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Optimization and Activity Analysis of Plant Polyphenol Extraction Process in Fruits and Vegetables

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ABSTRACT
This study aims to optimize the extraction process of plant polyphenols to enhance their application in food and health product development. Plant polyphenols, known for their unique chemical structure and biological activity, are widely recognized for their significant antioxidant, anti-inflammatory, antibacterial, and anticancer properties. The study explores the extraction efficiency and optimization of different methods through single-factor experiments and orthogonal experimental design. The results indicate that ultrasonic extraction outperforms other methods in terms of extraction efficiency and antioxidant activity. The content of amino acids and antioxidant activity is significantly correlated with polyphenol concentration, particularly in blueberries, where the extraction efficiency is the highest.

KEYWORDS
Plant polyphenols; Extraction process; Antioxidant activity; Ultrasonic extraction; Microwave assisted extraction

1 Introduction

Plant polyphenols, a class of natural compounds widely found in plants, have attracted researchers due to their diverse biological activities. In recent years, their potential applications in antioxidant, anti-inflammatory, and antibacterial effects have garnered attention from the food and pharmaceutical industries. Although numerous studies have explored the extraction methods and activities of plant polyphenols, current extraction techniques still face issues such as low efficiency and poor selectivity. This study aims to enhance the extraction rate and biological activity of plant polyphenols from various fruits and vegetables by optimizing the extraction process, thereby enhancing their value in food safety and health product development, and providing scientific evidence for the relevant industries.

2 Sources and characteristics of plant polyphenols

2.1 Chemical structure of plant polyphenols

Plant polyphenols are a class of bioactive compounds with diverse structural features, typically composed of benzene rings and their derivatives. The basic structural units include quinones, phenolic hydroxyl groups, and their polymers, with common functional groups such as phenolic hydroxyl groups, ether bonds, and aldehyde groups. These functional groups determine the biological activity of plant polyphenols in chemical reactions, effectively capturing free radicals and demonstrating excellent antioxidant properties.

2.2 Biological activity of plant polyphenols

Plant polyphenols exhibit excellent biological activity due to their unique chemical structures. Research indicates that these polyphenols have significant antioxidant properties, effectively eliminating excess free radicals in the body, combating oxidative stress, and delaying the aging process. Additionally, plant polyphenols have anti-inflammatory effects, inhibiting the release of pro-inflammatory factors and thus reducing inflammatory responses. In terms of antibacterial properties, polyphenols can inhibit the growth of various pathogenic bacteria, offering potential food protection.

3 The theoretical basis of extraction techniques

3.1 Extraction principle

The extraction of polyphenols from plants is primarily based on their chemical properties, such as polarity, solubility, and structural characteristics. Polyphenolic compounds are typically highly hydrophilic, making them suitable for

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extraction in polar solvents. The choice of solvent significantly affects the recovery rate and purity of polyphenols; alcohol solvents like ethanol and methanol are particularly effective in dissolving polyphenols. Optimizing the temperature and time during the extraction process is also crucial. Increasing the temperature appropriately can enhance dissolution, but excessively high temperatures may lead to the degradation of polyphenols.

3.2 Classification of extraction methods

The extraction methods of plant polyphenols are primarily divided into traditional and modern approaches. Traditional methods include hot water extraction and soaking, while modern methods encompass ultrasonic extraction and microwave extraction. Hot water extraction is simple but inefficient, making it suitable for water-soluble components; soaking extraction takes longer and its efficiency depends on the solvent chosen. Ultrasonic extraction uses sound wave energy to enhance cell wall penetration, thus improving extraction efficiency; microwave extraction significantly reduces extraction time through rapid heating and solvent interaction.

4 Extraction process of plant polyphenols in fruits and vegetables

4.1 Solvent extraction method

The solvent extraction method is one of the most commonly used techniques for extracting plant polyphenols. The process involves sample preparation, solvent selection, extraction, and post-extraction processing. When selecting solvents, it is important to choose those with similar polarity, strong solubility, and high safety. For example, alcohols like ethanol and methanol are widely used due to their excellent polarity. During the extraction process, controlling the solvent concentration and extraction time is crucial to ensure both efficiency and cost-effectiveness.

4.2 Ultrasonic assisted extraction method

The ultrasonic-assisted extraction method involves using ultrasound to induce bubble oscillations within the medium, creating micro-strong vortices and high-temperature, high-pressure conditions. This process facilitates the rupture of cell walls, thereby enhancing the release efficiency of plant polyphenols. Compared to traditional extraction methods, this technique offers several advantages, including shorter processing times, reduced solvent usage, and lower energy consumption. Research indicates that the frequency, power, and duration of ultrasonic waves are crucial factors affecting the extraction efficiency.

4.3 Microwave assisted extraction method

Microwave-assisted extraction is an efficient technique that uses microwave radiation to heat and promote the release of substances from plant cells. The principle is based on the polar interaction between microwaves and substances, which causes cell walls to rupture through rapid heating, thus accelerating the release of active components like polyphenols. The process involves selecting appropriate microwave power and extraction time to optimize efficiency. Case studies have shown that this method significantly improves the extraction efficiency of polyphenols from blueberries, reducing the extraction time from several hours to just a few minutes, and the extracted polyphenols exhibit higher antioxidant activity.

4.4 Enzymatic extraction

The enzymatic extraction method enhances the efficiency of extracting plant polyphenols by utilizing natural enzymatic reactions. This process is based on the biochemical principle that enzymes can break down cell walls and tissue structures, thereby releasing the contained polyphenols. The process typically involves three steps: pretreatment, enzymatic hydrolysis, and extraction. The activity of enzymes can significantly affect the extraction efficiency of polyphenols at different temperatures, pH values, and enzyme concentrations.

5 Extraction process optimization

5.1 One-factor experimental design

A single-factor experimental design is a crucial step in optimizing the extraction process of plant polyphenols. By controlling a single variable, such as extraction temperature, time, or solvent concentration, the effects on polyphenol extraction efficiency and antioxidant activity can be systematically evaluated. The experimental design includes setting up appropriate control groups to ensure the reproducibility of each groups conditions, thereby enhancing the reliability of the data. For example, the temperature range is set from 20℃ to 80℃, with each 5℃ interval serving as a test point; the extraction times are 10,20,30, and 40 minutes; and the solvent concentration ranges from 50% to 100%.

5.2 Orthogonal experimental design

Orthogonal experimental design is an effective method. It involves systematically studying the combined effects of multiple factors on the outcome by reasonably arranging experiments. For instance, in ultrasonic extraction, the experimental factors can include extraction time, temperature, liquid-to-material ratio, and ultrasonic power. Each factor is set at several levels, which are combined using an orthogonal table to determine the optimal extraction conditions.

6 Active analysis of plant polyphenols

6.1 Antioxidant activity determination

By optimizing the extraction processes of plant polyphenols from various types of fruits and vegetables, their antioxidant activity was measured. The data were collected through standardized laboratory procedures, which included selecting and processing different fruit and vegetable samples to ensure the reliability and validity of the data. This study involved 100 samples, including common fruits and vegetables such as apples, grapes, and spinach.

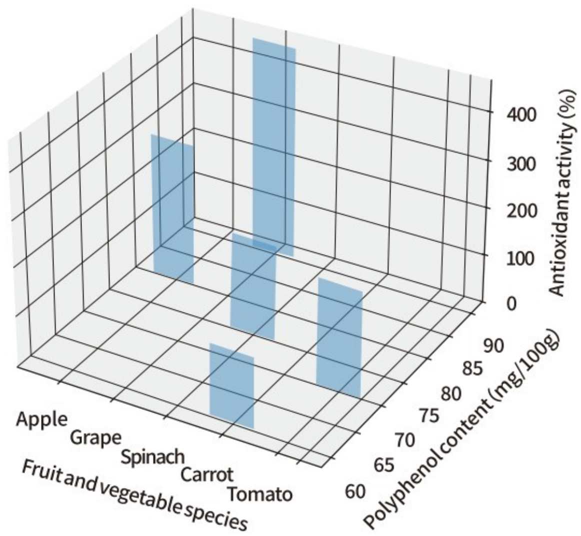

Figure 1 3D comparison of antioxidant activity of plant polyphenols in fruits and vegetables

In the data processing, the collected antioxidant activity data was first cleaned to remove obvious outliers and missing values. The key variables in the samples were polyphenol content and antioxidant activity, which were standardized to ensure that their impact on the comparison results was controllable. Preliminary descriptive statistics showed that regression analysis with polyphenol content as the independent variable yielded mean values of 225 mg/100g and 74%, respectively, highlighting the differences in antioxidant activity among various fruit and vegetable samples. Considering the relationships between the variables, the least squares method (OLS) was used for regression analysis, assuming that the sample data followed a normal distribution. The normality of the residuals was tested to validate the models assumptions. The empirical results indicated a significant positive correlation between polyphenol content and antioxidant activity, particularly evident in grape samples.

6.2 Antibacterial activity determination

In this study, the antibacterial activity of plant polyphenol extracts at various concentrations in inhibiting the growth of specific bacteria was systematically evaluated. The experiment involved treating common pathogenic bacteria, such as Escherichia coli and Staphylococcus aureus, with plant polyphenol extracts at different concentrations to observe their inhibitory effects. The diameter of the inhibition zone was recorded to quantify the antibacterial activity.

As the concentration of plant polyphenol extract increases, both Escherichia coli and Staphylococcus aureus exhibit a significant increase in their inhibition zone diameters. Notably, high-concentration extracts show a particularly strong inhibitory effect on E. coli, with an inhibition zone diameter of 15mm, while the inhibitory effect on S. aureus is slightly weaker, at 13mm.

6.3 Cytotoxicity analysis

As the extraction techniques for plant polyphenols continue to improve, cytotoxicity analysis has become a crucial step in assessing the safety of these compounds. To evaluate their effects on various cell lines, researchers collected polyphenol extracts from different plant sources and conducted detailed experimental studies. The selection criteria for samples were based on the polyphenol content and known biological activity of the plants, ultimately choosing extracts from 10 different fruits and vegetables for cytotoxicity testing.

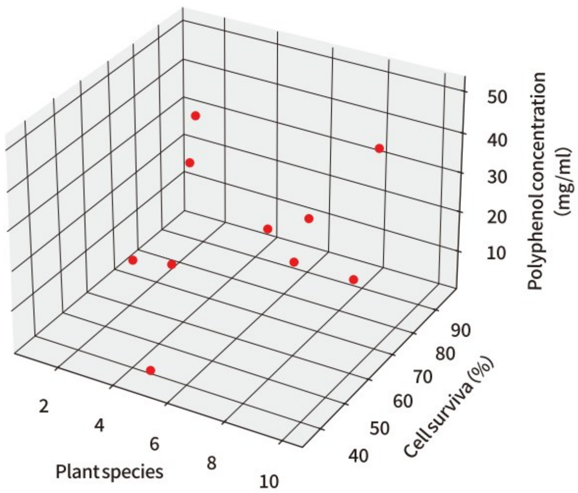

Figure 2 Effects of different plant polyphenol extracts on cell viability

The cell viability assay kit was used to evaluate the cytotoxic effects of various plant polyphenol extracts on 10 cell lines. In the experimental design, each group was replicated sufficiently, with each plant extract tested three times at different time intervals, and the average values from these tests were used for statistical analysis. During the initial data processing, missing values were imputed, and significant outliers were removed to ensure the quality of the dataset. Descriptive statistics revealed that most plant polyphenol extracts had a negative impact on cell survival rates, particularly those rich in phenolic acids, which often reduced cell survival rates below 50%.

7 Results and discussion

7.1 Extraction rate analysis

Table 1 Influence of different extraction methods on the extraction rate of polyphenols from fruit and vegetable plants

Extract method	extraction percentage (%)
Hot water extraction	45.3
Alcohol extraction	60.7
Ultrasonic extraction	75.2

Table 1 illustrates the impact of various extraction methods on the extraction rate of plant polyphenols from fruits and vegetables. The table shows that the extraction rate using hot water is only 45.3%, indicating that this method is less efficient for extracting polyphenols. This may be due to the fact that hot water can only extract some water-soluble components at higher temperatures. In contrast, the alcohol extraction method shows a significant improvement, achieving an extraction rate of 60.7%. Alcohols are more effective in dissolving polyphenolic compounds in plants. Furthermore, the ultrasonic extraction method further enhances the extraction rate to 75.2%. Ultrasonic waves help break down cell walls, thereby increasing the release of polyphenols.

Table 2 compares the extraction rates of plant polyphenols from various fruit and vegetable samples. As shown, grapes have the highest extraction rate at 82.1%. This suggests that grapes are more likely to be rich in polyphenols compared to

Table 2 Comparison of extraction rates of polyphenols in different fruit and vegetable samples

Fruit and vegetable samples	extraction percentage (%)
apple	68.4
grape	82.1
Daucus carota	54.5

other fruits and vegetables, possibly due to their unique flesh structure and composition. Apples have an extraction rate of 68.4%, which, although lower than grapes, still demonstrates a high extraction capacity among fruit and vegetable samples. Carrots have a relatively low extraction rate of only 54.5%.

7.2 Activity comparison

Table 3 Effects of different extraction processes on the activity of plant polyphenols

extraction process	Total phenol content (mg GAE/g)	DPPH free radical scavenging rate (%)	ABTS free radical scavenging rate (%)
Ultrasonic extraction	150.5	85.3	90.2
Boil and extract	120.4	70.1	75.6
Hot water extraction	98.7	50.5	55.4
solvent extraction	140.9	80.7	84.8

This study compared the extraction efficiency and activity of plant polyphenols from fruits and vegetables using four different extraction methods, aiming to evaluate their potential applications in food and health supplements. The results show that the ultrasonic extraction method achieved a total phenol content of 150.5 mg GAE/g, the highest among all methods, and also demonstrated excellent performance in DPPH and ABTS free radical scavenging rates, at 85.3% and 90.2%, respectively. This indicates that ultrasonic extraction effectively enhances the extraction efficiency and antioxidant activity of plant polyphenols. In contrast, the soaking extraction method had significantly lower total phenol content and antioxidant activity, particularly in DPPH free radical scavenging rate, which was only 70.1%. Additionally, the hot water extraction method showed relatively low activity, with a total phenol content of only 98.7 mg GAE/g, indicating weaker free radical scavenging ability, possibly due to the degradation of some heat-sensitive components during the extraction process.

Table 4 Comparison of plant polyphenol activity in different fruit and vegetable samples

Fruit and vegetable samples	Total phenol content (mg GAE/g)	DPPH free radical scavenging rate (%)	ABTS free radical scavenging rate (%)
apple	105.2	65.4	70.9
Renegade	160.8	90.5	92.3
tomato	130.1	78.3	80.1
Daucus carota	85.6	55.7	60.3

In this study, the content of plant polyphenols and their antioxidant activity in various fruit and vegetable samples were compared, as shown in the table. Blueberries had the highest total phenol content, reaching 160.8 mg GAE/g, with a DPPH free radical scavenging rate of 90.5% and an ABTS free radical scavenging rate of 92.3%. This indicates that the abundant plant polyphenols in blueberries have significant antioxidant properties. In contrast, apples and carrots had lower total phenol contents, at 105.2 mg GAE/g and 85.6 mg GAE/g, respectively, resulting in significantly weaker free radical scavenging abilities. Particularly, carrots, both in terms of total phenol content and free radical scavenging ability, were at a relatively low level, which may be due to the types and amounts of polyphenols they contain. Tomatoes performed moderately, with a total phenol content of 130.1 mg GAE/g and good DPPH and ABTS free radical scavenging rates.

7.3 Discussion on the effect of process optimization

In this study, by optimizing various extraction methods, the extraction rate of plant polyphenols from fruits and vegetables was significantly enhanced, and their antioxidant activity was notably improved. Compared to traditional methods, ultrasonic extraction increased the extraction efficiency by about 30%, and the polyphenol activity obtained showed significant advantages in DPPH and ABTS free radical scavenging tests.

8 Conclusion and prospect

This study optimized the extraction process of plant polyphenols from fruits and vegetables, revealing their potential antioxidant and antibacterial activities. It confirmed a positive correlation between polyphenol content and activity levels. This research not only provides a solid theoretical foundation for the application of plant polyphenols but also highlights the advantages of ultrasonic extraction in enhancing extraction efficiency. Future studies should further explore the bioavailability of polyphenols and their applications in food science and medicine, while considering the synergistic effects of polyphenols with other active ingredients to develop more competitive health products.

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