The Development Prospects and Predicaments of Plant-derived Polyphenols Added in Food and Food Additives

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Abstract: Plant polyphenols are a large class of naturally existing phenolic compounds. They can exert effective functions in antioxidation and combating various diseases and chronic diseases in the human body. However, during the process of entering human cells, polyphenols encounter many obstacles, resulting in low bioavailability. In recent years, the academic community has attempted to combine various biological macromolecules with polyphenols to protect polyphenols from being damaged during transportation, and hopes that polyphenols can exist as a common food component or food additive in processed foods. This article introduces various active molecules that can interact with polyphenols and protect polyphenols from entering the human body, and elaborates on their mechanism of action. It also discusses the advantages and current predicaments of polyphenols as food additives and food components, and finally discusses the development prospects of polyphenols as food components. The author believes that although polyphenols have not been widely applied to processed foods at present, their market potential is huge, and they may be fully popularized in the near future.

Keywords: Polyphenols; Plant Polyphenols; Interaction of Polyphenols with Proteins; Interaction of Polyphenols with Lipids; Interaction of Polyphenols with Polysaccharides

1. Introduction

Polyphenols are also known as polyhydroxybenzene, which are a large category of phenolic compounds naturally existing in nature. They are mainly divided into two types: plant-derived polyphenols and microbial-derived polyphenols. Plant-derived polyphenols are abundant in plants and have diverse structures, most plant-derived polyphenols are secondary metabolites of plants. Polyphenols have strong antioxidant activity and may also have potential free radical scavenging properties. Furthermore, polyphenols have antibacterial, antioxidant, antivirus (Duda-Chodak & Tarko, 2023) [1]. Anti-cardiovascular and cerebrovascular diseases, protect against ultraviolet radiation, Fight against diabetes, Anti-cancer drugs have outstanding performance even in resisting the damage caused by radiotherapy to cancer cells, it also demonstrates a certain degree of neuroprotective effect and the regulatory effect on the intestinal flora, also has therapeutic effects on the prevention and treatment of Alzheimer's symptoms. From the above research, it can be seen that polyphenols have multiple benefits for the human body. However, due to the fact that the structure of polyphenols in nature is prone to damage, the low bioavailability in the human body and other reasons have led to the fact that polyphenols have not yet been widely used in the market (Guo et al., 2024)[2]. Based on this, several methods for protecting the structure of polyphenols have been developed by the academic community at present.

2. Engineering Polyphenols Byutilizing Polyphenol-Protein Interactions

Polyphenols can bind to proteins through covalent or non-covalent bonds(Jian et al., 2019) [5]. This is undoubtedly a new method that allows polyphenolic compounds to be retained in food additives for a long time. Some polyphenol-protein complexes can protect the sensitive chemical groups of polyphenols from oxidative attack even resistant to degradation by certain enzymes. Some polyphenol-protein complexes can even enhance their physiological functions.

Significantly enhance polyphenol activity

In 2016, a group of researchers discovered that polyphenols could inhibit the migration of tumor cells, while covalent modification could

significantly enhance the activity of polyphenols. Meanwhile, polyphenols binding with proteins can protect polyphenols from being degraded by stomach acid , and significantly increase the level of intact structural polyphenols(Li et al., 2021)[7], For example, the EGCG and lysozyme amyloid fibrils interaction forms a mixed nanofiber that can deliver EGCG to the intestines, prolonging its residence time in the colon, which can enhance EGCG's ability to regulate microbial imbalance and strengthen the intestinal mucosal barrier function to improve the efficiency of polyphenol absorption in the intestines.

Enhance cellular absorption efficiency

Some polyphenol-protein complexes are more efficient at entering human cells. For example, a type of peptide called cell-penetrating peptides (CPPs) can enhance cell uptake of nutrients such as DNA fragments or various small molecular chemicals, both in vivo and in vitro. CPPs contain arginine and lysine residues, which are typically positively charged. Therefore, they can form stable double-headed hydrogen bonds with cell membrane components. Meanwhile, polyphenols can enhance trans-membrane efficiency by binding to it through electrostatic and covalent interactions (Simion et al., 2016) [10].

3. Utilizing the Interaction Between Polyphenols and Polysaccharides

The polyphenols and polysaccharides interaction is widespread in nature and has a significant impact on the quality of fruits and vegetables. With the assistance of the intestinal microbiota, the interaction between polyphenols and polysaccharides can exert beneficial effects on human health by regulating glucose and lipid metabolism. The interaction between polyphenols and polysaccharides can be classified into two forms: non-covalent interaction and covalent bonding interaction.

3.1 Covalent Bonding Effect

Polyphenols and polysaccharides can interact through oxidation reactions, enzyme-mediated effects, carbodiimide-mediated free radical induction, free radical grafting and other mechanisms to form polyphenol-polysaccharide covalent complexes(Huang et al., 2023)[3].

3.2 Non-Covalent Interactions

The non-covalent interactionsare mainly mediated by hydrogen bonds, van der Waals forces, hydrophobic interactions and electrostatic interactions(Zhu et al., 2018) [11].

4. Utilizing the Interaction Between Polyphenols and Lipids

Generally speaking, the interaction between polyphenols and other components involves electron transfer, but the interaction between polyphenols and liposomes relies on hydrophobic interactions. (Pan et al., 2025)[8], This does not involve the transfer of electrons and has a relatively small impact on the properties of polyphenols themselves. Therefore, using liposomes as carriers is a relatively safe method. In fact, many studies have shown that using liposomes as drug delivery systems is feasible, However, it should be noted that simple liposomes also carry the risk of being degraded by digestive enzymes in the body. The affinity of polyphenols for liposomes has a significant impact on the bioavailability of polyphenols. The co-carriers formed by polyphenols and liposomes not only have a transporting effect but also enhance the biological benefits of polyphenols. For instance, Hu et al. found that EGCG can inhibit autophagy and apoptosis of H9c2 cardiomyocytes caused by A/R injury and I/R injury by mediating 14-3-3η.

Lipids are molecules that contain a hydrophilic head and two hydrophobic tails (though there are many exceptions). In water, lipids self-assemble into lipid bilayers, which form two-dimensional biomolecular sheets composed of two layers of lipid molecules almost parallel to each other, creating bilayer vesicles that can enclose biomolecules. Due to the special structure of lipid molecules, they can enclose both hydrophilic and hydrophobic molecules. This provides a good transport platform for the structurally diverse polyphenolic substances.

Liposome-polyphenol polymers offer multiple benefits, including but not limited to: enhancing solubility, preventing the degradation of polyphenols during their transport in the body, providing targeted delivery, and improving the bioavailability of polyphenols.

5. Toxicological Controversy

As a natural extract and a rich variety of compounds, the effects of many polyphenols on the human body remain unknown. Currently, some studies have shown that if some polyphenolic compounds are ingested

inappropriately, they can cause certain harm to the human body. Multiple studies have shown that the metal chelating activity of polyphenolic compounds (quercetin, flavonoids and catechins) can to some extent limit the formation of free radicals and treat metal ion overload. However, for some special groups (such as iron-deficient people), polyphenols may instead aggravate this symptom and cause anemia.

In addition, the interaction between polyphenols and proteins can also affect the biological activity of proteins. The amino acid composition and content of dietary proteins determine their nutritional value, but the interaction between polyphenols and dietary proteins can change the distribution of amino acids in proteins, affecting the digestion and absorption of dietary proteins. For example, the interaction between chlorogenic acid and β-lactoglobulin leads to a decrease in the content of methionine, cysteine, lysine and tryptophan in β-lactoglobulin, a reduction in nitrogen digestibility, and a decrease in its nutritional value. Polyphenols may also inhibit the action of digestive enzymes in the human body. Polyphenolic compounds may also cause hormonal imbalance in the body, leading to endocrine disorders. For instance, isoflavones, due to their structural similarity to estrogen, can disrupt the endocrine system(Jamali et al., 2010)[4]. It may cause insufficient secretion of estrogen.

Polyphenols may alter the dose-response curve of biomacromolecules after binding to them. For example: Although the lignin-VB1 nanocomplexes (LEVs) enhance their activity in antibacterial applications, high doses may cause cytotoxicity to cell membranes due to the accumulation of quaternary ammonium groups[9].(Perrone & D'Angelo, 2025)

6. Strict Legal Supervision

At present, there is a lack of new legal regulations for polyphenol additives worldwide. A new type of food additive needs to undergo strict toxicological review before being officially launched on the market. Taking the European region as an example, the verification of food additive safety is handled by the European Commission and the European Food Safety Authority (EFSA). The latter conducts long-term and strict scientific evaluations. It usually takes at least two years, starting with an applicability check, followed by a risk assessment, and finally obtaining the opinion of EFSA as well as the authorization of member states and the European Union[6]. (Le Bloch et al., 2024). For polyphenols, a class of complex chemical substances with unclear toxicological effects on the human body, the strictness of their review will seriously delay their entry into the market.

7. Market Acceptance

7.1 Cost Issue

Most of the research is still in the laboratory stage, with high costs and uncertain success rates. Especially, some concepts of nano-molecular delivery systems pose high demands on processing facilities, which is unfavorable for the cost control of the final products.

7.2 Sensory Analysis

Sensory analysis is a method that uses human senses as analytical assessment tools to evaluate and analyze samples. and statistical analysis is conducted on the evaluation data. It has the characteristics of strong practicability and high sensitivity. It can also evaluate the difficult-to-quantify indicators through conventional physicochemical analysis. It plays an important role in food development experiments. Unfortunately, the current combination effect of polyphenols with various biological macromolecules is still at the laboratory stage, and the most important step before the product is put on the market has not yet received due attention.

8. Conclusion and Prospect

From the above discussion, it can be seen that plant polyphenols, as a class of pure natural phenolic substances, are highly promising as food additives or ingredients from both health and marketing perspectives. However, due to various reasons, polyphenols are currently generally only found in fresh plant-based products on the market (such as fruits), and are extremely rare in processed foods. At the same time, the combination of polyphenols with other biological macromolecules has attracted increasing attention from researchers, and various methods have been developed to assist polyphenols in entering the human body and better remaining in processed products. It is believed that in the near future, plant polyphenols will become a common component in our food.

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