

Review

Not peer-reviewed version

Intelligent and Active Packaging: A Review of the Application of Cyclodextrins for Improvement Food Quality

[Andres Leobardo Puebla-Duarte](#) , Irela Santos-Sauceda , [Francisco Rodríguez-Félix](#) , [Rey David Iturralde-García](#) , [Jesús Daniel Fernández-Quiroz](#) , Ingrid Daniela Perez-Cabral , [Carmen Lizette Del-Toro-Sánchez](#) *

Posted Date: 6 September 2023

doi: 10.20944/preprints202309.0308.v1

Keywords: cyclodextrin; smart packaging; intelligent packaging; active packaging; food additives, biopolymers; polysaccharide



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Review

Intelligent and Active Packaging: A Review of the Application of Cyclodextrins for Improvement Food Quality

Andres Leobardo Puebla-Duarte ¹, Irela Santos-Sauceda ², Francisco Rodríguez-Félix ¹, Rey David Iturralde-García ¹, Jesús Daniel Fernández-Quiroz ³, Ingrid Daniela Perez-Cabral ¹ and Carmen Lizette Del-Toro-Sánchez ^{1,*}

¹ Departamento de Investigación y Posgrado en Alimentos, Universidad de Sonora. Blvd. Luis Encinas y Rosales S/N, Col. Centro, C.P. 83000, Hermosillo, Sonora.

² Departamento de Investigación en Polímero y Materiales, Universidad de Sonora. Blvd. Luis Encinas y Rosales S/N, Col. Centro, C.P. 83000, Hermosillo, Sonora.

³ Departamento de Ingeniería Química y Metalurgia, Universidad de Sonora. Blvd. Luis Encinas y Rosales S/N, Col. Centro, C.P. 83000, Hermosillo, Sonora.

* Correspondence: carmen.deltoro@unison.mx (C.L.D.-T.-S.)

Abstract: Cyclodextrin (CD) is made up of 7 glucose molecules linked in a ring, creating a cone shape. Its interior can house hydrophobic molecules while the exterior is hydrophilic enough to interact with water molecules. Until now, this feature has been used for the development of active and intelligent packaging applied to food, interacting with the product or its environment to improve one or more aspects of its quality or safety. As well, it is used to provide information on monitoring the time in which food is optimal for consumption, an aspect considered very important for the consumer and for the merchant. A known problem with some of these types of packaging is that the bioactive compounds that are housed in the CD can interact with food and can modify its taste, smell, color and/or texture. Therefore, this review will focus on discerning which packaging is most appropriate for each situation.

Keywords: cyclodextrin; smart packaging; intelligent packaging; active packaging; food additives; biopolymers; polysaccharide

1. Introduction

For some years now, and even faster with the passing of the pandemic (COVID-19), consumers have chosen to have food stored in their homes for easy access and, in case of an emergency, as a future food supply. Therefore, the time frame in which these packaged foods are no longer suitable for consumption is a concern [1,2,3]. Food packaging was developed to serve several purposes, such as limiting food loss and preserving food quality for longer periods. Its main functions can be summarized as protection against possible contaminations (acting as a barrier), containment, communicating package information about brands and nutritional content, and convenience to adapt to the fast-paced customer lifestyle [4].

Food placed in commercial containers are limited to just ease transportation and containment once it leaves the production plant, without worrying about the conditions in which they are stored inside and the state of the food with respect to time, showing a suggested consumption date and, sometimes, the appropriate temperature range [5]. This is where smart packaging (SP) comes in, which are technologies applied in the packaging system to extend shelf life and reduce food waste [6]. SP can be divided into two categories: active packaging (AP) and intelligent packaging (IP). AP interacts directly with the food, focusing on incorporating food additives to prevent or delay deterioration, considering factors of the food such as its respiration rate, humidity, and microbial attack, in order to maintain a remarkable quality by reacting against unfavorable components. On

the contrary, IP does not directly interact with the food, it only provides real-time information on the state of the food, indicating whether it is still optimal for consumption, working in the distribution chain at all times, from the industrial plant to the consumer's home [5].

Therefore, researchers and industries have focused on finding efficient ways to achieve this, designing them based on polymers, improving the characteristics of foods without affecting their sensory properties, synthesizing molecules with complex structures capable of stopping catalytic reactions or even slowing them down, and assembling with the 'problem molecules' by trapping them inside their cavity. This can be achieved, for example, with inclusion complexes, with a 'host' and a 'guest' molecule [7,8,9].

Inclusion complexes are aggregates of molecules stabilized via non-covalent bonds (for example, van der Waals, hydrogen bonds, and hydrophobic interactions) [10]. Host molecules are characterized by having an inner cavity where another molecule, usually referred to as "guest molecule" can be incorporated [11]. Therefore, hosts will act as receptors and guests as substrates, inhibitors, or cofactors [12]. The resulting molecular inclusion complex can easily break under determined physiological environments [13].

The application of these inclusion systems can improve the physicochemical properties of the molecules that are hosted in the cavity, such as solubility, dissolution, absorption, bioavailability, and biological activity [14,15].

A variety of inclusion complexes have been synthesized, amongst them, cyclodextrins, existing both modified and native, highlighting the latter as the most used [16].

Our article includes the most recent studies applied to the field of food packaging using the CD polymer, which has presented important applications. Over the last decades, important reviews such as Pereira et al. have developed [17] where they review the latest advances in the application of the CDs, as well as their current legislation. The main difference between their study and ours is that they focus on the general sensory qualities of all varieties, both native and modified, without indicating their direct (active packaging) or indirect (smart packaging) interaction with food and not highlighting disadvantages of their application.

Other more recent studies such as Zhou et al. [18] also does not highlight the organoleptic qualities enhanced by this packaging method. This study shines light on the improved properties of CD, as well as the differences in the applications of the two packaging methods (active and intelligent), discerning their application disadvantages.

2. Cyclodextrins

Cyclodextrins (CDs), as polymers, have piqued the interest of the scientific community due to their structural characteristics for which various applications have been found. CDs are cyclic oligosaccharide structures composed of α -1,4 D-glucopyranoside bonds that have a hydrophobic core inside and a hydrophilic outer surface due to the position of their hydroxyl groups [19,20,21]. They can be differentiated by the number of glucoses that present their α , β and γ structure. The main differences are found in Table 1. The main characteristic that distinguishes CDs is the property of being able to easily interact with water due to its hydrophilic surface, presenting good solubility, and the interior hydrophobic cavity forming inclusion complexes with molecules that are lipophilic [22,23,24,25].

In order to know which CD is the most apt to encapsulate a guest inside its cavity, the size of the cavity must first be evaluated to see if host-guest interaction is possible. α -CD has the smallest cavity, therefore it cannot accept some large molecules. γ -CD presents the largest cavity, being able to encapsulate larger molecules. α -CD and γ -CD present the highest solubilities in contrast to β -CD, which has an intermediate size cavity and a poor solubility compared to the first two (Table 1). However, the most widely used due to its encapsulation performance is β -CD, added to the fact that it can encapsulate molecules such as lipids, vitamins, and other hydrophobic compounds [26,27]. Furthermore, it results in having the greatest strength due to hydrogen bond interactions, which provides greater interaction strength with the host molecule, avoiding its early release upon application [28]. β -CD consists of 7 glucopyranose units in the shape of a truncated cone [29,30,31,32].

It has been widely used as an encapsulant or carrier of food additives because it improves the water solubility of the guest component, as well as its permeability, and provides stability to lipophilic compounds thanks to the hydroxyl groups that allow it to form hydrogen bonds (weak bonds), resulting in its nonpolar character [33,34,35,36,37].

Table 1. Main properties of the three native cyclodextrins. Created based on information from [38,39,40].

Physicochemical Properties	α -CD	β -CD	γ -CD
Chemical formula	C ₃₆ H ₆₀ O ₃₀	C ₄₂ H ₇₀ O ₃₅	C ₄₈ H ₈₀ O ₄₀
Glucose units	6	7	8
Molecular weight (<i>Da</i>)	972	1135	1297
Internal diameter (<i>nm</i>)	0.47-0.53	0.60-0.65	0.75-0.83
Outer diameter (<i>nm</i>)	1.46	1.54	1.75
Height of torus (<i>nm</i>)	0.79	0.79	0.79
Internal volume (<i>nm</i> ³)	0.174	0.262	0.427
Solubility in water at 25°C (mg/mL)	145	18.5	232
Internal water molecules	6-8	11-12	13-17

In this review, an overview of the published works about active and intelligent packaging involving CDs is provided, along with a discussion of the diverse applications given in the industry, highlighting the focus of each analyzed study as well as the enhanced property of the guest molecule. The review was based on articles published between - and 2023.

3. Solubility and toxicological considerations

CDs have high solubility in water because their hydrophilic outer part is polar, possessing the ability to form stable emulsions due to the difference in polarity with their cavity [22].

Solubility is a quality that can be attributed to CDs, making it a very important application option within packaging systems, since it can release hydrophobic host molecules found in its cavity in aqueous phase.

CDs have numerous uses in different industrial areas such as chemistry, pharmaceuticals, food, etc. In the pharmaceutical area, native and modified CDs have been utilized as a drug release system due to their high solubility, easy dilution, and to improve the physicochemical properties of the guest molecule, maintaining the conditions specified on the package, such as effectiveness and purity for established periods of time [41,42,43,44,45]. Considerable improvement in active pharmaceutical ingredients (APIs) have been observed, presenting greater solubility in water, effectiveness, physical and chemical stability [46]. Within the chemical industry, CDs have been used for some years to increase the solubility of hydrophobic molecules, such example are essential oils in perfumes [47]. Specifically for food, CDs have been employed to take care of the organoleptic properties, increasing the shelf life of products and partially, or completely, eliminating odors, flavors, and unwanted compounds. They are also applied as aroma stabilizers, as well as to increase the solubility of vitamins and lipids in aqueous systems [22,48,49,50,51,52]. In Figure 1, we can see some of the qualities most attributable to β -CD [53,54,55].

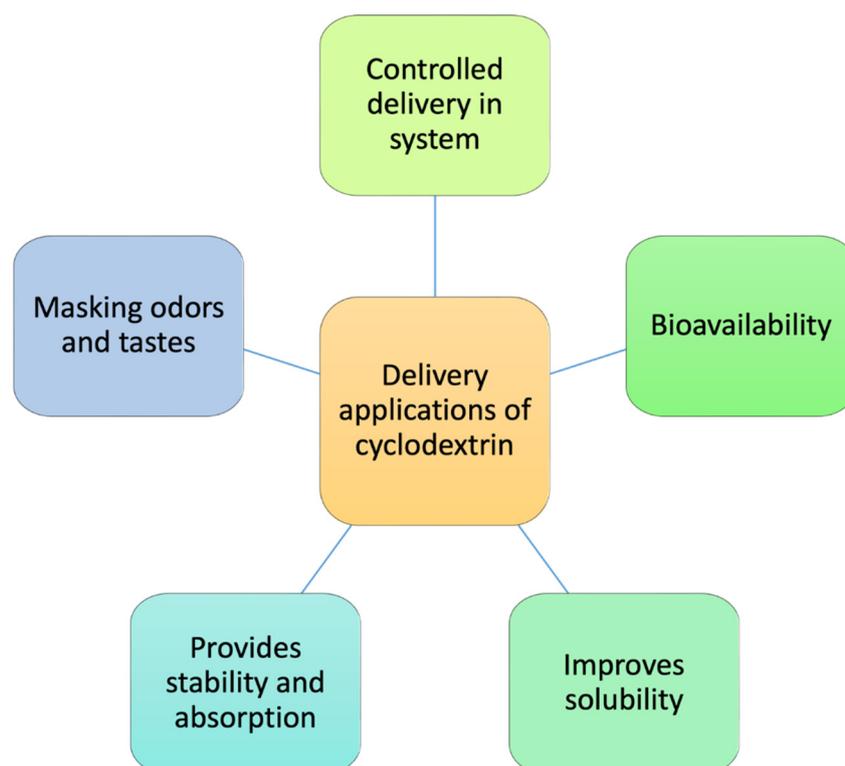


Figure 1. Main delivery applications of cyclodextrin.

These processes of entrapment of molecules with a hydrophobic character turn out to be reversible when the inclusion complex encounters a solvent. In response to this interaction, the molecules are released into the medium in which this solution is found [17].

Consequently, the CDs have obtained some recognition, namely their entry to the GRAS list (list of food additives by the Food and Drug Administration that recognizes them as safe) and their approval by the European Medicines Agency (EMA) which allows its commercialization with a certain degree of purity [56]. The World Health Organization (WHO) recommends a maximum level of 5 mg/kg per day for its use as a food additive. It is important to take this into account when devising an active container, which will be in contact with the food and could be ingested by the consumer. The Environmental Protection Agency (EPA) also ruled out the need to have maximum permissible levels for the residues of the 3 main native CDs (α , β and γ). Therefore, it is concluded that, according to all the available studies, CD presents an almost insignificant toxicity [57,58,59].

4. Formation of inclusion complexes

The formation of inclusion complexes has been studied using analytical techniques to know the possible structures that can be formed by encapsulation [60]. Inclusion complexes are formed when the host molecule, with the correct size for absorption, is positioned within the CD cavity. It should be mentioned that CD has the possibility of including both hydrophobic and hydrophilic molecules in its structure [40,54,61]. Once encapsulated, the hydrophobic molecule can increase its water solubility and bioavailability [62].

There are some parameters to consider before carrying out the encapsulation or packaging of the molecule inside the cavity of the CDs. The size of the cavity is essential to know if the host molecule could habituate in it. In Table 1 are the respective sizes for each native CD. In addition, it should also be considered that CDs crystallizes by two mechanisms, which depend on the guest molecule and the CDs that forms the complex. This will result in one of the categories of the crystal packing phenomenon resulting in channel or cage structures [40].

Inclusion complex formation is governed by the equilibrium association/dissociation constant for the host molecule, CDs, and inclusion complex. [63]. Because CDs are governed by weak interactions, it is possible for the encapsulated host to break free of the environment it is in without

much effort [40]. The higher the formation constant (K_f) for this reversible process (Figure 2), the more stable the inclusion complex will be and the less in favor of dissociation [35,38].

In the same way, the formation of inclusion complexes is also strongly affected by interaction forces such as hydrogen bonds, van der Waals forces and electrostatic and hydrophobic interactions [10,35,36]. In other words, to increase the entropy of the system, the water molecules located in the CDs cavity are displaced by the hydrophobic molecules to form an apolar-apolar association, achieving better energetic stability for the complex [34].

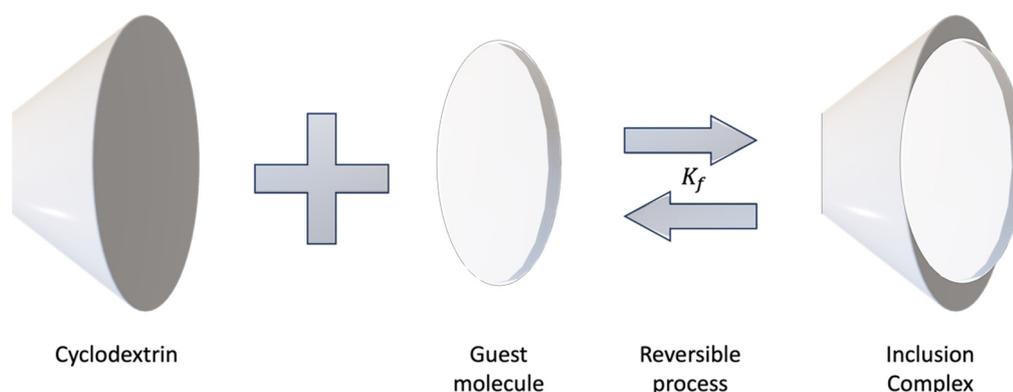


Figure 2. Schematic illustration of the formation of an inclusion complex.

4.1. Inclusion complex formation techniques

To know the appropriate encapsulation method, it is necessary to take into account the physicochemical properties of the host and guest molecule to increase the performance of the inclusion complex, as well as its release rate and bio-accessibility [64]. Mentioning some of the industrial techniques for their large-scale productions and low temperatures for their preparation, we can highlight spray drying, supercritical fluid and freeze drying. However, they present a high production cost and require more sophisticated equipment [38,65]. We also highlight two other techniques, the precipitation method and physical mixture (well known as kneading) being the most accessible at laboratory scale due to its simplicity and high performance [56,66], which we will detail below.

4.1.1. Precipitation method

It is the most widely used method due to the ease and efficiency it represents at the laboratory level. It is also used when the host molecule is insoluble in water. First, the CD is placed in an aqueous solution where it is heated until it dissolves in the medium, and, if the guest molecule withstands the dilution temperature of the CD, it is added at this moment. Subsequently, it is shaken to provoke the interaction between host and guest, which can be in refrigeration or in low temperatures. Lastly, the solution is decanted or filtered and dried to obtain the inclusion complex powder [18,40]. To mention some studies with this methodology, we can highlight the preparation of a container based on lutein and β -CD with possible application as IP or AP [67].

4.1.2. Physical mixture

It results in a simple method with low encapsulation yields in which a mass can be obtained instead of a fine powder. This method consists of adding a small amount of water to the host molecule to form a paste (slurry) followed by adding the guest molecule. Afterwards, kneading is applied until a uniform mixture is formed. The kneading time required will depend on the host molecule [40]. Some studies elaborated with this methodology: preparation of physical mixture from naringenin and β -CD in a mortar and refrigerated at 4°C [68], and the elaboration of nanocomposites from zein catechin/ β -cyclodextrin as AP. [69].

4.2. Characterization techniques

To confirm that the structure of an inclusion complex was formed, we can perform a characterization on the sample obtained. The most common chemical-structural characterizations are thermal analysis, Fourier transform infrared spectroscopy (FTIR), nuclear magnetic resonance (NMR), X-ray diffraction (XRD), (Figure 3) [62,70-76]. Observing any conformational change in the different chemical-structural studies, we can assume that a new polymer has been formed, better said, an inclusion complex (Table 2). Thanks to the inclusion complex formation properties of β -CD, we can generate different applications in food to provide protection to hydrophobic molecules (non-polar character) such as oils, vitamins, lipids, and fats, serving as smart or active packaging for these molecules.

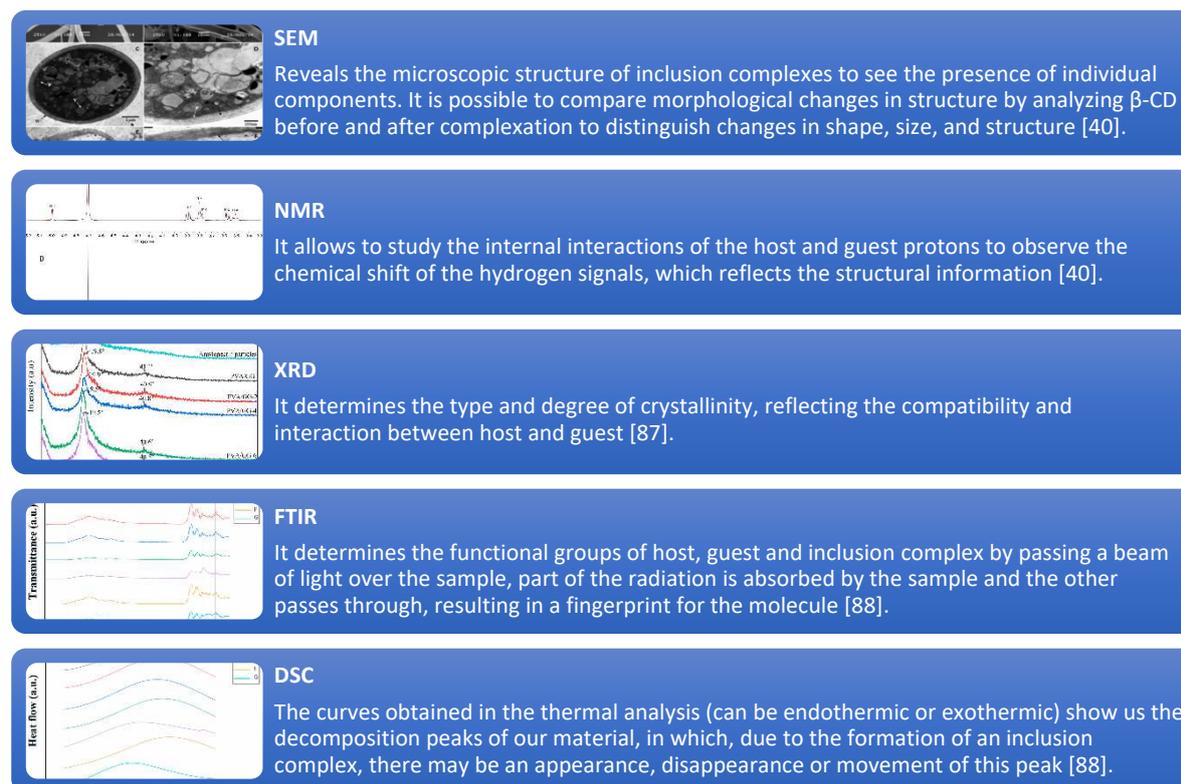


Figure 3. Characterization techniques to confirm the formation of a package.

Table 2. Most frequently used techniques for structural characterization.

CDs	Guest molecule	Technique	Results	References
β -	Curcumin	SEM, FT-IR, TGA, UV-vis spectra	SEM: pores disappeared attributed to CD. FT-IR: no new chemical bonds were broken or formed. TGA: didn't present water loss.	[62]
β -	Sage essential oil	FT-IR	FT-IR: peak attributed to SEO disappeared.	[75]
β -	Eucalyptus essential oil	FT-IR, DSC, TGA, SEM	FT-IR: blue-shifted. DSC & TGA: improve the stability of EEO and retard the volatilization. SEM: structure of particle has transformed, resulting in a smooth surface of the crystal structure	[80]

	p-Anisaldehyde		SEM: reduction in size and rhomboid crystals in shape. TGA: protection of the inclusion structure for the volatile compounds. FT-IR: peaks disappeared. XRD: new sharp peaks.	[81]
β -		SEM, XRD, TGA, FT-IR		
β - HP- β -	(-) borneol	DSC & TG, FT-IR, SEM, XRD, NMR	Comparative study. Promising results demonstrated by TG analysis.	[82]
β -	Rosemary essential oil	FT-IR, TGA-DSC	FT-IR: signal of the oil constituents appeared in the capsule spectrum. TGA-DSC: yeast reduction	[77]
β -	d-limonene	SEM, FT-IR (ATR), TGA, DSC	SEM: particles appeared homogeneously distributed. DSC: prevents the loss of the volatile essential oil.	[74]
β -	Ginger essential oil	SEM, DSC, TGA, FT-IR, XRD	FT-IR: red shift. XRD: disappearance and formation of diffraction peaks and the intensities changed.	[83]
β -	Peppermint oil	FT-IR	TGA: thermal protection for GEO. Confirmation of the formed structure.	[84]
β -	Concentrated orange oil	SEM, FT-IR	SEM: differences in shape and size. FT-IR: changes in spectra.	[85]
α	Benzyl isothiocyanate (BITC)	FT-IR, XRD	FT-IR: slight wavelength shifts XRD: formation of amorphous complex.	[86]
γ -	BITC, phenethyl isothiocyanate (PEITC), and 3-methylthiopropyl isothiocyanate (MTPITC)	FT-IR, TGA, XRD	TGA: elevated temperature required for the complete decomposition of ITCs. XRD: Sharp peaks appeared.	[87]
γ -	Watermelon flavor	SEM, FT-IR, DSC, XRD	SEM: particles smaller than CD. FT-IR: peaks of watermelon disappeared. DSC: higher temperature for evaporation.	[88]
γ -	thymol	SEM, XRD, FT-IR, NMR, DSC, TGA	TGA: improved by hydrogen bonding. XRD: characteristic diffraction peaks disappeared. SEM: smooth surface.	[89]

4.3. Effect on the guest properties

As we have seen, CDs are used to improve the stability of their guest molecules, promoting their resistance to temperature, light, oxygen, among others. It is because it provides protection against different factors, masks unwanted odors and flavors, and attributes to a prolonged release, that make it a viable option for an SP since it is presented as an alternative choice to solve food quality problems. In this way, food packaging plays an important role, mitigating food waste and caring in a certain way for the planet on which we live.

4.3.1. Protection

CDs are generally used to protect molecules in their cavity, including essential oils, lipids, vitamins, flavors, and colors [22]. In the same way, its protective function is not only based on caring for the attributes of food, but also protecting from molecules that are naturally included in food, an example of which is the removal of cholesterol from dairy products [90,91], where it was observed that it effectively removed cholesterol, obtaining efficiencies of over 95% for milk, cream, butter, and cottage cheese. Additionally, a decrease in Aflatoxin was found, which is a toxin present in these dairy products associated with the extraction by packaging of cholesterol, without affecting its textural properties.

Likewise, volatile phenols from wine [92]; where an instantaneous removal of 45 to 77% of the phenolic compounds present as unwanted odors in heavily tainted wines was obtained and mycotoxins such as alternariol (AOH) from cereals, tomatoes, grapes, and other susceptible fruits were removed by packaging this mycotoxin, which, with prolonged exposure, can cause cancer. β -CD, γ -CD and CD polymers were used to package this potentially damaging molecule. More stable complexes were formed with γ -CD presenting higher fluorescence [93]. It has also been found that β -CD-based AP presents effective protection to dry food products, demonstrating antimicrobial properties and delaying mold growth in wheat grains, maintaining their normal germination properties [94].

4.3.2. Taste modifications

When food is stored for long periods of time, their odors and flavors sometimes begin to decrease or become unpleasant. This is where CDs come in with their ability to encapsulate, stabilizing their smells and flavors, preserving for extended storage times, and protecting from heat treatments, such as freezing or thawing in microwaves, which can somewhat degrade food compounds. [40,95]. Some studies have used CDs packaging to enhance flavors or delay degradation. Such is the case of the use of β -CD, which resulted in the thermal stabilization of the formation of Amadori products and a decrease in the degradation constant, slowing down the appearance of brown-colored compounds and enhancing good flavors [96]. Likewise, determinations have been made to standardize the degrees of spiciness in sauces and other products, such is the case where an electrochemical sensor was built based on a multiwall of carbon nanotubes, incorporating β -CD/carboxylated, and having effective results thanks to the fact that the CD caused the dispersion of the nanotubes and achieving the detection of trace contents of capsaicinoids in soy sauce and meat products [97].

Another example of a study with good results is on the influence of yeasts and CD for preservation through the packaging of the bioactive compounds that give flavor to a red apple-based cider drink, where it was obtained that the β -CD significantly influenced packaging these compounds and achieving flavor retention of up to 18% during storage time [98].

5. Cyclodextrins in food packaging

There has been an unceasing interest for a long time in preventing food spoilage by increasing its shelf life and controlling spoilage reactions such as the action of polyphenol oxidase (PPO) and enzymatic browning reactions. This is why microbial inhibition mechanisms, among others, have been studied to increase the shelf life of food [70,71,99,100,101]. Many of the food containers commonly sold in convenience stores contain polymers derived from the petrochemical industry, which damages the food packaged in them and the environment, due to its difficulty to degrade [102]. This said, the development of more environmentally friendly packaging has become a necessity.

Consumers are currently looking for more natural and organic foods that meet specific characteristics including meeting their nutritional needs and being regarded as healthy. That is why scientists and researchers have focused on developing new technologies that meet these requirements, developing additives, treatments with modified atmospheres, and intelligent and active packaging techniques to preserve their nutritional value. Encapsulation is presented as an

advantage to meet the needs requested by consumers, being able to stabilize the compounds present in food that cause their degradation, oxidation and unpleasant flavors and odors, as well as to improve sensory quality. It is a technology for packaging solids, liquids, and gases to be released under specific conditions, considering that they can also be affected by external factors such as temperature, light, humidity, etc. [83].

Intelligent and active packaging are emerging technologies that are presented as a great potential option to erase the problem or somehow delay the deterioration of natural and everyday foods that are consumed further satisfying the needs that are constantly changing within the international market. The benefit of taking advantage of these packaging systems lie in prolonging the shelf life of food products, proving to be safe to consume, and at the same time, reducing food waste; managing to reduce negative environmental impacts [103]. An active packaging that comes into contact with food releases, emits, absorbs, or scavenges substances directly or indirectly into the food to maintain quality or delay degradation. Intelligent packaging is a type of packaging that acts as an indicator that provides information on the quality of the product without coming into direct contact with the food. It provides information to the consumer about the condition of packaged food using materials that monitor and interact with the environment of the package through an internal or external indicator.

It has been observed that when molecules are encapsulated in β -CD, not only do they increase their stability when subjected to light, temperature, and oxygen, but they also increase their organoleptic characteristics [72,104]. Likewise, multicomponent encapsulations are sometimes carried out using a third molecule that can increase the stability and interaction between the CD and the guest molecule [105,106].

5.1. Active packaging

Food packaging has an important role within the supply chain as a precursor in maintaining the integrity of food in perfect conditions and meets consumer demands for foods with higher quality standards [5,6]. Therefore, active packaging technology emerges as an application strategy to improve food safety [107]. Studies show that packaging with antimicrobial properties comes into contact with food, in order to reduce, slow down or inhibit the growth of microorganisms that damage food [108].

An example of this can be fruits. When fruits receive any cut or minimal processing, they begin to lose water, favoring microbial growth and oxidative reactions that generate bad-tasting compounds [109]. With this, interest has been aroused in the development of active packaging that stops the microbial attack of the fruit, as is the case of an intelligent packaging based on a film of polylactic acid (PLA) and β -cyclodextrin and allyl isothiocyanate inclusion complexes (AITC), where the results showed that the incorporation of a high concentration of this AP gave a more humid and polar surface in the PLA films, encouraging the diffusion of water through the matrix when it was immersed in a fat food simulant [73].

Like this essential oil, CDs have the ability to serve as a container for hydrophobic molecules such as lipids and vitamins [26]. Similar studies have been done with other CDs in order to supplement vitamins to people with diseases or disorders that do not allow the correct processing of hydrophobic compounds through active packages that increase their solubility. Such is the case of the deficiencies presented by people with fibrosis due to poor digestion, exhibiting insufficient vitamins coupled with poor absorption, therefore, they incorporated vitamin D3 and vitamin E to γ -CD, improving its bioavailability through its packaging [110].

In the same way, CDs have been used as active packaging with other nanoparticles as food preservatives that can alter the flavor of the same. Goñi et al improved the functionality of nanoparticles (NPs) with CDs, packaging sorbic acid (SA) and benzoic acid (BA) to be used as preservatives in food due to their antifungal and antibacterial properties, finding the association constants for this inclusion complex low. However, they obtained a high loading efficiency of these acids and had a prolonged release profile, thus achieving an inhibition system from the AP with CDs [111]. Likewise, packaging has been manufactured with β -CD and carbon quantum dots composite

nanoparticles (CQDs), improving not only the antioxidant activity but also increasing the efficiency of naringenin encapsulation. Checking the formation of the active container through chemical-structural characterization by XRD, finding the formation of the complex by the change from crystalline to amorphous structure, indicating that an AP based on CD is indeed formed.

Other molecules that present great antioxidant activity are carotenoids such as β -carotene, lycopene and lutein, which present instability and can often undergo isomerization and decomposition due to oxidation. With the help of CDs, this damage can be slowed down, encasing it in its interior cavity. In a study, an AP based on β -CD and lutein was performed, where it was guaranteed that the encapsulated lutein protected its antioxidant properties [67]. Other plant pigments, like carotenoids, are flavonoids, which also have antioxidant activity. However, their low solubility in aqueous phase limits them in the food field. In one study, γ -CD was used as a package to protect it from photo-oxidation. Thanks to its application, the solubility increased 100 times compared to the pure extract of quercetin, significantly improving its antioxidant activity, and resulting in greater inhibition of free radicals [112]. This opens up the possibilities of using the quercetin: γ -CD complex as active or smart packaging.

Mizera et al, developed composites made with linear low-density polyethylene (LLDPE) and β -CD:D-limonene, allowing to avoid the loss by evaporation of the volatile compounds of this terpene by subjecting it to high temperatures and mechanical shearing processes, allowing it to be used for its antibacterial properties. CDs have also been used to perform extractions of bioactive compounds due to the ability to encapsulate in their cavity, being able to act as a container [74]. Vhangani et al, used β -CD for the purpose of packaging raw green rooibo. It was shown that the increase in the concentration of β -CD improved the extraction yield of flavonoid polyphenols, which in turn increased the antioxidant activity. Moreover, when carrying out the packaging, higher temperatures could be applied in the extraction and avoiding the degradation of the polyphenols [113]. Likewise, essential oils have acquired their reputation for having good antioxidant activity, however, since they have high volatility and chemical instability, their applications in the food industry are limited.

Wu et al made an active packaging based on cinnamon essential oil (CEO) with five varieties of β -CD. In general, good control in its release was observed, increasing its antioxidant and antibacterial activity, presenting itself as an alternative for storage [101]. Encapsulation in modified CDs affects the solubility, stability, and bioactive properties of the packaged compounds in different ways, but in all the cases studied, the solubility of essential oils increased [114,115,116]. This demonstrates the protective role that CD plays as an active container for essential oils through encapsulation, protecting the antioxidant and antimicrobial properties, however, it is important to improve its poor solubility in aqueous phases, which limits its application in the food industry.

Christaki et al made an active package from sage essential oil (SEO) and β -CD, showing satisfactory values for encapsulation efficiency and correct inhibition for *S. aureus* and *L. monocytogenes* [75]. From these results, it is shown that it may have a possible application to extend the shelf life of food to stop microbial attack. Other guest molecules packaged in CDs with powerful chemical effects on resistant bacteria have been elaborated to verify their antibacterial properties and their possible application in the food sector.

Li et al packaged benzyl isothiocyanate (BITC) in β -CD, finding its great bactericidal effect on *Escherichia coli* and *Staphylococcus aureus*. Subsequently, it was evaluated on broccoli juice, demonstrating stability and controlled release by BITC [117]. It is important to find ways to mitigate microbial contamination of food as they represent a threat to the consumer. Until now, active packaging has been presented as a good option to control this problem [22]. Numerous investigations have been carried out on the applications of CDs, using them as active packaging, and thus improving sensory properties, extending shelf-life and pickering emulsions (Table 2).

An example of the latter is the one developed by Liu et al, where they made an active packaging based on β -CD and cinnamaldehyde (CA) to be applied to different types of oil. This AP was confirmed to have good storage stability, pleasant taste, lower malondialdehyde (MDA) content and antioxidant activity [118]. Foods that contain a higher amount of lipids can promote the faster formation of bad-tasting compounds and unwanted odors due to their ease of oxidation compared

to other foods. With this said, and knowing that CDs have this amphiphilicity ability, CD becomes a great option as a stabilizer for emulsions.

Another very common use of active packaging is as a coating or film for meat foods, where they are strongly influenced by their high moisture, fat, and protein content, resulting in strong microbial attack, and causing food spoilage [100,119]. Wu et al designed an antibacterial film based on an active packaging of curcumin and β -CD where they were able to extend the shelf life of chilled pork, inhibiting microbial growth and lipid oxidation during storage, likewise, there was a notable improvement in the coloring. This study lays the foundations for the application of this active packaging to other meat systems, preventing mass loss due to decomposition [100].

The preservation of food through an active packaging system is presented as an advantage to meet the needs of consumers, as well as reduce food waste, thus meeting the sustainable development goals (SDGs).

Table 3. Studies of cyclodextrins (CDs) as active packaging (AP).

Packaging	Enhanced properties	References
PLA/ β -CD:AITC	<ul style="list-style-type: none"> Increases solubility Increases absorption Increases releases rate 	[73]
LLDPE/ β -CD:D-limonene	<ul style="list-style-type: none"> Prevents the loss of the volatile compounds Antibacterial and antifungal activities Protects from oxidation Prolongs shelf-life one week 	[74]
PLA/ β -CD-thymol	<ul style="list-style-type: none"> Microbial inhibition Decreases in the weight loss Reduces changes in color 	[120]
CGRE: β -CD	<ul style="list-style-type: none"> Increases polyphenol content Protect against temperature 	[113]
SEO: β -CD	<ul style="list-style-type: none"> Microbial inhibition 	[75]
CA: β -CD	<ul style="list-style-type: none"> Increases solubility Antioxidant function Thermal stability Reduces microbial counts 	[118]
Curcumin: β -CD	<ul style="list-style-type: none"> Inhibit the lipid oxidase activity Extends storability Improves color 	[100]
CEO: β -CD	<ul style="list-style-type: none"> Increases antioxidant activity Increases antibacterial activity Inhibition of <i>S. aureus</i> and <i>E. coli</i> growth 	[101]
BITC: β -CD	<ul style="list-style-type: none"> Improves shelf-life Improves the stability and controlled release Flavor masking 	[117]
Chicken lipid: β -CD	<ul style="list-style-type: none"> Thermal and oxidative stability Stability in the fatty components 	[121]
Vitamin: γ -CD	<ul style="list-style-type: none"> Enhanced the bioavailability of vitamin D3 and E 	[110]
SA: β -CD/NPs	<ul style="list-style-type: none"> Loading efficiency 	[111]
BA: β -CD/NPs	<ul style="list-style-type: none"> Prolonged and sustained release profile 	[111]
Naringenin: β -CD/CQDs	<ul style="list-style-type: none"> Antioxidant properties Improves encapsulation efficiency 	[68]
Lutein: β -CD	<ul style="list-style-type: none"> Improves stability and bioavailability 	[67]
Quercetin: γ -CD	<ul style="list-style-type: none"> Improves solubility Enhanced the free radical scavenging ability 	[112]
CNC/zein:catechin: β -CD	<ul style="list-style-type: none"> Inhibits oxidation 	[69]

-
- Prolongs shelf-life
-

PLA: poly lactic acid; AITC: allyl isothiocyanate inclusion complexes; LLDPE: linear low-density polyethylene; CGRE: crude green rooibos extraction; SEO: sage essential oil; CA: cinnamaldehyde; CEO: cinnamon essential oil; BITC: benzyl isothiocyanate; SA: sorbic acid; BA: benzoic acid; CNC: cellulose nanocrystals.

5.2. Intelligent Packaging

Plastic materials have had a strong impact on the food packaging sector due to their low cost, durability, and different mechanical barrier properties (optical, rheological, transport) [122,123]. In addition, to mention a few examples, they promise, through food packaging, protection against oxidation, humidity, light and microbial contamination [124,125].

Food safety consists of keeping food away from unsafe conditions that endanger its safety. Food quality and safety greatly impact consumers, acting as indicators that guarantee the freshness of food. Since freshness is manifested as a need by consumers, it has become a priority. Because of this, different technologies have been developed to let the customer know that their food continues to preserve its original quality [126,127].

Intelligent packaging is an improvement on the traditional packaging of the food industry with implementations of sensors or indicators to inform the consumer of the state of the food, detecting changes in its initial conditions and indicating its state in real time [124,128,129]. In this way, consumers obtain a better shopping experience, avoiding spending on foods that do not meet their ideal characteristics, as well as preventing food waste. In general, consumers use the shelf-life information (expiry date) to determine the level of freshness and quality according to the proximity to this date embodied on the package [130]. However, some foods with a "best-before date", such as fruits, vegetables, and meat, are not as reliable due to the changes they experience since their production or harvest.

The main and only function of intelligent packaging, that act as sensors or indicators, is to measure any alteration of the initial conditions or conditions in which the food was offered to the consumer, responding to different stimuli, visualizing through the change in the intensity of a color scale and determining the presence or absence of foreign matter inside the container [131,132,133,134]. The indicators are added to the food packaging as a visible label that, according to the variations presented by the food, will indicate the quality status for consumption [5]. In intelligent packaging, we can highlight the application of CDs in some indicators or sensors: leak indicators, freshness indicators, pH indicators and electrochemical sensors (Table 2).

5.2.1. Leak indicators

These indicators or sensors show the quality of the food according to the atmosphere contained within the container. The alterations can be caused by enzymatic reactions of the food or by the diffusion of gases through the container wall, and there may be variations in the optimal concentrations for storage [135]. Within the food distribution chain, there is the possibility that the packaging may be damaged, and cracks may be generated that compromise its integrity and, therefore, affect the quality of the food. An example of this are foods that are susceptible to oxidation such as oils, vitamins, and lipids, impacting microbial growth and the appearance of unwanted odors and flavors. The reagents that give colorimetric scales as oxygen input indicators are the most commonly used, governed by oxidation-reduction reactions and having simple manufacturing processes.

Nevertheless, these reagents present a high instability because of their easy degradation in the presence of oxygen. Some of these indicators apply photocatalytic nanoparticles (NPs) to achieve the oxidation-reduction stability of some dyes such as methylene blue. Jarupatnadech et al, designed intelligent packaging based on chitosan and montmorillonite packed in β -CD with methylene blue/glucose. Methylene blue was reduced to its colorless form by glucose and turned blue on exposure to oxygen. Films based on these polymers demonstrated storage stability at low

temperatures, which makes them a great option for cold-stored food products, due to their effectiveness as colorimetric oxygen indicators [136].

5.2.2. Freshness indicators

There are two different types of freshness indicators, direct and indirect. As the name implies, direct freshness indicators detect analytes in the food to indicate its condition. The indirect ones are based on reactions triggered by the degradation of food due to factors such as time or temperature [5]. Zhang et al developed an intelligent film using PVA, β -CD and acylated anthocyanins. The PCRA film presented good mechanical properties, stability, and sensitivity to color change slightly lower than normal anthocyanins. However, the color of the PCRA film changed from pink to yellow/green, indicating that it can satisfactorily indicate beef freshness. In addition, they found a high correlation between the physical chemistry of meat and the information from the colorimetric film, which demonstrates its potential application as an intelligent sensor for meat foods [137]. PVA has also been used in a film as in the case of Lin et al, where they developed a SP based on PVA, chitosan in a container of curcumin: β -CD as a freshness indicator for the observation and maintenance of pork and shrimp. The intelligent packaging curcumin: β -CD improved the antioxidant and antibacterial activity, water vapor permeability and mechanical properties of the PVA/chitosan film. The results are promising for its potential application as intelligent packaging [138].

5.2.3. pH indicators

Compared to other intelligent packaging, colorimetric pH indicators turn out to be very accurate in providing deterioration and safety information [139,140]. These intelligent packaging present changes in their color scale when there is any alteration in the food [133]. An example of this are products with a high protein content such as meat, where microbial growth or oxidation can be triggered by contact with the environment, activating the intelligent pH packaging. Due to the activation with these characteristics, it is considered one of the best options as an intelligent indicator [141]. Eze et al developed a colorimetric film based on chitosan and broken riceberry. The results showed an increase in hydrophobicity, thermal stability, and antioxidant activity. In addition, an easily observable colorimetric response was obtained when it was applied to fresh shrimp, obtaining a change in color from red/orange to yellow, as a response to its deterioration, presenting itself as a feasible option for foods with similar conditions. When colorimetric pH indicators are manufactured, extracts with high phenol contents increase the detection of changes in pH and antioxidants [142]. Demonstrating that bioactive ingredients such as carotenoids, anthocyanins and chlorophylls possess strong antioxidant and antimicrobial activity. However, their application is difficult, since they present high instability under certain environmental conditions, being able to suffer oxidation or degradation by light [143].

Bakhshizadeh et al, developed an intelligent film based on chitosan nanofibre (CNF) and β -CD:corn poppy (CP) for monitoring shrimp deterioration. The addition of the intelligent packaging significantly reduced the water solubility from 96% to 42%. The results showed that, during storage, the film changed from coral to gold due to changes in pH (8.3 to 10.5) and the release of ammonium vapors due to protein decomposition. Demonstrating that this intelligent film could effectively be applied to marine products to monitor their shelf life [144].

5.2.4. Spoilage indicators

Microbial deterioration and the reactions of the food impact freshness because of metabolites that degrade the compounds present, producing off-flavors and sensory rejection. Wei et al developed a colorimetric sensor to detect the bacterium *Salmonella typhimurium* (*S. typhimurium*) from exadecyl trimethyl ammonium bromide (CTAB) and an intelligent packaging of β -CD:capped gold nanoparticles (β -CD-AuNPs). This results in supramolecular aggregation accompanied by a color change. In milk samples, the recovery was higher than 93%, which suggests its vital application in the food field [145]. Another type of optical sensors are biosensors, which send signals through a

receiver to be translated and give an electrical response. Sun et al designed an intelligent packaging based on 6G-adamantanamine and β -CD on a nonwoven polyethylene terephthalate (NPET) support, used as a sensor to measure food quality through an irreversible fluorescence change. β -CD, in addition to acting as the intelligent packaging for 6G-adamantanamine, also enhanced the fluorescence response.

5.2.5. Electrochemical sensors

The use of sensors in food is essential to avoid negative effects on the health of consumers. Electrochemical sensors determine the electro-activity of the analytes present in food that may be the cause of contamination. They are based on redox reactions on electrode surfaces, resulting in electrical signals [119,146].

Zhao et al developed a intelligent packaging with β -CD and ginkgo nut-derived porous carbon (GNDPC) to incorporate it into a glassy carbon electrode (GCE)-based lattice for the recovery of the pesticide methyl parathion (MP), designing an electrochemical sensor. β -CD increased the dispersibility of GNDPC and improved the recognition and accumulation capacity towards the MP. The synergy of this intelligent packaging showed a good absorption of this pesticide in apple and pear juices, with a recovery of more than 95% [147]. Also, Ahmadi et al designed an electrochemical sensor to identify food dyes in juices. β -CD and arginine were used with AuNPs on a gold electrode surface. The manufactured sensor showed selectivity to analyze the dyes in the presence of other agents that interfere with the signals. The mass transport mechanism was through diffusion and reaction, quasi-reversible. The data obtained from the different juices ensured the potential that the application of this methodology represents for the verification of modified drinks [148].

Electrochemical sensors have been incorporated for the detection of molecules because of their low manufacturing cost. For this reason, the incorporation of CDs into these types of sensors has been sought, trying to combine them with novel materials that present good synergy between them. Yun et al carried out an intelligent packaging applied to capsaicin based on GCE modified with β -CD accompanied by reduced graphene oxide (rGO). β -CD was found to have a higher degree of charge transfer. The packaging based on β -CD/rGO/GCE obtained a recovery of over 94% in the quantification of red pepper oil [149].

GCE has been used for different applications, including adsorbents for dye separation. In addition, they present excellent electrical and mechanical properties, which provides stability to the compounds that are applied on it [150]. Chen et al designed a conductive molecularly imprinted gel (CMIG) using cationic guar gum (CGG), chitosan β -CD and multiwalled carbon nanotubes (MWCNTs) by magnetic stirring in a single vessel at low temperature. β -CD enhanced the adsorption of CMIG. Subsequently, the CMIG was brought into contact with a GCE surface. AM extraction was carried out on samples of powdered milk and white vinegar, and recoveries greater than 88% were obtained. This research demonstrated the correct application of an electrochemical sensor, which could be used to detect other agents [151].

The use of MWCNTs, compared to other nanocarriers, are more highly effective for the release of compounds, due to their physical chemical properties [152]. An example of this is the study carried out by Gu et al where they created an electrochemical sensor with β -CD and MWCNTs to determine the content of capsaicinoids in soy sauce and meat. The results showed that β -CD played a very important role in causing the dispersal of MWCNTs on the GCE surface. The recovery rates were higher than 83%, showing the correct application for detection of trace remains [97]. Similarly, Avan and Filik designed an intelligent packaging to detect vitamins (A, D3, E and K) in aqueous media of micellar solutions, based on MWCNTs, β -CD and GCE, where it was found that β -CD due to the interaction with MWCNTs presented high selectivity for soluble vitamins [153].

Table 4. Studies of cyclodextrins (CDs) as intelligent packaging (AP).

Packaging	Sensor	Indicator	References
Chitosan/montmorillonite: β -CD	Oxygen	Colorimetric (changing the color from colorless to blue)	[136]

CNF/CP: β -CD	pH	Colorimetric (changing the color from coral to gold)	[144]
PVA/ β -CD/acylated roselle anthocyanin	Freshness	Colorimetric	[137]
Chitosan/PVA/curcumin: β -CD	Freshness	Colorimetric	[138]
Rhodamine 6G-adamantamine and β -CD	Shelf-life	Fluorescence	[154]
GCE/GNDPC: β -CD	Electrochemical	Recovery (MP)	[147]
Chitosan/cation guar gum/MWCNTs/ β -CD/GCE	Electrochemical	Recovery (amaranth)	[151]
MWCNTs/ β -CD/GCE	Electrochemical	Recovery (capsaicin)	[97]
MWCNTs/ β -CD/GCE	Electrochemical	Quantification (vitamins)	[153]
β -CD:AuNPs	Spoilage	Colorimetric	[145]
rGO/GCE/ β -CD	Electrochemical	Quantification (capsaicin)	[149]
AuNPs: β -CD/arginine	Electrochemical	Quantification (colorant)	[148]

CP: corn poppy; CNF: chitosan nanofiber; PVA: polyvinyl alcohol; MP: methyl parathion; GCE: glassy carbon electrode; GNDPC: ginkgo nut-derived porous carbon; MWCNTs: multi-walled carbon nanotubes; AuNPs: capped gold nanoparticles.

6. Conclusion and future trends

The widespread use of CD as packaging in food systems has generated many technological advances in the industry in recent years. The improvement of the organoleptic properties of food is an indisputable advantage provided by the well-defined structure of CD. Thanks to its stoichiometric arrangement, it allows it to combine with different molecules, improving its characteristics without altering its function.

The potential application lies in its ability to protect the guest molecules that are housed in its cavity, increasing its shelf life by acting as a stabilizing packaging and protecting the compounds from external factors such as decomposition due to temperature, oxidation, and photosensitivity. Additionally, this container based on the CD polymer acts as a transport medium, increasing the solubility of the encapsulated compounds, allowing them to be stably used as dry powders. Among other qualities present in CD, they are most responsible for improving the sensory quality of food, hiding unwanted odors and flavors. In addition, they reduce the effects of evaporation, delay the action of compounds that change food coloration, and thus deliver friendlier flavors to consumers.

Furthermore, it can still have adverse effects related to kidney failure due to its irritant effect. However, its toxicity remains low, and it is accepted by international organizations in charge of human health and govern the use of additives. Therefore, it is applied in low concentrations both in the food and pharmaceutical fields, since the qualities that offers this type of packaging are higher. As a result of this, healthier and more functional products are obtained, being an option to consider when you want to improve properties in the food, pharmaceutical, chemical, cosmetic, and textile industries, among others. The opportunities that CD can have in the food industry are remarkable and copious, as consumers demand ever higher standards, and companies compete to improve their products to deliver higher quality.

Author Contributions: Conceptualization, R.D.I.-G., F.R.-F. and J.D.F.-Q; writing—original draft preparation, A.L.P.-D.; writing—review and editing, I.D.P.-C.; supervision, C.L.D.-T.-S. and I.S.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Andrés Leobardo Puebla Duarte acknowledges the Consejo Nacional de Humanidades, Ciencias y Tecnologías (CONAHCyT, Mexico) for a Master scholarship.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Accorsi, R.; Manzini, R. (Eds.) Modeling inclusive food supply chains toward sustainable ecosystem planning. In *Sustainable Food Supply Chains*; Academic Press: Dordrecht, The Netherlands, 2019; pp. 1–21.
2. Haji, M.; Kerbache, L.; Al-Ansari, T. Food Quality, Drug Safety, and Increasing Public Health Measures in Supply Chain Management. *Processes* 2022, 10, 1715.
3. Huang, J.; Zhang, M.; Fang, Z. Perspectives on Novel Technologies of Processing and Monitoring the Safety and Quality of Prepared Food Products. *Foods* 2023, 12, 3052.
4. Han, J. W., Ruiz-Garcia, L., Qian, J. P., & Yang, X. T. (2018). Food Packaging: A Comprehensive Review and Future Trends. In *Comprehensive Reviews in Food Science and Food Safety* (Vol. 17, Issue 4, pp. 860–877). Blackwell Publishing Inc.
5. Alam, A.U.; Rathi, P.; Beshai, H.; Sarabha, G.K.; Deen, M.J. Fruit Quality Monitoring with Smart Packaging. *Sensors* 2021, 21, 1509.
6. Stramarkou, M.; Boukouvalas, C.; Koskinakis, S.E.; Serifi, O.; Bekiris, V.; Tsamis, C.; Krokida, M. Life Cycle Assessment and Preliminary Cost Evaluation of a Smart Packaging System. *Sustainability* 2022, 14, 7080.
7. Da Hu, Q.; Tang, G.P.; Chu, P.K. Cyclodextrin-based host-guest supramolecular nanoparticles for delivery: From design to applications. *Acc. Chem. Res.* 2014, 47, 2017–2025.
8. Matencio, A.; Navarro-Orcajada, S.; García-Carmona, F.; López-Nicolás, J.M. Applications of cyclodextrins in food science. A review. *Trends Food Sci. Technol.* 2020, 104, 132–143.
9. Astray, G.; Mejuto, J.C.; Simal-Gandara, J. Latest developments in the application of cyclodextrin host-guest complexes in beverage technology processes. *Food Hydrocoll.* 2020, 106, 105882.
10. Liu, H.-N.; Jiang, X.-X.; Naeem, A.; Chen, F.-C.; Wang, L.; Liu, Y.-X.; Li, Z.; Ming, L.-S. Fabrication and Characterization of β -Cyclodextrin/Mosla Chinensis Essential Oil Inclusion Complexes: Experimental Design and Molecular Modeling. *Molecules* 2023, 28, 37.
11. Bortolus, P.; Grabner, G.; Köhler, G.; Monti, S. Photochemistry of cyclodextrin host-guest complexes. *Coord. Chem. Rev.* 1993, 125, 261–268.
12. Cram, D.J.; Cram, J.M. Host-Guest Chemistry. *Science* 1974, 183, 803–809.
13. Lehn, J.M. Supramolecular chemistry: Receptors, catalysts, and carriers. *Science* 1985, 227, 849–856.
14. Aiassa, V.; Garnero, C.; Zoppi, A.; Longhi, M.R. Cyclodextrins and Their Derivatives as Drug Stability Modifiers. *Pharmaceuticals* 2023, 16, 1074.
15. Mazurek, A.H.; Szeleszczuk, Ł. A Review of Applications of Solid-State Nuclear Magnetic Resonance (ssNMR) for the Analysis of Cyclodextrin-Including Systems. *Int. J. Mol. Sci.* 2023, 24, 3648.
16. Stella, V.J.; Rajewski, R.A. Sulfobutylether- β -cyclodextrin. *Int. J. Pharm.* 2020, 583, 119396.
17. González Pereira, A. ; Carpena, M. ; García Oliveira, P. ; Mejuto, J.C. ; Prieto, M.A. ; Simal Gandara, J. Principales aplicaciones de las ciclodextrinas en la industria alimentaria como los compuestos de elección para formar complejos huésped-invitado. *Int. J. Mol. Sci.* 2021, 22, 1339.
18. Zhou, J.; Jia, J.; He, J.; Li, J.; Cai, J. Cyclodextrin Inclusion Complexes and Their Application in Food Safety Analysis: Recent Developments and Future Prospects. *Foods* 2022, 11, 3871.
19. Jansook, P.; Ogawa, N.; Loftsson, T. Cyclodextrins: Structure, physicochemical properties and pharmaceutical applications. *Int. J. Pharm.* 2018, 535, 272–284.
20. Munoz-Shuguli, C.; Vidal, C.P.; Cantero-Lopez, P.; Lopez-Polo, J. Encapsulation of plant extract compounds using cyclodextrin inclusion complexes, liposomes, electrospinning and their combinations for food purposes. *Trends Food Sci. Technol.* 2021, 108, 177–186.
21. Chizhov, A.O.; Tsvetkov, Y.E.; Nifantiev, N.E. Gas-Phase Fragmentation of Cyclic Oligosaccharides in Tandem Mass Spectrometry. *Molecules* 2019, 24, 2226.
22. Szente, L.; Szejtli, J. Cyclodextrins as food ingredients. *Trends Food Sci. Technol.* 2004, 15, 137–142.
23. van der Veen, B.A.; Uitdehaag, J.C.M.; Penninga, D.; van Alebeek, G.; Smith, L.M.; Dijkstra, B.W.; Dijkhuizen, L. Rational design of cyclodextrin glycosyltransferase from *Bacillus circulans* strain 251 to increase alpha-cyclodextrin production. *J. Mol. Biol.* 2000, 296, 1027–1038.
24. Messner, M.; Kurkov, S.V.; Flavia-Piera, R.; Brewster, M.E.; Loftsson, T. Self-assembly of cyclodextrins: The effect of the guest molecule. *Int. J. Pharm.* 2011, 408, 235–247.
25. Wang, X.; Luo, Z.; Xiao, Z. Preparation, Characterization, and Thermal Stability of β -Cyclodextrin/Soybean Lecithin Inclusion Complex. *Carbohydr. Polym.* 2014, 101, 1027–1032.

26. Braithwaite, M.C.; Kumar, P.; Choonara, Y.E.; du Toit, L.C.; Tomar, L.K.; Tyagi, C.; Pillay, V. A novel multi-tiered experimental approach unfolding the mechanisms behind cyclodextrin-vitamin inclusion complexes for enhanced vitamin solubility and stability. *Int. J. Pharm.* 2017, 532, 90–104.
27. Szente, L.; Fenyvesi, É. Cyclodextrin-Enabled Polymer Composites for Packaging. *Molecules* 2018, 23, 1556.
28. Li, Z.; Chen, S.; Gu, Z.; Chen, J.; Wu, J. Alpha-cyclodextrin: Enzymatic production and food applications. *Trends Food Sci. Technol.* 2014, 35, 151–160.
29. Samuelsen, L.; Holm, R.; Schönbeck, C. Simultaneous Determination of Cyclodextrin Stability Constants as a Function of pH and Temperature—A Tool for Drug Formulation and Process Design. *J. Drug Deliv. Sci. Technol.* 2021, 65, 102675.
30. Wei, X.; Yu, C.-Y.; Wei, H. Application of Cyclodextrin for Cancer Immunotherapy. *Molecules* 2023, 28, 5610.
31. Murrieta-Rico, F.N.; Yocupicio-Gaxiola, R.I.; Antúnez-García, J.; Reyes-Serrato, A.; Sánchez, P.; Petranovskii, V. Textile Functionalization Using LTA and FAU Zeolitic Materials. *Polymers* 2022, 15, 99.
32. Sadjadi, S.; Koohestani, F. Composite of β -cyclodextrin and bentonite clay: A promising support for Pd immobilization and developing a catalyst for hydrogenation of nitroarenes under mild reaction condition. *J. Phys. Chem. Solids* 2021, 151, 109894.
33. Loftsson, T.; Brewster, M.E. Pharmaceutical Applications of Cyclodextrins: Basic Science and Product Development. *J. Pharm. Pharmacol.* 2010, 62, 1607–1621.
34. Păduraru, D.N.; Niculescu, A.G.; Bolocan, A.; Andronic, O.; Grumezescu, A.M.; Bîrlă, R. An Updated Overview of Cyclodextrin-Based Drug Delivery Systems for Cancer Therapy. *Pharmaceutics* 2022, 14, 1748.
35. Crini, G.; Fourmentin, S.; Fenyvesi, É.; Torri, G.; Fourmentin, M.; Morin-Crini, N. Fundamentals and applications of cyclodextrins. In *Cyclodextrin Fundamentals, Reactivity and Analysis*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 1–55.
36. Řezanka, M. Synthesis of cyclodextrin derivatives. In *Cyclodextrin Fundamentals, Reactivity and Analysis*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 57–103.
37. Leclercq, L. Interactions between cyclodextrins and cellular components: Towards greener medical applications? *Beilstein J. Org. Chem.* 2016, 12, 2644–2662.
38. Liu, Y.; Chen, Y.N.; Gao, X.L.; Fu, J.J.; Hu, L.D. Application of cyclodextrin in food industry. *Crit. Rev. Food Sci. Nutr.* 2022, 62, 2627–2640.
39. Szejtli, J. Introduction and general overview of cyclodextrin chemistry. *Chem. Rev.* 1998, 98, 1743–1754.
40. Del Valle, E.M.M. Cyclodextrins and their uses: A review. *Process Biochem.* 2004, 39, 1033–1046.
41. Rehman, Q.; Akash, M.S.H.; Imran, I.; Rehman, K. Stability of Pharmaceutical Products. In *Drug Stability and Chemical Kinetics*; Akash, M.S.H., Rehman, K., Eds.; Springer: Singapore, 2020; pp. 147–154. ISBN 978-981-15-6426-0.
42. Loftsson, T. Introduction. In *Drug Stability for Pharmaceutical Scientists*; Loftsson, T., Ed.; Academic Press: New York, NY, USA, 2014; pp. 1–3. ISBN 9780124115484.
43. Przybyła, M.A.; Yilmaz, G.; Becer, C.R. Natural cyclodextrins and their derivatives for polymer synthesis. *Polym. Chem.* 2020, 11, 7582–7602.
44. Jambhekar, S.S.; Breen, P. Cyclodextrins in pharmaceutical formulations II: Solubilization, binding constant, and complexation efficiency. *Drug Discov. Today* 2016, 21, 363–368.
45. Lachowicz, M.; Stańczak, A.; Kołodziejczyk, M. Characteristic of Cyclodextrins: Their Role and Use in the Pharmaceutical Technology. *Curr. Drug Targets* 2020, 21, 1495–1510.
46. Saokham, P.; Muankaew, C.; Jansook, P.; Loftsson, T. Solubility of cyclodextrins and drug/cyclodextrin complexes. *Molecules* 2018, 23, 1161.
47. De Marco, I.; Franco, P. Effect of the Carrier on the Coprecipitation of Curcumin through Supercritical-Assisted Atomization. *ChemEngineering* 2021, 5, 59.
48. Linde, G.A.; Laverde, A.; Colauto, N.B. Changes to Taste Perception in the Food Industry: Use of Cyclodextrins. In *Handbook of Behavior, Food and Nutrition*; Preedy, V.R., Watson, R.R., Martin, C.R., Eds.; Springer: Berlin/Heidelberg, Germany, 2011; pp. 99–118.
49. Blanch, G.P.; Ruiz del Castillo, M.L.; del Mar Caja, M.; Pérez-Méndez, M.; Sánchez-Cortés, S. Stabilization of all-trans-lycopene from tomato by encapsulation using cyclodextrins. *Food Chem.* 2007, 105, 1335–1341.
50. Andreu-Sevilla, A.J.; López-Nicolás, J.M.; Carbonell-Barrachina, Á.A.; García-Carmona, F. Comparative Effect of the Addition of α -, β -, or γ -Cyclodextrin on Main Sensory and Physico-Chemical Parameters. *J. Food Sci.* 2011, 76, S347–S353.

51. Dos Santos, C.; Buera, P.; Mazzobre, F. Novel trends in cyclodextrins encapsulation. Applications in food science. *Curr. Opin. Food Sci.* 2017, 16, 106–113.
52. Irie, T.; Uekama, K. Pharmaceutical applications of cyclodextrins. III. Toxicological issues and safety evaluation. *J. Pharm. Sci.* 1997, 86, 147–162.
53. Krawczyk, K.; Silvestri, D.; Nguyen, N.H.; Ševců, A.; Łukowiec, D.; Padil, V.V.; Řezanka, M.; Černík, M.; Dionysiou, D.D.; Waclawek, S. Enhanced degradation of sulfamethoxazole by a modified nano zero-valent iron with a β -cyclodextrin polymer: Mechanism and toxicity evaluation. *Sci. Total Environ.* 2022, 817, 152888.
54. Jumah, M.N.B.; Eid, M.H.; AL-Huqail, A.A.; Mohammad, M.A.; Bin-Murdhi, N.S.; Abu-Taweel, G.M.; Altoom, N.; Allam, A.A.; AbuKhadra, M.R. Enhanced remediation of As (V) and Hg (II) ions from aqueous environments using β -cyclodextrin/MCM-48 composite: Batch and column studies. *J. Water Process. Eng.* 2021, 42, 102118.
55. Paramita, V.; Novia, S.F.; Ariyanto, H.D.; Pramudono, B.; Yoshii, H.; Kusumayanti, H.; Amalia, R. The influence of α -cyclodextrin on the stability and fatty acids of medium-chain triglycerides high oil load nanoemulsion. *Mater. Today: Proc.* 2022, 63, S312–S317.
56. Cid-Samamed, A.; Rakmai, J.; Mejuto, J.C.; Simal-Gandara, J.; Astray, G. Cyclodextrins inclusion complex: Preparation methods, analytical techniques and food industry applications. *Food Chem.* 2022, 384, 132467.
57. Astray, G.; Gonzalez-Barreiro, C.; Mejuto, J.C.; Rial-Otero, R.; Simal-Gandara, J. A review on the use of cyclodextrins in foods. *Food Hydrocoll.* 2009, 23, 1631–1640.
58. Mortensen, A.; Aguilar, F.; Crebelli, R.; Di Domenico, A.; Dusemund, B.; Frutos, M.J.; Galtier, P.; Gott, D.; Gundert-Remy, U.; Leblanc, J.; et al. Re-evaluation of β -cyclodextrin (E 459) as a food additive. *EFSA J.* 2016, 14, e04628.
59. Munro, I.C.; Newberne, P.M.; Young, V.R.; Bär, A. Safety assessment of γ -cyclodextrin. *Regul. Toxicol. Pharmacol.* 2004, 39, 3–13.
60. Mura, P. Analytical Techniques for Characterization of Cyclodextrin Complexes in Aqueous Solution: A Review. *J. Pharm. Biomed. Anal.* 2014, 101, 238–250.
61. Jiang, Y.; Abukhadra, M.R.; Refay, N.M.; Sharaf, M.F.; El-Meligy, M.A.; Awwad, E.M. Synthesis of chitosan/MCM-48 and β -cyclodextrin/MCM-48 composites as bio-adsorbents for environmental removal of Cd²⁺ ions; kinetic and equilibrium studies. *React. Funct. Polym.* 2020, 154, 104675.
62. Chen, L.; Dong, Q.; Shi, Q.; Du, Y.; Zeng, Q.; Zhao, Y.; Wang, J.J. Novel 2,3-Dialdehyde Cellulose-Based Films with Photodynamic Inactivation Potency by Incorporating the β -Cyclodextrin/Curcumin Inclusion Complex. *Biomacromolecules* 2021, 22, 2790–2801.
63. Muankaew, C.; Loftsson, T. Cyclodextrin-based formulations: A non-invasive platform for targeted drug delivery. *Basic Clin. Pharmacol. Toxicol.* 2018, 122, 46–55.
64. Novac, M.; Musuc, A.M.; Ozon, E.A.; Sarbu, I.; Mitu, M.A.; Rusu, A.; Petrescu, S.; Atkinson, I.; Gheorghe, D.; Lupuliasa, D. Design and Evaluation of Orally Dispersible Tablets Containing Amlodipine Inclusion Complexes in Hydroxypropyl- β -cyclodextrin and Methyl- β -cyclodextrin. *Materials* 2022, 15, 5217.
65. Hernandez-Sanchez, P.; Lopez-Miranda, S.; Guardiola, L.; Serrano-Martinez, A.; Gabaldon, J.A.; Nunez-Delgado, E. Optimization of a method for preparing solid complexes of essential clove oil with beta-cyclodextrins. *J. Sci. Food Agric.* 2017, 97, 420–426.
66. Jiang, L.W.; Yang, J.D.; Wang, Q.; Ren, L.; Zhou, J. Physicochemical properties of catechin/beta-cyclodextrin inclusion complex obtained via co-precipitation. *CyTA-J. Food* 2019, 17, 544–551.
67. Shi, Z.; Kong, G.; Wang, F.; Gao, H.; Wei, A.; Ren, S.; Yan, X. Improvement in the stability and bioavailability of pumpkin lutein using β -cyclodextrin microcapsules. *Food Sci Nutr* 2023, 11(6):3067-3074.
68. Liang Y, Hou D, Ni Z, Cao M, Cai L. Preparation, characterization of naringenin, β -cyclodextrin and carbon quantum dot antioxidant nanocomposites. *Food Chem* 2022, 375:131646.
69. Jiang, L.; Han, Y.; Meng, X.; Xiao, Y.; Zhang, H. Cellulose Nanocrystals Reinforced Zein/Catechin/ β -Cyclodextrin Inclusion Complex Nanoparticles Nanocomposite Film for Active Food Packaging. *Polymers* 2021, 13, 2759.
70. Salazar Sandoval, S.; Bruna, T.; Maldonado-Bravo, F.; Bolaños, K.; Adasme-Reyes, S.; Riveros, A.; Caro, N.; Yutronic, N.; Silva, N.; Kogan, M.J.; et al. β -Cyclodextrin Nanosponges Inclusion Compounds Associated with Silver Nanoparticles to Increase the Antimicrobial Activity of Quercetin. *Materials* 2023, 16, 3538.
71. Farouk, A.; Sharaf, S.; Refaie, R.; Abd El-Hady, M.M. Highly Durable Antibacterial Properties of Cellulosic Fabric via β -Cyclodextrin/Essential Oils Inclusion Complex. *Polymers* 2022, 14, 4899.

72. Wang, H.; Hu, L.; Peng, L.; Du, J.; Lan, M.; Cheng, Y.; Ma, L.; Zhang, Y. Dual encapsulation of β -carotene by β -cyclodextrin and chitosan for 3D printing application. *Food Chem.* 2022, 378, 132088.
73. Muñoz-Shugulí, C.; Rodríguez-Mercado, F.; Benbettaieb, N.; Guarda, A.; Galotto, M.J.; Debeaufort, F. Development and Evaluation of the Properties of Active Films for High-Fat Fruit and Vegetable Packaging. *Molecules* 2023, 28, 3045.
74. Dobrzyńska-Mizera, M.; Knitter, M.; Piss, M.; Del Barone, C.; Mallardo, S.; Santagata, G.; Di Lorenzo, M.L. Thermal and Morphological Analysis of Linear Low-Density Polyethylene Composites Containing d-limonene/ β -cyclodextrin for Active Food Packaging. *Molecules* 2023, 28, 1220.
75. Christaki, S.; Kelesidou, R.; Pargana, V.; Tzimopoulou, E.; Hatzikamari, M.; Mourtzinou, I. Inclusion Complexes of β -Cyclodextrin with *Salvia officinalis* Bioactive Compounds and Their Antibacterial Activities. *Plants* 2023, 12, 2518.
76. Li, W.; Liu, X.; Yang, Q.; Zhang, N.; Du, Y.; Zhu, H. Preparation and characterization of inclusion complex of benzyl isothiocyanate extracted from papaya seed with β -cyclodextrin. *Food Chem.* 2015, 184, 99–104.
77. Garcia-Sotelo, D.; Silva-Espinoza, B.; Perez-Tello, M.; Olivas, I.; Alvarez-Parrilla, E.; González-Aguilar, G.A.; Ayala-Zavala, J.F. Antimicrobial activity and thermal stability of rosemary essential oil: β -cyclodextrin capsules applied in tomato juice. *LWT* 2019, 111, 837–845.
78. Liu, D.; Zhong, Y.; Pu, Y.; Li, X.; Chen, S.; Zhang, C. Preparation of pH-Responsive Films from Polyvinyl Alcohol/Agar Containing Cochineal for Monitoring the Freshness of Pork. *Foods* 2023, 12, 2316.
79. Liu, F.; Yu, Z.; Wang, B.; Chiou, B.-S. Changes in Structures and Properties of Collagen Fibers during Collagen Casing Film Manufacturing. *Foods* 2023, 12, 1847.
80. Ren, X.; Yue, S.; Xiang, H.; Xie, M. Inclusion complexes of eucalyptus essential oil with β -cyclodextrin: Preparation, characterization and controlled release. *J. Porous Mater.* 2018, 25, 1577–1586.
81. Lin, Y.; Huang, R.; Sun, X.; Yu, X.; Xiao, Y.; Wang, L.; Hu, W.; Zhong, T. The p-Anisaldehyde/ β -cyclodextrin inclusion complexes as a sustained release agent: Characterization, storage stability, antibacterial and antioxidant activity. *Food Control* 2022, 132, 108561.
82. Santana, D.V.S.; Trindade, I.A.S.; Carvalho, Y.M.B.G.; Carvalho-Neto, A.G.; Silva, E.C.D.; Silva-Júnior, E.F.; Leite, R.F.S.; Quintans-Júnior, L.J.; Aquino, T.M.; Serafini, M.R.; et al. Analytical techniques to recognize inclusion complexes formation involving monoterpenes and cyclodextrins: A study case with (–) borneol, a food ingredient. *Food Chem.* 2021, 339, 127791.
83. Zhang, Y.; Zhang, H.; Wang, F.; Wang, L.-X. Preparation and Properties of Ginger Essential Oil β -Cyclodextrin/Chitosan Inclusion Complexes. *Coatings* 2018, 8, 305.
84. Grgac, S.F.; Jablan, J.; Inić, S.; Malinar, R.; Kovaček, I.; Čorak, I. The Effect of Ultrasonic Treatment on the Binding of the Inclusion Complex β -Cyclodextrin-peppermint Oil with Cellulose Material. *Materials* 2022, 15, 470.
85. Torres-Alvarez, C.; Castillo, S.; Sánchez-García, E.; Aguilera González, C.; Galindo-Rodríguez, S.A.; Gabaldón-Hernández, J.A.; Báez-González, J.G. Inclusion Complexes of Concentrated Orange Oils and β -Cyclodextrin: Physicochemical and Biological Characterizations. *Molecules* 2020, 25, 5109.
86. Wu, H.; Ao, X.; Liu, J.; Zhu, J.; Bi, J.; Hou, H.; Hao, H.; Zhang, G. A Bioactive Chitosan-Based Film Enriched with Benzyl Isothiocyanate/ α -Cyclodextrin Inclusion Complex and Its Application for Beef Preservation. *Foods* 2022, 11, 2687.
87. Liu, J.; Wu, H.; Ao, X.; Hao, H.; Bi, J.; Hou, H.; Zhang, G. Characterization of the Inclusion Complexes of Isothiocyanates with γ -Cyclodextrin for Improvement of Antibacterial Activities against *Staphylococcus aureus*. *Foods* 2022, 11, 60.
88. Xiao, Z.; Hou, W.; Kang, Y.; Niu, Y.; Kou, X. Encapsulation and sustained release properties of watermelon flavor and its characteristic aroma compounds from γ -cyclodextrin inclusion complexes. *Food Hydrocolloids* 2019, 97, 105202.
89. Zhang, Y.; Tan, Y.; OuYang, Q.; Duan, B.; Wang, Z.; Meng, K.; Tan, X.; Tao, N. γ -Cyclodextrin encapsulated thymol for citrus preservation and its possible mechanism against *Penicillium digitatum*. *Pesticide Biochemistry and Physiology* 2023, 194, 105501.
90. Šimko, P.; Kolarič, L. Decrease in Aflatoxin M1 Concentration in Milk during Cholesterol Removal by Application of β -Cyclodextrin. *Toxins* 2022, 14, 379.
91. Kolarič, L.; Kántorová, P.; Šimko, P. β -Cyclodextrin as the Key Issue in Production of Acceptable Low-Cholesterol Dairy Products. *Molecules* 2022, 27, 2919.

92. Dang, C.; Jiranek, V.; Taylor, D.K.; Wilkinson, K.L. Removal of Volatile Phenols From Wine Using Crosslinked Cyclodextrin Polymers. *Molecules* 2020, 25, 910.
93. Fliszár-Nyúl, E.; Lemli, B.; Kunsági-Máté, S.; Szente, L.; Poór, M. Interactions of Mycotoxin Alternariol with Cyclodextrins and Its Removal from Aqueous Solution by Beta-Cyclodextrin Bead Polymer. *Biomolecules* 2019, 9, 428.
94. Kiel S, Poverenov E. Rechargeable films for protection of dry foods: A sustainable method for covalent grafting of β -cyclodextrin-thymol complex on PET/viscose platform. *Food Chem*, 2023, 412:135560.
95. Szejtli, J.; Szente, L. Elimination of bitter, disgusting tastes of drugs and foods by cyclodextrins. *Eur. J. Pharm. Biopharm.* 2005, 61, 115–125.
96. Wu, X.; Fu, B.; Ma, Y.; Dong, L.; Du, M.; Dong, X.; Xu, X. A Debittered Complex of Glucose-Phenylalanine Amadori Rearrangement Products with β -Cyclodextrin: Structure, Molecular Docking and Thermal Degradation Kinetic Study. *Foods* 2022, 11, 1309.
97. Gu, Q.; Lu, C.; Chen, K.; Chen, X.; Ma, P.; Wang, Z.; Xu, B. Electrochemical Determination of Capsaicinoids Content in Soy Sauce and Pot-Roast Meat Products Based on Glassy Carbon Electrode Modified with β -Cyclodextrin/Carboxylated Multi-Wall Carbon Nanotubes. *Foods* 2021, 10, 1743.
98. Lachowicz S, Oszmiański J, Uzdzička M, Chmielewska J. The Influence of Yeast Strain, β -Cyclodextrin, and Storage Time on Concentrations of Phytochemical Components, Sensory Attributes, and Antioxidative Activity of Novel Red Apple Ciders. *Molecules* 2019, 13, 2477.
99. Jia, S.; Jiang, S.; Chen, Y.; Wei, Y.; Shao, X. Comparison of Inhibitory Effects of Cinnamic Acid, β -Cyclodextrin, L-Cysteine, and Ascorbic Acid on Soluble and Membrane-Bound Polyphenol Oxidase in Peach Fruit. *Foods* 2023, 12, 167.
100. Wu, J.; Li, J.; Xu, F.; Zhou, A.; Zeng, S.; Zheng, B.; Lin, S. Effective Preservation of Chilled Pork Using Photodynamic Antibacterial Film Based on Curcumin- β -Cyclodextrin Complex. *Polymers* 2023, 15, 1023.
101. Wu, K.; Zhang, T.; Chai, X.; Duan, X.; He, D.; Yu, H.; Liu, X.; Tao, Z. Encapsulation Efficiency and Functional Stability of Cinnamon Essential Oil in Modified β -cyclodextrins: In Vitro and In Silico Evidence. *Foods* 2023, 12, 45.
102. Zhang, N.; Bi, F.; Xu, F.; Yong, H.; Bao, Y.; Jin, C.; Liu, J. Structure and functional properties of active packaging films prepared by incorporating different flavonols into chitosan based matrix. *Int. J. Biol. Macromol.* 2020, 165, 625–634.
103. Beshai, H.; Sarabha, G.K.; Rathi, P.; Alam, A.U.; Deen, M.J. Freshness Monitoring of Packaged Vegetables. *Appl. Sci.* 2020, 10, 7937.
104. Bangalore, D.V.; McGlynn, W.; Scott, D.D. Effect of beta-cyclodextrin in improving the correlation between lycopene concentration and ORAC values. *J. Agric. Food Chem.* 2005, 53, 1878–1883.
105. Choi, M.-J.; Ruktanonchai, U.; Min, S.-G.; Chun, J.-Y.; Soottitawat, A. Physical characteristics of fish oil encapsulated by β -cyclodextrin using an aggregation method or polycaprolactone using an emulsion-diffusion method. *Food Chem.* 2010, 119, 1694–1703.
106. Li, J.; Xiong, S.; Wang, F.; Regenstein, J.M.; Liu, R. Optimization of Microencapsulation of Fish Oil with Gum Arabic/Casein/Beta-Cyclodextrin Mixtures by Spray Drying. *J. Food Sci.* 2015, 80, C1445–C1452.
107. Kuswandi, B. Jumina Active and intelligent packaging, safety, and quality controls. In *Fresh-Cut Fruits and Vegetables: Technologies and Mechanisms for Safety Control*; Wasim Siddiqui, M., Ed.; Academic Press: Cambridge, MA, USA, 2020; pp. 243–294. ISBN 9780128161845.
108. Wyrwa, J.; Barska, A. Innovations in the food packaging market: Active packaging. *Eur. Food Res. Technol.* 2017, 243, 1681–1692.
109. Iturralde-García, R.D.; Cinco-Moroyoqui, F.J.; Martínez-Cruz, O.; Ruiz-Cruz, S.; Wong-Corral, F.J.; Borboa-Flores, J.; Cornejo-Ramírez, Y.I.; Bernal-Mercado, A.T.; Del-Toro-Sánchez, C.L. Emerging Technologies for Prolonging Fresh-Cut Fruits' Quality and Safety during Storage. *Horticulturae* 2022, 8, 731.
110. Nowak, J.K.; Sobkowiak, P.; Drzymała-Czyż, S.; Krzyżanowska-Jankowska, P.; Sapiejka, E.; Skorupa, W.; Pogorzelski, A.; Nowicka, A.; Wojsyk-Banaszak, I.; Kurek, S.; et al. Fat-Soluble Vitamin Supplementation Using Liposomes, Cyclodextrins, or Medium-Chain Triglycerides in Cystic Fibrosis: A Randomized Controlled Trial. *Nutrients* 2021, 13, 4554.
111. Goñi-Ciaurriz L, González-Gaitano G, Vélaz I. Cyclodextrin-grafted nanoparticles as food preservative carriers. *Int J Pharm* 2020, 588:119664.

112. Wang, Z.; Ma, Y.; Jiang, Y.; Zhou, F.; Wu, Y.; Jiang, H.; Wang, R.; Xu, Q.; Hua, C. Encapsulating quercetin in cyclodextrin metal-organic frameworks improved its solubility and bioavailability. *J. Sci. Food Agric.* 2022, 102, 3887-3896.
113. Vhangani, L.N.; Favre, L.C.; Rolandelli, G.; Van Wyk, J.; del Pilar Buera, M. Optimising the Polyphenolic Content and Antioxidant Activity of Green Rooibos (*Aspalathus linearis*) Using Beta-Cyclodextrin Assisted Extraction. *Molecules* 2022, 27, 3556.
114. Cao, C.; Xie, P.; Zhou, Y.; Guo, J. Characterization, Thermal Stability and Antimicrobial Evaluation of the Inclusion Complex of Litsea cubeba Essential Oil in Large-Ring Cyclodextrins (CD9-CD22). *Foods* 2023, 12, 2035.
115. Arrais, A.; Bona, E.; Todeschini, V.; Caramaschi, A.; Massa, N.; Roncoli, M.; Minervi, A.; Perin, E.; Gianotti, V. Thymus vulgaris Essential Oil in Beta-Cyclodextrin for Solid-State Pharmaceutical Applications. *Pharmaceutics* 2023, 15, 914.
116. Wu, K.; Zhang, T.; Chai, X.; Duan, X.; He, D.; Yu, H.; Liu, X.; Tao, Z. Encapsulation Efficiency and Functional Stability of Cinnamon Essential Oil in Modified β -cyclodextrins: In Vitro and In Silico Evidence. *Foods* 2023, 12, 45.
117. Li, H.; Ming, X.; Wang, Z.; Li, J.; Liang, Y.; Xu, D.; Liu, Z.; Hu, L.; Mo, H. Encapsulation of Benzyl Isothiocyanate with β -Cyclodextrin Using Ultrasonication: Preparation, Characterization, and Antibacterial Assay. *Foods* 2022, 11, 3724.
118. Liu, C.; Tian, Y.; Ma, Z.; Zhou, L. Pickering Emulsion Stabilized by β -Cyclodextrin and Cinnamaldehyde/ β -Cyclodextrin Composite. *Foods* 2023, 12, 2366.
119. Zhai, X.; Zou, X.; Shi, J.; Huang, X.; Sun, Z.; Li, Z.; Sun, Y.; Li, Y.; Wang, X.; Holmes, M.; et al. Amine-responsive bilayer films with improved illumination stability and electrochemical writing property for visual monitoring of meat spoilage. *Sens. Actuators B Chem.* 2020, 302, 127130.
120. Velázquez-Contreras, F.; García-Caldera, N.; Padilla de la Rosa, J.D.; Martínez-Romero, D.; Núñez-Delgado, E.; Gabaldón, J.A. Effect of PLA Active Packaging Containing Monoterpene-Cyclodextrin Complexes on Berries Preservation. *Polymers* 2021, 13, 1399.
121. Hădărugă, N.G.; Chirilă, C.A.; Szakal, R.N.; Gălan, I.M.; Simandi, M.D.; Bujancă, G.S.; David, I.; Riviș, A.; Stanciu, S.M.; Hădărugă, D.I. FTIR-PCA Approach on Raw and Thermally Processed Chicken Lipids Stabilized by Nano-Encapsulation in β -Cyclodextrin. *Foods* 2022, 11, 3632.
122. Kato, L.S.; Conte-Junior, C.A. Safety of plastic food packaging: The challenges about non-intentionally added-substances (NIAS) discovery, identification and risk assessment. *Polymers* 2021, 13, 2077.
123. Liu, D.; Cui, Z.; Shang, M.; Zhong, Y. A colorimetric film based on polyvinyl alcohol/sodium carboxymethyl cellulose incorporated with red cabbage anthocyanin for monitoring pork freshness. *Food Packag. Shelf Life* 2021, 28, 100641.
124. Drago, E.; Campardelli, R.; Pettinato, M.; Perego, P. Innovations in Smart Packaging Concepts for Food: An Extensive Review. *Foods* 2020, 9, 1628.
125. Hong, L.G.; Yuhana, N.Y.; Zawawi, E.Z.E. Review of bioplastics as food packaging materials. *AIMS Mater. Sci.* 2021, 8, 166-184.
126. Gallo, M.; Ferrara, L.; Calogero, A.; Montesano, D.; Naviglio, D. Relationships between food and diseases: What to know to ensure food safety. *Food Res. Int.* 2020, 137, 109414.
127. Petrescu, D.C.; Vermeir, I.; Petrescu-Mag, R.M. Consumer Understanding of Food Quality, Healthiness, and Environmental Impact: A Cross-National Perspective. *Int. J. Environ. Res. Public Health* 2020, 17, 169.
128. Fang, Z.; Zhao, Y.; Warner, R.D.; Johnson, S.K. Active and intelligent packaging in meat industry. *Trends Food Sci. Technol.* 2017, 61, 60-71.
129. Cheng, H.; Xu, H.; McClements, D.J.; Chen, L.; Jiao, A.; Tian, Y.; Miao, M.; Jin, Z. Recent advances in intelligent food packaging materials: Principles, preparation and applications. *Food Chem.* 2022, 375, 131738.
130. Ghaani, M.; Cozzolino, C.A.; Castelli, G.; Farris, S. An overview of the intelligent packaging technologies in the food sector. *Trends Food Sci. Technol.* 2016, 51, 1-11.
131. Ahmed, I.; Lin, H.; Zou, L.; Li, Z.; Brody, A.L.; Qazi, I.M.; Lv, L.; Pavase, T.R.; Khan, M.U.; Khan, S.; et al. An overview of smart packaging technologies for monitoring safety and quality of meat and meat products. *Packag. Technol. Sci.* 2018, 31, 449-471.
132. Soltani Firouz, M.; Mohi-Alden, K.; Omid, M. A critical review on intelligent and active packaging in the food industry: Research and development. *Food Res. Int.* 2021, 141, 110113.

133. Chen, S.; Wu, M.; Lu, P.; Gao, L.; Yan, S.; Wang, S. Development of pH Indicator and Antimicrobial Cellulose Nanofibre Packaging Film Based on Purple Sweet Potato Anthocyanin and Oregano Essential Oil. *Int. J. Biol. Macromol.* 2020, 149, 271–280.
134. Chaudhary, V.; Punia Bangar, S.; Thakur, N.; Trif, M. Recent Advancements in Smart Bio-genic Packaging: Reshaping the Future of the Food Packaging Industry. *Polymers* 2022, 14, 829.
135. Müller, P.; Schmid, M. Intelligent Packaging in the Food Sector: A Brief Overview. *Foods* 2019, 8, 16.
136. Jarupatnadech, T.; Chalitangkoon, J.; Monvisade, P. Colorimetric oxygen indicator films based on β -cyclodextrin grafted chitosan/montmorillonite with redox system for intelligent food packaging. *Packaging Technol. and Sci* 2022, 35(6), pp. 515–525.
137. Zhang, J.; Zou, X.; Song, W.; Du, L.; Shi, J.; Huang, X.; Zhang, J.; Li, Z.; Liu, L. Development and Application of Visual Freshness Indicator Film with High Stability Based on Acylated Anthocyanins. *Shipin Kexue/Food Science* 2023, 44(3), pp. 194–200.
138. Lin, W.; Hong, W.; Sun, Y.; Huang, J.; Li, Z. Triple-function chitosan-based film for pork and shrimp packaging. *Food Chemistry* 2023, 417, 135903.
139. Rawdkuen, S.; Faseha, A.; Benjakul, S.; Kaewprachu, P. Application of Anthocyanin as a Color Indicator in Gelatin Films. *Food Biosci.* 2020, 36, 100603.
140. Ge, Y.; Li, Y.; Bai, Y.; Yuan, C.; Wu, C.; Hu, Y. Intelligent Gelatin/Oxidized Chitin Nanocrystals Nanocomposite Films Containing Black Rice Bran Anthocyanins for Fish Freshness Monitorings. *Int. J. Biol. Macromol.* 2020, 155, 1296–1306.
141. Eze, F.N.; Jayeoye, T.J.; Singh, S. Fabrication of Intelligent pH-Sensing Films with Antioxidant Potential for Monitoring Shrimp Freshness via the Fortification of Chitosan Matrix with Broken Riceberry Phenolic Extract. *Food Chem.* 2022, 366, 130574.
142. H. Yong, X. Wang, R. Bai, Z. Miao, X. Zhang, J. Liu. Development of antioxidant and intelligent pH-sensing packaging films by incorporating purple-fleshed sweet potato extract into chitosan matrix. *Food Hydrocolloids*, 90 (2019), pp. 216-224.
143. Ghosh, S.; Sarkar, T.; Das, A.; Chakraborty, R. Natural colorants from plant pigments and their encapsulation: An emerging window for the food industry. *LWT* 2022, 153, 112527.
144. Bakhshizadeh, M.; Moghaddam, T.N.; Tavassoli, M.; Ayaseh, A.; Bangar, S.P. Gelatin/chitosan nanofibres containing β -cyclodextrin complex and corn poppy (*Papaver rhoeas* L.) for intelligent packaging. *Int. J. of Food Sci. and Technol.* 2023, 58(5), pp. 2360–2368.
145. Wei, S.; Wang, X.; Wang, F.; Hao, X.; Li, H.; Su, Z.; Guo, Y.; Shi, X.; Liu, X.; Li, J.; Zhao, C. Colorimetric detection of *Salmonella typhimurium* based on hexadecyl trimethyl ammonium bromide-induced supramolecular assembly of β -cyclodextrin-capped gold nanoparticles. *Analytical and Bioanalytical Chemistry* 2022, 414(20), pp. 6069–6076.
146. Mustafa, F.; Andreescu, S. Nanotechnology-based approaches for food sensing and packaging applications. *RSC Adv.* 2020, 10, 19309–19336.
147. Zhao, H.; Zhu, G.; Li, F.; Liu, Y.; Guo, M.; Zhou, .; Liu, R.; Komarneni, S. 3D interconnected honeycomb-like ginkgo nut-derived porous carbon decorated with β -cyclodextrin for ultrasensitive detection of methyl parathion. *Sensors and Actuators B: Chemical* 2023, 380, 133309.
148. Ahmadi, S.; Hasanzadeh, M.; Ghasempour, Z. Sub-micro electrochemical recognition of carmoisine, sunset yellow, and tartrazine in fruit juices using P(β -CD/Arg)/CysA-AuNPs/AuE. *Food Chemistry* 2023, 402, 134501.
149. Yun, N.; Lu, C.; Sun, T.; Xu, B.; Song, C.; Zong, Z.; Chen, K.; Huang, G.; Chen, X.; Gu, Q. High Sensitivity Detection of Capsaicin in Red Pepper Oil Based on Reduced Graphene Oxide Enhanced by β -Cyclodextrin. *Food Analytical Methods* 2023, 16(2), pp. 318–329.
150. Yao, H.; Yu, H.; Zhang, B.Y.; Chen, K.; Yi, Q.; Xie, H.; Hu, X.; Tang, T.; Cheng, Y.; Tao, X.; et al. Approximately 1 nm-sized artificial tunnels in wrinkled graphene-graphene oxide composite membranes for efficient dye/dye separation and dye desalination. *Chem. Eng. J.* 2022, 445, 136753.
151. Chen, Y.; Sun, Y.; Wang, R.; Waterhouse, G.I.N.; Xu, Z. One-pot synthesis of a novel conductive molecularly imprinted gel as the recognition element and signal amplifier for the selective electrochemical detection of amaranth in foods. *Biosensors and Bioelectronics* 2023, 228, 115185.
152. Patra, J.K.; Das, G.; Fraceto, L.; Campos, E.; Rodríguez-Torres, M.D.P.; Acosta-Torres, L.; Diaz-Torres, L.; Grillo, R.; Swamy, M.; Sharma, S.; et al. Nano based drug delivery systems: Recent developments and future prospects. *J. Nanobiotechnol.* 2018, 16, 1–33.

153. Avan, A.A. and Filik, H. Simultaneous Determination of Fat-Soluble Vitamins by Using Modified Glassy Carbon Electrode. *Russian Journal of Electrochemistry* 2021, 57(8), pp. 858–871.
154. Sun, W.; Fan, L.; Zhao, Y.; Dong, T.; Jin, Y.; Saldaña, M.D.A.; Sun, W. Preparation, characterization, and morphology of on/off detection indicator based on rhodamine 6G-adamantanamine loaded onto nonwoven polyethylene terephthalate. *Packaging Technology and Science* 2020, 33(9), pp. 385–394.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.