide an added layer of protection against UV damage (Crini *et al.*, 2018). This could be particularly beneficial for outdoor consumers, offering a novel way to support skin health from the inside out.

4.4.2 Sunscreen-Containing Foods

The concept of sunscreen-containing foods involves formulating food products with cyclodextrin-UVR absorber complexes to offer a unique combination of nutrition and UV protection. These products could include snacks, bars, or even confections designed to be consumed as part of a daily diet while providing UV protection benefits. By integrating UVR absorbers into foods via cyclodextrin complexes, it becomes possible to offer consumers edible products that help protect against the harmful effects of UV radiation (Mori *et al.*, 2019). Such innovations align with the growing trend towards functional foods that do more than just satisfy hunger they contribute to overall wellness. This could be particularly appealing in regions with high UV exposure, where daily consumption of such foods might complement the use of traditional sunscreens.

The protective mechanism in sunscreen-containing foods involves cyclodextrins forming inclusion complexes with UV absorbers. The hydrophobic cavity of the CD encapsulates the UV absorber, improving its solubility and stability within the food matrix. This complexation protects against UV-induced degradation and allows for a more uniform distribution of the UV absorber. While enhanced bioavailability after sunscreen ingestion does not directly increase the efficacy of sunscreen in food matrices, increased efficacy can potentially permit the use of lower UV absorber concentrations, although further experimentation is required to examine this effect across specific goods (Mori *et al.*, 2019).

4.4.3 Topical Applications

In addition to traditional edible products, cyclodextrin-UVR absorber complexes can be used in topical food applications, such as spreads, dressings, and marinades. These products could be applied directly to the skin or consumed, providing localized or systemic UV protection (Matencio *et al.*, 2020). Topical food products that include cyclodextrin-UVR absorber complexes could be marketed as dual-purpose items serving both as a tasty food product and as a functional skin protector. For example, a salad dressing or spread infused with such complexes could be applied to food and then consumed, offering an added layer of protection against UV radiation for those spending time outdoors. Some examples of CDs in different food items are shown in the Table 2.

5 Applications of Cyclodextrin-UVR Absorber Complexes in Agriculture

In addition, Cyclodextrin-UVR absorber complexes serve a crucial function in the domain of agriculture by augmenting the efficacy of agrochemicals and fostering plant development. These complexes enhance the solubility and stability of agricultural substances, thereby facilitating controlled release and mitigating environmental repercussions. Cyclodextrins generate inclusion complexes that markedly elevate the solubility of agrochemicals with poor solubility, thereby ensuring their effective utilization in plant treatments.

Table 2. Studies of Cyclodextrins in Various Food Items

Type of Cyclodextrin	Type of Food Item	Parameter Tested	Result	Reference
β-CD	Essential oils in beverages	Flavor retention	Enhanced stability and controlled release of flavors.	(Loftsson *et al.*, 2010)
β- CD	Dairy products	Fat reduction	Improved texture and mouthfeel in low-fat dairy products.	(Kurkov *et al.*, 2013)
α- CD	Baked goods	Shelf-life extension	Slowed staling process and extended shelf-life.	(Szente *et al.*, 2004)
γ- CD	Vitamin-enriched foods	Vitamin stability	Increased stability and bioavailability of vitamins.	(Astray *et al.*, 2009)
β- CD	Fermented dairy drinks	Off-flavor reduction	Reduced undesirable flavors from fermentation processes.	(Fenyvesi *et al.*, 2016)
γ- CD	Polyphenol-enriched foods	Antioxidant activity	Enhanced solubility and antioxidant activity of polyphenols.	(Del Valle, 2004)
β- CD	Spices	Volatile compound retention	Improved retention and release of volatile compounds in spices.	(Szente *et al.*, 2004)
α- CD	Nutritional supplements	Stability of active compounds	Increased stability and bioavailability of active compounds.	(Szejtli, 1998)
γ- CD	Fat-soluble vitamins in milk	Vitamin stability	Enhanced stability and bioavailability of fat-soluble vitamins.	(Szente *et al.*, 2004)
CD-MOFs	Functional Foods	Bioactive Compound Stability	Increased stability of bioactive compounds	(Liang *et al.*, 2024)
β- CD	Guava leaf oil	Antioxidant activity	More stable to sunlight exposure.	(Rakmai *et al.*, 2018)

Inclusion complex formation with cyclodextrins enhances the bioavailability of growth-promoting agents, thereby improving plant development and yield (Kelanne *et al.*, 2024). The controlled release of active agents mitigates loss attributable to environmental factors such as precipitation or irrigation, thereby improving the efficiency of agrochemicals (Crini *et al.*, 2018). This mechanism is congruent with sustainable agricultural practices by diminishing the frequency of applications and reducing chemical runoff (Farooq *et al.*, 2023). Cyclodextrin complexes can be used to generate biodegradable pesticides, presenting a more sustainable alternative to traditional pesticides while upholding their effectiveness (Bao *et al.*, 2024). Although the added advantages of cyclodextrin-UVR absorber complexes are substantial, hardships remain in refining their compositions for specific agricultural applications, necessitating further investigation to fully realize their capabilities. Applications of the cyclodextrin-UVR (Ultraviolet Radiation) absorber complexes in agriculture are reported in Table 3.

5.1 Protection of Crop Pigments and Nutrients

5.1.1 Preservation of Carotenoids

The preservation of carotenoids using cyclodextrin complexes has emerged as a viable method for improving their stability and bioavailability. Cyclodextrins' unique molecular structure effectively encapsulates carotenoids, protecting them from degradation caused by light and oxygen. Cyclodextrins protect carotenoids like β-carotene and lycopene from environmental factors by forming inclusion complexes (Durante *et al.*, 2020; Yildiz *et al.*, 2023). Using 2-hydroxypropyl-β-cyclodextrin to produce Z-isomer-rich carotenoid complexes improves stability and bioactivity, suggesting that structural modifications can improve preservation (Honda *et al.*, 2023).

5.1.2 Protection of Vitamins

Cyclodextrin-UVR absorber complexes significantly improve the stability and bioavailability of a variety of vitamins, including water-soluble and fat-soluble types. The protective mechanism is essential for increasing the efficacy of vitamins in therapeutic and nutritional applications. CDs encapsulate vitamins, protecting them from environmental degradation. β-CD complexes with vitamin-A exhibit higher thermal stability and solubility than free vitamin-A (Xu *et al.*, 2021). β-CD complexes containing vitamin D-3 and A have been developed for functional foods, resulting in improved dosing and reduced bitterness (Halavach *et al.*, 2022). Adding vitamins, such as the amino acid L-ascorbic acid (vitamin C), to hydroxypropyl-β-CD nano-fibers improved their antioxidant activity and reduced oxidative degradation (Khan *et al.*, 2023). Vitamin E's antioxidant properties were significantly increased when encapsulated in β-cyclodextrin, demonstrating the complex's ability to improve vitamin efficacy (Chen *et al.*, 2021).

5.2 Enhancement of Pesticide Efficacy

Using cyclodextrin UVR-absorbing complexes in pesticide formulations increases stability as well as efficacy. Particularly under Ultra-violet radiation exposure, CDs preserve active components from degradation and enable controlled release systems that maximize application while limiting environmental impact, hence improving pesticide durability.

Under UV irradiation, CD-UVR absorber complexes encapsulate insecticides such as emamectin benzoate, therefore prolonging their half-life about three-fold over unencapsulated versions (Zuo *et al.*, 2024). Cyclodextrins' unusual arrangement stops sensitive agrochemical components from degrading, so guaranteeing continuous effectiveness (Varan, 2023). CD-based formulations allow for controlled release triggered by external stimuli, including infrared (IR) radiation or environmental factors, improving the accuracy of pesticide deployment (Dong *et al.*, 2021; Liu *et al.*, 2021). These formulations can be engineered to discharge pesticides in response to particular conditions, such as alterations in pH or the occurrence of specific enzymes, thereby maximizing their impact while minimizing environmental contamination (Chen *et al.*, 2023).

5.3 Promotion of Plant Growth and Development

Cyclodextrins protect growth factors and make it easier for plants to absorb nutrients. This makes plants grow and develop much faster. Because these substances are different, they can form inclusion complexes. These complexes make plant hormones more stable and nutrients more available, which increases food production. CDs protect plant growth hormones such as auxins and cytokinins from UV destruction, preserving their effectiveness in stimulating growth. The creation of stable complexes with these hormones increases their lifetime and efficacy in plant development. Studies have demonstrated that cyclodextrin inclusion complexes containing growth-promoting chemicals considerably boost nutrient absorption in plants, resulting in increased growth metrics such as stem thickness (Yamamoto *et al.*, 2023). CDs can improve nutrient availability to plants by forming complexes that increase the solubility and uptake of essential minerals. They can also stabilize plant growth factors, protecting them from degradation and enhancing their activity (Yamamoto *et al.*, 2023).

5.4 Soil Remediation

CDs have proven to be excellent agents for soil remediation, namely in dissolving toxic contaminants and improving nutrient availability. Their distinctive capacity to create inclusion complexes with organic pollutants enhances solubility and bioavailability, promoting the breakdown of pesticides and herbicides. In addition, CDs can help plants absorb nutrients better, which speeds up growth and reduces their need for chemical fertilizers.

5.4.1 Degradation of Contaminants

Cyclodextrin-based nanosponges have demonstrated considerable effectiveness in eliminating diverse contaminants, such as heavy metals and organic compounds, from polluted soils (Shukla *et al.*, 2023). β-Cyclodextrin has been recognized for its function in the bioremediation of petroleum hydrocarbons, successfully mitigating pollution from refineries (Rozsnyai *et al.*, 2023). The solubility of polycyclic aromatic hydrocarbons (PAHs) in creosote-contaminated soils has been improved by the use of cyclodextrins, suggesting their efficacy in degrading persistent organic pollutants (Dutta, 2004).

5.4.2 Improved Nutrient Accessibility

Cyclodextrins enhance nutrient bioavailability in soils, resulting in improved plant development and less reliance on chemical fertilizers (Morillo *et al.*, 2020). Modified cyclodextrins have been emphasized as an eco-friendly alternative to conventional remediation techniques, fostering sustainable farming practices (Yadav *et al.*, 2022). Cyclodextrins provide potential answers for soil remediation; yet, issues persist concerning their application at field size and the necessity for more study to enhance their efficacy across various environmental conditions.

CDs can facilitate the breakdown of pollutants by increasing their solubility and bioavailability, making them more accessible to microorganisms that degrade them. CDs can also complex with pollutants, reducing their toxicity and mobility in the soil (Morillo *et al.*, 2020; Shukla *et al.*, 2023).

5.5 Seed Coatings and Germination

Coming to seed-protection from ultraviolet light, speeding up the germination process, and allowing for regulated nutrient release to nurture seedling growth, CD-encapsulated seed coverings excel. CD-coats have the ability to protect seeds from the damaging effects of ultraviolet radiation, which is essential for the survival of seeds (Javed *et al.*, 2022). A new study (Chen *et al.*, 2023; Gong *et al.*, 2023) has found that coats with micronutrients and microbes make seedlings much stronger and increase the number of times they germinate in tough conditions like salt stress. Adding nutrients to cyclodextrin coats allows for controlled release, which improves nutrient absorption during important stages of growth (Chakkalakkal *et al.*, 2022). Research demonstrates that these coatings can augment the growth characteristics of crops such as maize, resulting in enhanced yield and quality (Chen *et al.*, 2023). Despite the evident advantages of cyclodextrin-encapsulated coatings, obstacles persist in refining formulations for different environmental

Table 3. Applications of the Cyclodextrin-UVR (Ultraviolet Radiation) Absorber Complexes in Agriculture

Application	Description	Reference
UV Protection of Crops	Provide protection from harmful UV radiation, reducing sunburn damage.	(Milano *et al.*, 2025)
Prolongation of Herbicide Activity	CD-UVR complexes-Inhibit photodegradation, extending the efficiency of UV-sensitive herbicides.	(Villaverde *et al.*, 2007)
Improved Pesticide Stability	CD-UVR complexes-stabilize UV-degrading insecticides, improving their efficacy and decreasing reapplication.	(Zhou *et al.*, 2008)
Controlled Release of Agrochemicals	CD-UVR complexes-control the release of UV-sensitive agrochemicals, which improves performance and lowers toxicity	(Nicolaescu *et al.*, 2025)
Augmented Development of Seedlings	CD-UVR complexes shield young seedlings from UV light, increasing growth and lowering mortality.	(Yamamoto *et al.*, 2023)
Photoprotection in Greenhouses	Greenhouse coatings with CD-UVR complexes filter UV-rays but permits light in, boosting plant growth.	(Fouda-Mbanga *et al.*, 2025)
Reduction of UV-Induced Mutations in Plants	CD complexes reduce UV-induced mutations in sensitive plant species, maintaining genomic stability.	(Suvarna *et al.*, 2022)
Preservation of Phytochemicals in Fruits	CD complexes preserve vitamins and antioxidants in fruits against UV destruction.	(Koontz *et al.*, 2009)

circumstances and crop varieties, requiring more study to enhance their efficacy in varied agricultural contexts.

6 Applications of Cyclodextrin-UVR Absorber Complexes in Beverages

The beverage industry employs cyclodextrin-UVR absorber complexes to ameliorate stability and flavor. These complexes capitalize on the unique host-guest properties of cyclodextrins (CDs) to encapsulate UV absorbers, thereby increasing their solubility and efficacy in liquid formulations. Cyclodextrins can stabilize volatile compounds, which extends shelf life and maintains product quality (Astray *et al.*, 2020). According to Matencio *et al.*, (2020), CDs also protect sensitive ingredients from degradation due to heat or light exposure, ensuring the product's functional integrity. The formation of these inclusion complexes can also mask undesirable tastes and aromas, enhancing the overall sensory profile of beverages (Astray *et al.*, 2020; Crini *et al.*, 2018). This feature is especially particularly valuable for products containing strong flavors or off-notes that may deter consumer acceptance. These complexes are typically formed using techniques, such as co-precipitation and slurry complexation (Crini *et al.*, 2018), allowing formulators to precisely tailor the final product.

6.1 Preservation of Color and Flavor

The use of CD complexes in beverages has demonstrated considerable promise in maintaining taste and color. These complexes increase the stability of volatile compounds, thereby improving sensory qualities and shelf life. Inclusion complexes formed by cyclodextrins stabilize flavor compounds against environmental factors including heat and light, preventing their breakdown. Studies in which β-CD considerably enhanced the aroma and flavor scores of coffees illustrate how the encapsulating process improves the release and retention of flavors (He *et al.*, 2023; Zhang *et al.*, 2024). CDs are also used to mask unpleasant tastes and aromas, which enhances the overall sensory experience of beverages (Astray *et al.*, 2020). For example, research has demonstrated that complexing alcohol aroma compounds with β-CD not only stabilizes flavors but also increases the shelf life of goods such as strawberries, highlighting their versatility (Kou *et al.*, 2024).

6.2 Enhanced Bioavailability of Nutrients

CDs markedly improve the bioavailability of vitamins and minerals while safeguarding delicate antioxidants in beverages. Their distinctive structure facilitates the formation of inclusion complexes that enhance solubility and stability, resulting in improved nutrient absorption and antioxidant effectiveness. CDs enhance the solubility and bioavailability of hydrophobic nutraceuticals, including vitamins D3 and A, by forming stable complexes that inhibit aggregation and improve intestinal absorption (Uberti *et al.*, 2023; Uekaji & Terao, 2019).

Research indicates that β-CD complexes with fat-soluble vitamins can transform oils into powdered formats, thereby enhancing their integration into functional foods (Halavach *et al.*, 2022). CDs also safeguard sensitive antioxidants such as flavonoids from UV degradation, improving their stability and bioactivity. The incorporation of flavonoids into cyclodextrin complexes markedly enhances their pharmacokinetic parameters, including area under the curve (AUC) and maximum plasma concentration (Cmax), compared to their un-complexed forms (dos Santos Lima *et al.*, 2019).

6.3 Development of Functional Beverages

The incorporation of CD-UVR absorber complexes into functional beverages represents a strategic approach to enhance health benefits and protect active ingredients from UV degradation. In response to consumer demand for multipurpose products, this innovative method fortifies beverages while providing integrated UV protection. CDs can encapsulate bioactive compounds, enhancing their stability and bioavailability in beverages. The addition of these complexes to fat-soluble vitamins and other hydrophobic ingredients to these complexes improves the nutritional profile of the product (Kurchenko *et al.*, 2022). The incorporation of UVR absorbers safeguards the beverage's active components while providing a novel approach to sun protection, consistent with trends in the functional beverage sector (Astray *et al.*, 2020).

6.3.1 Improved Sensory Properties

CDs also improve the mouthfeel and flavor release of beverages. Their unique structure enables the encasement of flavor compounds, leading to a more controlled and prolonged release, thus enhancing the overall sensory experience. Cyclodextrins form inclusion complexes with flavor compounds, improving their stability and aiding their release during consumption. For example, a β-CD/flavor CD powder markedly enhanced the aroma and flavor ratings of coffee by 3.0–4.0 and 2.1–3.5 points, respectively (Zhang *et al.*, 2024). Inclusion complex formation with cyclodextrins facilitates the dispersion of hydrophobic compounds in aqueous matrices, thereby enhancing flavor bioavailability. The application of β-CD modified solid particles enhances mouthfeel by enabling the prolonged release of flavors, thereby improving the sensory experience. Cyclodextrins can also mask unpleasant flavors, which contributes to the overall improved mouthfeel of beverages (Kelanne *et al.*, 2024; Zhang *et al.*, 2022).

6.4 Extended Shelf Life

Cyclodextrin complexes effectively extend the shelf-life of beverages by protecting them from oxidation and improving their overall quality. These complexes can encapsulate sensitive compounds, thereby preventing their degradation and preserving sensory characteristics. Cyclodextrins form inclusion complexes with bioactive compounds, safeguarding them from oxidative degradation during storage (Liang *et al.*, 2024). The incorporation of CDs can significantly improve the stability of flavors and aromas in beverages, as demonstrated by the significant increase in coffee flavor ratings with β-CD (Zhang *et al.*, 2024). By improving the stability of volatile compounds which are necessary for flavor and aroma CDs enhance the sensory qualities of beverages (Kelanne *et al.*, 2024). Through inclusion complex formation, these compounds are protected and their bioavailability is increased, consequently enhancing the consumer experience (Matencio *et al.*, 2020). Cyclodextrin-based formulations can be customized for specific beverages, solving constraints like UV-induced degradation and enhancing nutritional value (Aiassa *et al.*, 2023). The versatility of CDs allows for their application in various beverage categories, which can encourage innovative product developments in the industry.

Regulatory authorities, including the Food and Drug Administration (FDA) and European Union (EU), recognize α, β-, and γ-cyclodextrins as safe food additives, with permitted levels varying depending on the type of CD and food application. For instance, α-cyclodextrin may be used up to 3% in certain food products, while β-cyclodextrin is authorized up to 2 g/kg in specific foods and beverages (Crini *et al.*, 2018). β-Cyclodextrin is specifically approved under the code E 459 in the EU, with an acceptable daily intake (ADI) of 5 mg/kg body weight per day established by the European Food Safety Authority (EFSA). γ-Cyclodextrin and α-CD are generally recognized as safe (GRAS) in various food applications, demonstrating good tolerance and metabolism similar to starch even at relatively high intake levels. These regulated concentrations ensure the safe and effective use of CDs for improving sensory qualities, stabilizing flavors, extending shelf life, and enhancing the bioavailability of lipophilic nutrients and bioactive compounds (EFSA, 2016).

7 Conclusions

Cyclodextrin-UVR absorber (CD-UVR) complexes offer a promising solution for enhancing the stability, quality, and safety of food, beverages, and agricultural products. These complexes work by protecting nutrients from degradation, preventing oxidation, and preserving color and flavor, which significantly extends the shelf life of food items. In agriculture, CD-UVR absorber complexes exhibit potential for promoting environmental sustainability and efficiency by shielding crops from harmful UV radiation, enhancing the stability of agrochemicals, and improving crop yield and quality. In the beverage sector, these complexes strategically counteract the negative effects of UV radiation on product quality, protecting sensitive ingredients such as flavors, colors, and vitamins. This ensures that beverages retain their sensory appeal and nutritional value, leading to extended marketability and shelf life. Overall, CD-UVR absorber complexes represent a valuable innovation across multiple sectors, with ongoing research expected to further enhance their effectiveness and applications.

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