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Food Industry Application of Cyclodextrin Inclusion System

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Abstract. Cyclodextrins (CDs), which belong to a family of cyclic oligosaccharides, are characterized by a distinctive hydrophobic internal cavity. This structural feature permits them to encapsulate various guest molecules, leading to the formation of inclusion complexes. The present article offers a thorough overview of the utilizations of cyclodextrin-based encapsulation systems within the food sector. Of particular significance are their contributions to augmenting antibacterial efficacy and prolonging food shelf-life via the encapsulation of naturally derived antimicrobial agents. Additional key functions comprise ameliorating the dissolution, stabilization, and absorptivity of lipophilic bioactive substances; the efficient extraction of cholesterol from dairy and animal-based produce; as well as the effective concealment of unpalatable flavors and odors. Furthermore, cyclodextrins are utilized in food packaging to preserve flavor and ensure quality, as well as in food safety monitoring for the detection of contaminants. Despite their versatility and low toxicity, challenges remain in the development of environmentally friendly preparation methods and practical analytical sensors. Future perspectives emphasize sustainable production techniques, advanced extraction methods, and the optimization of functional packaging to broaden the industrial applications of cyclodextrins.

Keywords: Cyclodextrin, Inclusion complex, Food industry, Food packaging

1. Introduction

Cyclodextrins (CDs) represent a family of cyclic oligosaccharides composed of D-glucopyranose subunits interconnected via α-(1→4) glycosidic linkages [1]. Their classification into types such as α-, β-, γ-, and δ-cyclodextrins is based on the number of constituent glucose units. Among these, the most widely utilized variants are α-, β-, and γ-cyclodextrins, which consist of six, seven, and eight glucose monomers, respectively (Figure 1). Since Villiers [2] discovered the cyclodextrin, the development of cyclodextrin has been more than 100 years. The most significant feature of cyclodextrin is that it has a three-dimensional chiral cavity with hydrophilic outside the ring and hydrophobic inside the ring and a certain size, which makes it have many special physical and chemical properties. Its cavity can envelop different compounds, such as organic compounds, noble gases, inorganic compounds, etc., to form clathics, the enveloped compound is called the guest body, and the cyclodextrin is called the body. In recent years, the global production of cyclodextrin has exceeded 10,000 tons, of which more than 90% is β-cyclodextrin. Furthermore, cyclodextrins and

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their modified derivatives have found extensive utility across a diverse range of sectors, including the food, pharmaceutical, chemical, flavor and fragrance, and agricultural industries.

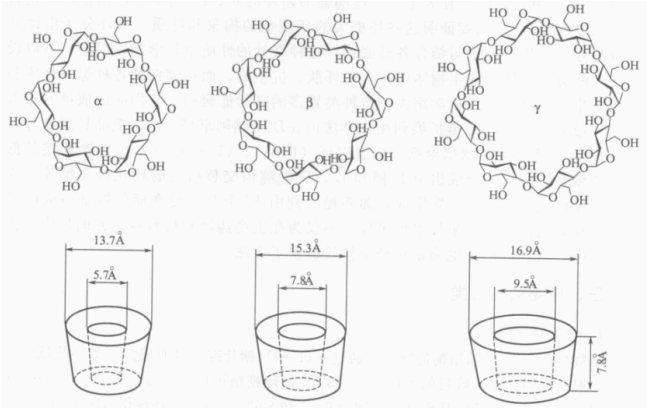

Figure 1. Molecular structures of three common cyclodextrins

1.1. Structure and physical properties of cyclodextrin

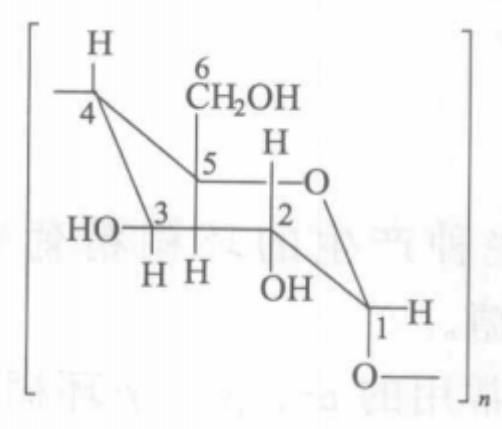

Figure 2. General formula of cyclodextrin structure

As shown in Figure 2, the D-type glucopyranose units that make up cyclodextrins are all in a chair conformation, and the sugar groups in the chair conformation cannot rotate freely around the glycosidic bonds, so the three-dimensional structure of the cyclodextrin molecule is a slightly conical cylindrical shape. Among them, the small port is composed of 7 primary hydroxyl groups on the C-6 position, and the large port is composed of 14 secondary hydroxyl groups on the C-2 and C-3 positions. Because the hydroxyl group is aggregated on the outer edge of its molecule, the outer wall of the cyclodextrin molecule is highly hydrophilic. The lumen of cyclodextrin is composed of hydrogen atoms at the C-3 and C-5 positions and oxygen atoms at the C-4 position. Because the oxygen atoms at the C-3 and C-5 positions have a shielding effect on the glycooxygen atoms at the C-4 position, the cyclodextrin lumen has strong hydrophobicity, so that many hydrophobic compounds can be encapsulated.

1.2. Embedding characteristics of cyclodextrin

The formation of inclusion complexes with guest molecules is one of the most important properties of cyclodextrins. The so-called inclusion is the phenomenon in which the subject and the object

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interact with each other to complete the process of identifying each other, and finally the object molecule is partially or fully embedded inside the subject. In 1932, Pringshem first proposed that cyclodextrin as a host molecule has a strong ability to recognize object molecules. Later, Freudenberg and his collaborators synthesized 54 cyclodextrin inclusion complexes and studied the interaction between cyclodextrins and these objects in aqueous solution.

2. Food industry application of cyclodextrin inclusion complex

Benefiting from their distinctive cavity architecture, which facilitates the formation of inclusion complexes with numerous compounds, coupled with their cost-effectiveness and high safety profile, cyclodextrins have been extensively employed in the food industry for applications such as potentiation of antimicrobial efficacy and prolongation of product shelf-life. Cyclodextrins are susceptible to metabolism by colonic microorganisms. Specifically, α- and β-cyclodextrins resist hydrolysis by human salivary and pancreatic amylases, whereas γ-cyclodextrin undergoes partial degradation in the presence of pancreatic enzymes. Owing to its relatively constricted cavity dimensions, α-cyclodextrin exhibits a predisposition for encapsulating smaller molecular guests, thereby constraining its applicability. In contrast, γ-cyclodextrin possesses a more expansive cavity; however, its widespread utilization is hampered by elevated production costs and limitations in scalable synthesis. Among these variants, β-cyclodextrin strikes a balance with an intermediate cavity size and demonstrates favorable preparative accessibility, rendering it a more economically viable option.Compared with α- and γ-cyclodextrin, β-cyclodextrin has a wider range of research and applications in the food industry.

2.1. Enhance antibacterial activity and shelf life

Foodborne pathogens represent a significant and ongoing risk to public health worldwide (e.g., Salmonella and E. coli) [3]. Consumers exhibit considerable apprehension regarding food safety issues, demonstrating a growing preference for the incorporation of natural antimicrobial agents into food products as a strategy to mitigate the risks associated with foodborne pathogens [4]. A number of food additives demonstrate effective antibacterial properties; however, their practical application is often constrained by limitations such as low aqueous solubility and excessively strong bacteriostatic effects that may impact food quality. Notable examples include eugenol and various essential oils, which exhibit broad-spectrum antimicrobial activity against pathogens such as Clostridium botulinum, Staphylococcus aureus, Escherichia coli, and Salmonella. Nevertheless, their utility is compromised by inherent hydrophobicity and chemical instability. Cyclodextrins offer a promising solution to these challenges. Their molecular structure, characterized by a hydrophilic exterior and a hydrophobic internal cavity, enables the effective encapsulation of lipophilic bioactive compounds. This complexation enhances the water solubility of such agents, reduces their volatility, and improves the stability and efficacy of their antimicrobial action in food systems. Lin et al [5] prepared a new cinnamon essential oil/β-cyclodextrin nanofiber was prepared, which had a good antibacterial effect on Bacillus cereus without affecting the sensory quality of beef. Experimental results indicated that the incorporation of clathrate nanofibers markedly prolonged the shelf life of beef samples, demonstrating considerable potential for utilization in advanced food packaging applications. Moreover, an investigation conducted by Rakmai et al. [6] examined the antioxidant and antibacterial characteristics of guava leaf essential oil encapsulated within hydroxypropyl-β-cyclodextrin. The findings revealed that the encapsulated oil exhibited a 26% to 38% enhancement in antioxidant activity compared to its non-encapsulated counterpart. Furthermore, the antibacterial

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efficacy against Staphylococcus aureus and Escherichia coli was augmented by four-fold and two-fold, respectively, following complexation with cyclodextrin. Moreover, Gong et al [7] Findings from the study revealed that the inclusion complex exhibited a marked inhibitory effect on mycelial growth. Structural and morphological analyses of Pseudomonas lychee development further demonstrated substantial alterations in both hyphal morphology and ultrastructural organization when treated with the inclusion complex, as compared to untreated controls. Post-treatment observations indicated abnormal hyphal development, evident extracellular leakage, and a loss of cellular integrity. These outcomes suggest a significant enhancement in the antimicrobial efficacy of the antibacterial agent following complexation.

Moreover, an investigation conducted by Rakmai et al. [6] examined the antioxidant and antibacterial characteristics of guava leaf essential oil encapsulated within hydroxypropyl-β-cyclodextrin. The findings revealed that the encapsulated oil exhibited a 26% to 38% enhancement in antioxidant activity compared to its non-encapsulated counterpart. Furthermore, the antibacterial efficacy against Staphylococcus aureus and Escherichia coli was augmented by four-fold and two-fold, respectively, following complexation with cyclodextrin.

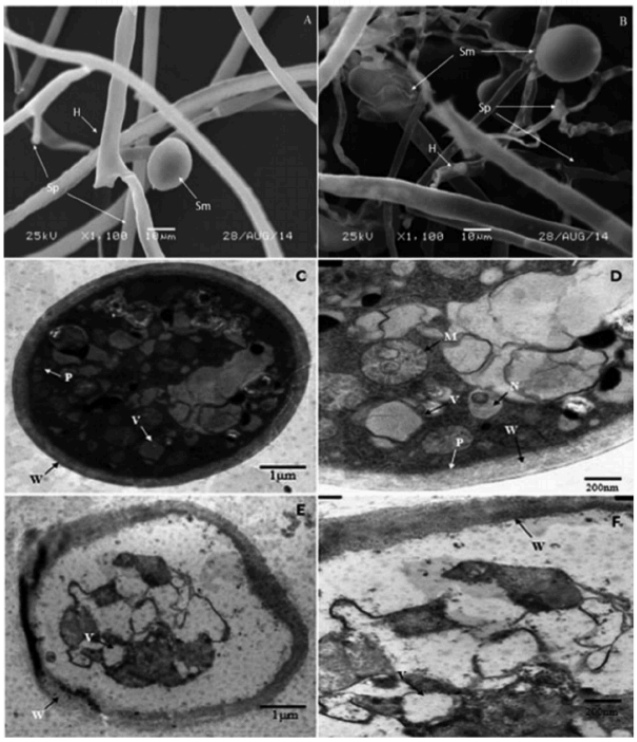

Figure 3. Scanning electron microscopy observation of lychee polysaccharide hyphae or sporangia treated with no inclusion (A) and inclusion (B). Transmission electron microscopy observation of the longitudinal section of mycelium without inclusion treatment (C, D) and inclusion treatment (E, F)

2.2. Increase the solubility of food ingredients

A number of food additives, including anethole, curcumin, and octanal, exhibit pronounced hydrophobicity, which substantially restricts their utilization within food systems. Encapsulation using cyclodextrins presents an effective strategy to mitigate these limitations by markedly enhancing their solubility. For instance, apigenin—a dietary polyphenol known for its antioxidant

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and anti-cancer properties—suffers from low aqueous solubility, resulting in inadequate absorption and reduced bioavailability [8]. Papay et al. use different cyclodextrins to encapsulate apigenin. Solubility of apigenin: RM-β-cyclodextrin> SBE-β-cyclodextrin>γ-cyclodextrin>HP-β-cyclodextrin>β-cyclodextrin>α-cyclodextrin. In addition, Matencio and others [4] found the biological activity of the resveratrol analogue trans-α-methylstilbene (TMS) was found to be almost entirely limited by its hydrophobicity. Consequently, tetramethylscutellarein (TMS) was encapsulated using various cyclodextrin types to augment its aqueous solubility, and the underlying inclusion mechanisms were systematically investigated. The results indicated a notable enhancement in the solubility of the resulting inclusion complexes. Among these, methyl-β-cyclodextrin exhibited the highest apparent formation constant, rendering it the most effective candidate for solubility improvement. In contrast, the complex formed with α-cyclodextrin demonstrated the weakest interaction, which was primarily attributed to suboptimal host-guest coordination and inferior hydrophobic stability. Conversely, β-cyclodextrin, hydroxypropyl-β-cyclodextrin, and methyl-β-cyclodextrin all displayed high encapsulation stability. Furthermore, ginger—a spice widely used in food—is known to possess diverse medicinal properties, such as antioxidant and anti-inflammatory effects. As demonstrated by Zhang et al. [9], encapsulation of ginger essential oil within cyclodextrin significantly enhanced its thermal stability, increased its water solubility, reduced its volatility, and broadened its potential applications.

2.3. Remove cholesterol from food

To mitigate the risk of coronary heart disease, dietary modifications aimed at reducing the intake of fats and cholesterol—present in foods such as eggs, dairy products, and animal fats—are often recommended. Research has identified cyclodextrin as a cost-effective and safe agent for cholesterol reduction, offering significant health advantages for individuals requiring cholesterol management.

The mechanism primarily relies on the affinity of cyclodextrin for cholesterol molecules present at oil-water interfaces. This promotes the formation of an insoluble β-cyclodextrin-cholesterol inclusion complex within the aqueous phase, facilitating the removal of cholesterol from food matrices through subsequent centrifugation. For instance, Alonso et al. [10] treated pasteurized whole milk with β-cyclodextrin and processed the resulting cream into low-cholesterol butter. This method achieved a cholesterol reduction rate of 95.53%, with only 0.04% cyclodextrin residue, demonstrating its viability for commercial butter production. Additionally, the study indicated that cyclodextrin treatment enhanced the bactericidal effect in pasteurized milk without altering the fatty acid profile.

Recent advances have enabled the synthesis of cyclodextrin polymers via cross-linking with suitable agents. These polymers retain the amphiphilic character and functional properties of native cyclodextrin, including cholesterol sequestration capabilities. Their structure features multiple branching points organized into a three-dimensional network, endowing them with improved mechanical strength and stability. As a result, cyclodextrin polymers exhibit broad utility in molecular recognition, chromatographic separation, environmental remediation, pharmaceuticals, and the food industry.

In a study by Somogyi et al. [11], various cyclodextrins were evaluated for cholesterol removal efficiency across different solution concentrations. The results highlighted dimethyl β-cyclodextrin as particularly effective. In vivo experiments further confirmed that cyclodextrin can form complexes with 80–85% of cholesterol, underscoring its efficacy and potential for dietary and therapeutic applications.

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2.4. Improve food stability

2.4.1. Improve the antioxidant efficiency of food ingredients

Numerous food constituents are susceptible to degradation triggered by oxygen, light, or enzymatic activity, often resulting in undesirable changes in color, aroma, and flavor. The stability of such biomolecules is influenced by a combination of hydrophobic, electrostatic, and hydrogen-bonding interactions. Cyclodextrins, by virtue of their hydrophobic internal cavities, can encapsulate poorly soluble compounds through clathrate formation. This molecular encapsulation serves to shield vulnerable ingredients from oxidative, photolytic, and hydrolytic degradation, thereby contributing to an extension of product shelf-life.

For instance, carotenoids in free oleoresins stored at 25°C are prone to rapid oxidative loss due to inherent chemical instability. The limited stability of such oil-based resins often restricts their use in food applications. Durante et al. [12] addressed this challenge by embedding wheat bran, tapioca, and tomato oleoresins within α-cyclodextrin to produce lyophilized powders suitable for direct incorporation into functional foods. Their findings demonstrated markedly enhanced stability of the bioactives post-encapsulation, with the inclusion complexes remaining stable under various storage conditions for up to 180 days.

Similarly, garlic oil—a valued flavoring agent and therapeutic compound used in the management of cardiovascular diseases—readily undergoes oxidation upon exposure to air. However, when formulated into cyclodextrin inclusion complexes, its oxidative stability is significantly enhanced, preserving both its functional and sensory properties.

2.4.2. Enhance the photothermal stability of food additives

Food additives play a crucial role in enhancing the color and aroma of food products. Nevertheless, many of these compounds are highly sensitive to external environmental factors such as oxygen, temperature, and light. Research has shown that encapsulating the reactive sites of additives within cyclodextrins can significantly improve their stability. For example, preservatives—commonly incorporated into beverages to maintain freshness—are prone to degradation under heat and light during production and storage, leading to off-flavors that compromise sensory quality and consumer acceptance.

Saldanha et al. [13] encapsulated limonene using β-cyclodextrin and observed a reduction in limonene content upon granule formation. However, after simulating storage conditions equivalent to nine months, approximately 40% of the limonene remained in the beverage. Accelerated degradation tests further confirmed that the encapsulated limonene exhibited markedly improved stability compared to its free form.

In a related study, He et al. developed an inclusion complex of oxidized resveratrol (Oxy). Their results indicated that the encapsulated Oxy was effectively protected against both photolytic and thermal degradation. Under illuminated storage conditions over 30 days, the relative content of free Oxy declined significantly with rising temperature—from 60.54% to 33.11%—while the inclusion complex demonstrated high stability. This approach offers a promising strategy for enhancing the applicability of sensitive bioactive compounds like Oxy in the food industry.

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2.4.3. Enhance the volatile stability of food additives

Certain food additives exhibit high volatility and instability throughout production, storage, and distribution processes. Consequently, achieving and maintaining desired flavor profiles often necessitates the incorporation of substantial quantities of these additives. Recent investigations have demonstrated that encapsulation using cyclodextrins represents an effective strategy for flavor preservation. Menthol, for instance, is a widely employed flavoring agent in food products; however, its application is constrained by pronounced volatility. As documented by Zhu et al. [14], a menthol/hydroxypropyl-β-cyclodextrin inclusion complex was developed to enhance stability. The findings revealed that this complex exhibited the most favorable morphological configuration and molecular orientation, thereby significantly improving the compound's resistance to volatilization and degradation. Take edible rose essence as an example, rose essence has a pure rose fragrance and can be used to fragrance candies and biscuits made at high temperatures. The volatility of rose essence limits its application. By microencapsulating the fragrance through cyclodextrin, the liquid fragrance can be converted into solid powder, which significantly improves the sustained release and overcomes the shortcomings of fast fragrance release and short fragrance retention.

2.5. Mask the unpleasant taste of food ingredients

Palatability serves as a fundamental criterion influencing consumer food choices, and undesirable sensory attributes such as bitterness, fishiness, or astringency often lead to low consumer acceptance. Consequently, the effective masking or elimination of such off-flavors represents a significant challenge within the food industry. The effect of cyclodextrin in removing food odors is very significant. For example, the bad odors produced by raw fish, salted fish and other seafood, mutton and other meat, animal offal, dairy products, soybean products, etc. can be effectively removed after cyclodextrin treatment. Bone meal used in food calcium supplementation often has an unpleasant odor, and the odor is significantly reduced after adding a small amount of cyclodextrin during preparation. The hesperidin, naringin and limonin in citrus juice have a heavy bitter taste, and the water solubility is poor, which often makes the orange juice bitter and turbid, which is not conducive to the production of bottled and canned products. Frozen foods such as ice cream and iced milk often have a distinctive odor of cream and poor solubility, but adding a small amount of cyclodextrin can significantly improve the flavor. Protein hydrolysates frequently exhibit pronounced bitterness and undesirable fishy notes, which considerably limit their palatability and consumer acceptance. Cyclodextrins offer a viable technological solution by forming stable inclusion complexes with bitter peptides and odor-active compounds. For instance, in wheat-based products, the incorporation of β-cyclodextrin has been shown to effectively mitigate the bitter taste of gluten protein hydrolysates [15]. Similarly, in the brewing industry, cyclodextrins have been employed to reduce bitterness in beer. A study by Pinho et al. demonstrated the encapsulation of bitter compounds from coffee using cyclodextrin, with detailed structural and thermodynamic analyses—including density functional theory (DFT) calculations and single-crystal X-ray diffraction—confirming the stability of the resulting clathrate complex. Thus, the application of β-cyclodextrin represents an effective strategy for masking offensive tastes and enhancing the overall sensory profile of food products, thereby improving consumer appeal.

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2.6. Improve the sensory quality and preserve the color of food

The visual quality of food, particularly its color brightness and intensity, serves as a critical indicator of overall product acceptability. To maintain desirable coloration, natural pigments—such as carotenoids from yellow and red bell peppers, carmine, curcumin from turmeric, and other plant-based colorants—are frequently employed. However, the utility of these natural colorants is often constrained by inherent limitations, including low solubility and high susceptibility to degradation during processing and storage.

Research has demonstrated that cyclodextrins can function as effective protective agents for such colorants. For instance, Marcolino et al. [16] encapsulated both carmine and curcumin within cyclodextrins and incorporated these complexes into cheese and curd, respectively. Colorimetric evaluations revealed that the inclusion complexes exhibited superior color stability and intensity compared to their free pigment counterparts. Sensory analyses further confirmed that the products containing encapsulated colorants maintained acceptable sensory attributes without compromising quality.

In a related application, the same researchers developed an inclusion complex containing yellow bell pepper pigment for use in beverages, observing significantly enhanced color retention over time. Another notable example involves astaxanthin, whose water solubility and stability are markedly improved following complexation with hydroxypropyl-β-cyclodextrin.

Beyond color preservation, cyclodextrins also contribute to aroma stability and the inhibition of enzymatic browning in fruits and vegetables. Fruit aromas, derived largely from volatile esters, aldehydes, alcohols, and hydrocarbons, are prone to degradation, often leading to loss of freshness and undesirable browning. Cyclodextrins can mitigate these issues by encapsulating key enzymes such as polyphenol oxidase (PPO). Singh et al. [17], for example, reported that polyphenol-rich fruit and vegetable juices are susceptible to browning via PPO activity, a process that can be suppressed through cyclodextrin-mediated inclusion.

In summary, cyclodextrin-based encapsulation offers a versatile and efficacious approach for enhancing the stability, solubility, and functional performance of natural colorants and aroma compounds, thereby extending the shelf life and improving the quality of fruit and vegetable products.

2.7. Enhance the pharmacological activity of natural ingredients in food

Many foods contain bioactive constituents with potential pharmacological benefits; however, their efficacy is often limited by poor bioavailability. Encapsulating these compounds within cyclodextrins has been shown to enhance key properties—such as membrane permeability, solubility, and binding affinity to proteins and nucleic acids—thereby significantly improving their bioavailability and therapeutic potential. In addition, Rodrigues et al. [18] basil essential oil cyclodextrin inclusion complex was prepared, and it was found that the unembedded essential oil weakly achieved the same anti-inflammatory effect as the inclusion complex, and the dose needed to be increased by 5 times. In conclusion, cyclodextrin inclusions can enhance the pharmacological activity of certain natural ingredients.

2.8. Food safety analysis

In recent years, the illicit adulteration of food products with hazardous chemical substances has seen a considerable rise, presenting severe risks to public health. Among these, melamine contamination

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—particularly in dairy and other food items—has raised significant concern due to its detrimental effects on children, adults, and animals. This urgency has driven the development of highly sensitive and selective detection systems for continuous melamine monitoring.

Singh et al. [19] developed a novel supramolecular sensing platform for melamine identification, consisting of sulfated cyclodextrin, silver ions, and melamine itself, which collectively encapsulate a molecular rotor dye—thioflavin T. This assembly exhibits a fluorescence turn-on response specifically triggered by the presence of melamine, enabling straightforward, highly sensitive, and selective detection of the contaminant.

3. Conclusions

Cyclodextrin has received increasing attention due to its inherent structural properties. This review synthesizes recent advancements in cyclodextrin research, with the aim of enhancing comprehension of their inclusion complex preparation methods, advancing analytical techniques, and expanding their applications within the food industry. By consolidating current knowledge, this work seeks to facilitate further innovative utilization of cyclodextrins in food science and technology. The versatility of cyclodextrin catalyzes innovation in food science. As people's understanding of cyclodextrin deepens, the potential applications of cyclodextrin are also expanding. Cyclodextrin and its derivatives have a wide range of uses in various fields, especially in the food industry. The utilization of cyclodextrins has seen significant growth in recent years, largely attributable to their capacity to form host–guest inclusion complexes with diverse compounds. Such molecular encapsulation enhances the physicochemical stability and solubility of various lipophilic substances, including fragrances, vitamins, colorants, and bioactive agents. Furthermore, owing to their favorable safety profile and low toxicity, cyclodextrins can be employed in applications without posing significant risks to human health. With the continuous expansion of the functional food market, consumers have an increasing demand for natural health products, and cyclodextrin has broad application prospects.

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