

Nature's Tiny Time Capsules: How Starch and β -Cyclodextrin Outplay Fruit Spoilage

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ABSTRACT

Postharvest spoilage of fruits causes major food and economic losses worldwide. This article highlights a natural and sustainable preservation method using p-anisaldehyde, a bioactive compound from fennel essential oil, encapsulated within V-type starch and β -cyclodextrin. The encapsulation system protects the compound and enables its slow release as a vapour, helping to reduce mould growth and extend the shelf life of cherries. This biodegradable and chemical-free approach offers a promising alternative for safer food preservation and sustainable packaging solutions.

INTRODUCTION

Imagine a farmer carefully harvesting a basket of ripe cherries on a warm morning. They look perfect, bright and glossy. By the time they travel from the farm to a market shelf and then to a kitchen table, some of those same cherries may already be soft, spoiled or covered in mould or mucilage. The cherries lose nutritional quality, shelf life and sensory attributes. What began as a fresh, valuable crop can quickly become waste. This

is not just a problem for one household or one shop. Every year, huge amounts of food are lost after harvest, even though the world produces more than enough to feed everyone (Gatto and Chepeliev 2024). Fresh fruits are especially vulnerable because they are delicate and perish quickly. When they spoil, farmers lose income, retailers lose stock. But the impact goes even deeper: all the water, energy, land, and labour used to grow that food is

wasted, too. In a time when food insecurity and environmental pressure are growing, reducing postharvest loss has become more important than ever. At present, the most prevalent methods for fruit preservation are used, such as refrigeration preservation, controlled atmosphere storage, irradiation treatment, chemical fungicides and synthetic preservatives. Given the challenges and high costs of physical methods, synthetic fungicides are the most common solution for managing postharvest microbial contamination in fruits (Gao *et al.*, 2025). However, their use raises concerns such as chemical residues on produce, development of microbial resistance, and risks to both the environment and human health. Consequently, there is an urgent need to develop eco-friendly and effective alternatives to synthetic fungicides to reduce or eliminate their use. Plants naturally produce antibacterial essential oils that can extend food shelf life safely and sustainably by creating an antibacterial environment for fruits and vegetables through contact or fumigation. These natural methods have shown excellent results in preserving fruits and vegetables. Nevertheless, these natural substances are often unstable and degrade quickly, losing their effectiveness. To address this, recent studies have employed encapsulation is utilized. For controlled release, protection of p-Anisaldehyde to enhance efficiency to reduce the amount of toxic residue accumulation and to mask odour/strong smells, edible and biodegradable coating (starch and β -cyclodextrin), thereby improving their application in fruit and vegetable preservation (Gao *et al.*, 2025).

1. Natural Preservatives: p-Anisaldehyde

p-Anisaldehyde, a "generally recognised as safe" (GRAS) natural compound approved by the US FDA from fennel essential oil, possesses antifungal, antibacterial and antioxidant properties (Gao *et al.*, 2025). The compound disrupts microbial cell membranes,

interferes with enzyme activity, and damages cellular metabolism, ultimately preventing microbial growth and decay in fruits. However, its application is limited by high volatility, low water solubility and instability under light, oxygen, and heat. Hence, encapsulation is essential to improve its stability and application potential.

2. Starch

Starch is a natural biopolymer that is non-toxic and low-cost, and it possesses good biocompatibility and biodegradability. As a natural polymer material, starch is an ideal choice for microcapsule wall materials. Under the controlled conditions, involving high-temperature treatment (160 °C for 3 h), followed by ethanol-induced precipitation and drying at 70 °C., starch's amylose chains twist into helical spirals (Gutiérrez *et al.*, 2022). These form V-type starch, with hollow tunnels precisely 0.5-1 nm wide, ideal cages, modified to trap hydrophobic components, including essential oils, holding them snugly without leakage.

3. Cyclodextrin:

β -Cyclodextrin (β -CD) is a natural sugar-based molecule made up of seven glucose units joined in a ring-shaped structure. Its outer surface easily mixes with water, while the inner cavity can trap hydrophobic molecules, allowing it to form protective inclusion complexes with different compounds. Its ability to encapsulate molecules of different sizes is relatively limited (Gao *et al.*, 2025).

4. Encapsulation

Encapsulation is a process in which tiny particles or droplets of a substance are surrounded by a protective coating to improve its stability, controlled release, and protect from environmental factors (Gao *et al.*, 2025). Due to good biocompatibility and similar helical structures, β -CD and V-type starch can

work together to create an efficient dual encapsulation system. A novel V-type starch–cyclodextrin composite carrier effectively encapsulates p-anisaldehyde and extends the shelf life of cherries stored at room temperature (Fig 1).

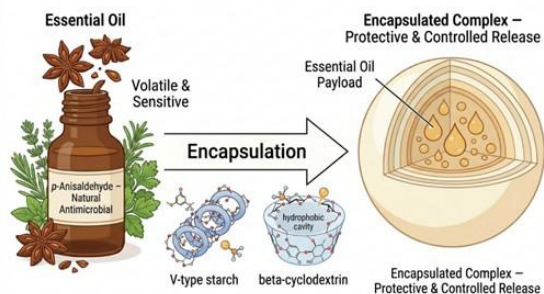


Figure 1: Encapsulation of essential oil for food preservation

5. A Capsule That Releases Protection

The optimised encapsulation material showed several advantages over starch or β -CD used alone. It could hold a larger amount of preservative, a more stable structure, and its porous particles securely trapped p-anisaldehyde inside (Gao *et al.*, 2025). Most importantly, the material released p-anisaldehyde slowly and continuously as a gentle vapour. This controlled release provides longer-lasting protection and improved preservation efficiency. To test the system, researchers placed small sachets containing starch– β -CD capsules loaded with p-anisaldehyde inside sealed cherry storage containers. The capsules slowly released the natural compound, creating an invisible protective layer around the fruit without affecting its taste or leaving any residue (Zabot *et al.*, 2022). As a result, the treated cherries remained fresh, firm, and free from mould for up to 12 days, nearly twice as long as untreated cherries, which developed mould within 6 days, as illustrated in Fig 2 (Gao *et al.*, 2025). The method also reduced weight loss, better preserved colour, sweetness and vitamin C, and extended shelf life.



Figure 2: Application in sweet cherry preservations

6. Why This Matters Far Beyond Cherries

This approach is important not only for cherries but also for the future of sustainable food preservation. Biopolymer-based encapsulation systems are natural, biodegradable and safe for consumers, making them ideal for non-contact, vapour-phase preservation methods (Zabot *et al.*, 2022). They can be easily incorporated into sustainable packaging materials such as sachets, edible coatings, and biodegradable films, as shown in Fig 3. These systems support global efforts to reduce food waste, minimise plastic use and create sustainable and climate-bond food systems (Gatto and Chepeliev 2024).



Figure 3: Advantages of Encapsulation Methods

CONCLUSION

The findings of this study show that a simple natural compound, p-anisaldehyde, when combined with starch and cyclodextrin, can provide a safer and more sustainable method for preserving fresh fruits. This is especially important for India, where nearly 10–15% of fruits are lost after harvest each year. With an annual fruit production of about 114.5 million metric tonnes, more than 15 million metric tonnes are wasted, leading to massive economic losses (Gatto and Chepeliev 2024). Encapsulation technology offers a promising

solution by reducing spoilage, extending shelf life, and helping to minimise post-harvest losses naturally.

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