

Lifestyle & Culture

Cyclodextrins: Structure, function, and applications across industries



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Cyclodextrins, a fascinating class of cyclic oligosaccharides, have garnered significant attention due to their unique molecular structure and versatile applications in various industries, including pharmaceuticals, food, cosmetics, and environmental science. Derived from starch through enzymatic reactions, cyclodextrins are composed of glucose monomers linked by alpha-1,4-glycosidic bonds to form a ring-shaped structure. Their ability to form inclusion complexes with hydrophobic molecules makes them particularly useful in improving the solubility, stability, and bioavailability of otherwise poorly soluble substances. This article will explore the structure, classification, and applications of cyclodextrins in depth.

Cyclodextrins: The basic structure

Cyclodextrins are cyclic molecules composed of glucose units. The cyclic nature of these molecules arises from the fact that the ends of the oligosaccharide chain are joined to form a ring. The typical cyclodextrins have six, seven, or eight glucose units, giving rise to three primary forms:

- Alpha-cyclodextrin (α -CD): Contains 6 glucose units.
- Beta-cyclodextrin (β -CD): Contains 7 glucose units.
- Gamma-cyclodextrin (γ -CD): Contains 8 glucose units.

The shape of cyclodextrins resembles a hollow, truncated cone rather than a perfect cylinder. This geometry arises because the glucose units are oriented in such a way that the wider opening of the cone is hydrophilic, while the inner cavity is hydrophobic. The hydrophilic exterior allows cyclodextrins to be soluble in water, while the hydrophobic interior enables them to interact with nonpolar substances. This dual nature – hydrophilic on the outside and hydrophobic on the inside – forms the basis for many of their applications, particularly in forming inclusion complexes.

Formation of inclusion complexes

The formation of inclusion complexes is one of the most significant features of cyclodextrins. An inclusion complex occurs when a molecule (referred to as a "guest") is partially or fully encapsulated by the cyclodextrin's hydrophobic cavity. This encapsulation does not involve covalent bonding but instead relies on weak interactions such as

van der Waals forces, hydrogen bonding, and hydrophobic effects.

The hydrophobic core of the cyclodextrin attracts nonpolar molecules or nonpolar regions of amphiphilic molecules. Once the guest molecule is trapped inside the cavity, it is protected from interactions with the surrounding aqueous environment. This can lead to significant changes in the guest molecule's properties, such as:

- **Increased solubility:** Many hydrophobic substances have limited solubility in water, but when encapsulated in cyclodextrins, they can dissolve more readily.
- **Improved stability:** Cyclodextrins can shield guest molecules from heat, light, and oxidation, prolonging their shelf life.
- **Controlled release:** In drug delivery systems, cyclodextrins can release encapsulated drugs at a controlled rate, enhancing their therapeutic efficacy.

Types of cyclodextrins and their properties

The three most common cyclodextrins – alpha, beta, and gamma – differ not only in the number of glucose units but also in the size of their cavities and their ability to form complexes with guest molecules.

1. **Alpha-cyclodextrin (α -CD):** Alpha-cyclodextrin has the smallest cavity of the three, making it suitable for encapsulating small molecules. Its limited cavity size restricts its application in encapsulating larger compounds, but it is still widely used in food and pharmaceutical industries.
2. **Beta-cyclodextrin (β -CD):** Beta-cyclodextrin has a cavity size that allows it to encapsulate medium-sized molecules, making it the most commonly used cyclodextrin in various applications. However, β -CD is less soluble in water compared to its alpha and gamma counterparts. To address this, chemical modifications such as methylation or hydroxypropylation are often applied to enhance its solubility.
3. **Gamma-cyclodextrin (γ -CD):** Gamma-cyclodextrin has the largest cavity, making it suitable for larger molecules. It also has better water solubility than beta-cyclodextrin, but its production cost is higher, which limits its use in large-scale applications.

Applications of cyclodextrins

1. **Pharmaceutical Industry:** The pharmaceutical industry is one of the largest sectors utilizing cyclodextrins. Their ability to form inclusion complexes allows them to improve the solubility, stability, and bioavailability of drugs. Many drugs are hydrophobic and have limited solubility in biological fluids, which hinders their absorption and therapeutic effectiveness. Cyclodextrins help overcome this limitation by encapsulating the drug molecules within their hydrophobic cavity.

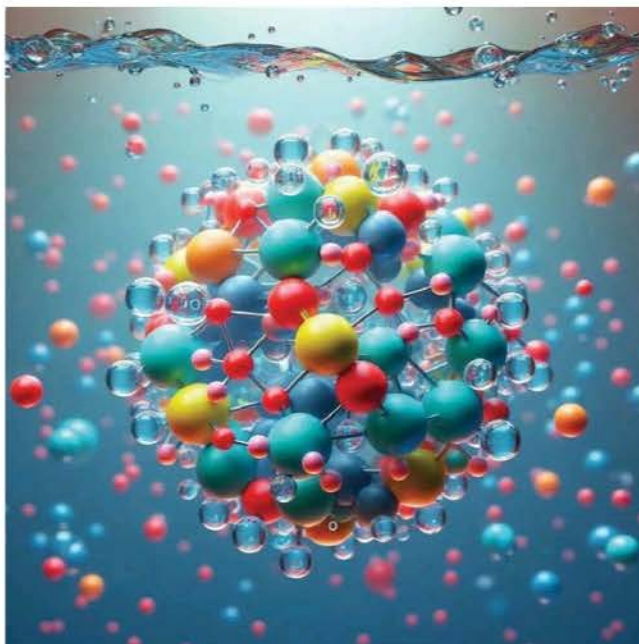


Photo: AI-generated image created by Prof. Blundell

- **Drug Solubilization:** Cyclodextrins enhance the solubility of poorly water-soluble drugs by forming inclusion complexes. For example, β -cyclodextrin is commonly used to improve the solubility of drugs like steroids, hormones, and anticancer agents.
- **Drug Stability:** Many drugs are prone to degradation due to exposure to light, heat, or moisture. Cyclodextrins protect these drugs by trapping them inside their cavities, thereby preventing environmental factors from reaching the encapsulated molecule. For instance, cyclodextrins are used to stabilize the formulation of vitamins, antibiotics, and anti-inflammatory drugs.
- **Controlled Drug Release:** Cyclodextrins can also be used in drug delivery systems to provide controlled and sustained release of drugs. This allows for prolonged therapeutic effects and reduces the frequency of drug administration.
- **Reducing Toxicity:** By encapsulating toxic or irritating drugs, cyclodextrins can reduce their side effects. This is particularly useful for drugs that would otherwise cause irritation at the site of administration.
- 2. **Food Industry:** Cyclodextrins have a wide range of applications in the food industry. Their ability to form inclusion complexes allows them to mask undesirable flavours and odours, stabilize volatile compounds, and improve the shelf life of food products.

Flavour Stabilization: Cyclodextrins are used to protect and stabilize flavour compounds, particularly those that are volatile or prone to oxidation. For example, they can encapsulate essential oils and aromatic compounds, preventing their degradation and preserving

the flavour profile of the food product.

- **Reduction of Off-Flavours:** In some cases, cyclodextrins are used to remove undesirable flavours or odours from food. For instance, they can trap and remove bitter compounds or unwanted fatty acids.
- **Fat Substitution:** Cyclodextrins can form complexes with lipids, and this property has been exploited to develop low-fat or fat-free food products. By mimicking the texture and mouthfeel of fat, cyclodextrins help create healthier alternatives to traditional high-fat foods.
- **Improving Food Stability:** Cyclodextrins can encapsulate and protect vitamins, antioxidants, and other sensitive nutrients in food products, extending their shelf life and enhancing their nutritional value.
- 3. **Cosmetics Industry:** In the cosmetics industry, cyclodextrins are used to improve the stability, effectiveness, and aesthetic properties of personal care products. Their ability to form inclusion complexes makes them valuable in formulations that require the stabilization of active ingredients or controlled release.
- **Stabilizing Active Ingredients:** Many cosmetic products contain active ingredients that are sensitive to environmental factors such as light, heat, or oxidation. Cyclodextrins protect these ingredients by encapsulating them, preventing degradation and ensuring their efficacy over time.
- **Controlled Release in Cosmetics:** Cyclodextrins enable the controlled release of active ingredients in skincare and haircare products. For example, they can encapsulate fragrances, releasing them gradually over time for a long-lasting effect.

- **Reduction of Greasiness:** Cyclodextrins can reduce the greasiness or oily texture of cosmetic products by encapsulating oils and fats. This results in products that feel lighter on the skin and are more comfortable to use.

4. **Environmental Applications:** Cyclodextrins also have significant applications in environmental science, particularly in the removal of pollutants and the treatment of contaminated water and soil.

- **Pollutant Removal:** Cyclodextrins can form complexes with hydrophobic pollutants, such as pesticides, herbicides, and industrial chemicals. This property has been exploited in water treatment and soil remediation efforts. Cyclodextrins can trap and immobilize these pollutants, making them easier to remove from the environment.

- **Wastewater Treatment:** Cyclodextrins are used in wastewater treatment to remove organic contaminants that are resistant to traditional treatment methods. By forming inclusion complexes with these contaminants, cyclodextrins facilitate their separation and degradation.

5. **Biomedical Applications:** In addition to pharmaceuticals, cyclodextrins have potential uses in various biomedical applications, including diagnostic imaging and gene delivery.

- **Diagnostic Imaging:** Cyclodextrins can be used to enhance the solubility and stability of contrast agents used in medical imaging, such as MRI and CT scans. This leads to clearer and more accurate images for diagnostic purposes.

- **Gene Delivery:** Cyclodextrins have been explored as carriers for gene delivery, where they can encapsulate DNA or RNA molecules and deliver them to target cells. Their biocompatibility and ability to form inclusion complexes make them attractive candidates for gene therapy applications.

- Cyclodextrins represent a versatile and valuable class of compounds with a broad range of applications across multiple industries. Their unique ability to form inclusion complexes with hydrophobic molecules enables them to improve the solubility, stability, and bioavailability of various compounds, from pharmaceuticals to food additives. As research into cyclodextrins continues, new and innovative uses are likely to emerge, further expanding their potential to solve complex problems in fields such as medicine, environmental science, and materials engineering.

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