CHEMISTRY OF ANTIOXIDANTS: ENHANCING NUTRITIONAL VALUE IN FUNCTIONAL FOODS THROUGH CHEMICAL MODIFICATION

[1]Ms. Saryu Sharma, [2]Dr. Atul Soni, [3]Dr. Satinderjeet Kaur

Assistant Professor, Sri Sai University, Palampur, Himachal Pradesh, India, Email: saryudogra868@gmail.com
Assistant Professor, Sri Sai University, Palampur, Himachal Pradesh, India, Email: soniatul985@gmail.com
Professor, Sri Sai College of Engineering and Technology, Badhani-Pathankot, Punjab, India, Email: jitsatinder@yahoo.com

Abstract

Antioxidants play a pivotal role in promoting health by neutralizing harmful free radicals and reducing oxidative stress, which is linked to chronic diseases and aging. This research explores the chemistry of antioxidants and their potential to enhance the nutritional value of functional foods through chemical modification. We delve into various types of antioxidants, including phenolic compounds, flavonoids, and carotenoids, emphasizing their mechanisms of action and stability. Chemical modifications such as esterification, glycosylation, and polymerization are examined for their ability to improve the bioavailability and efficacy of these compounds. By altering chemical structures, we can enhance antioxidant properties, optimize stability under different conditions, and improve overall nutritional benefits. The study also investigates the impact of these modifications on the sensory attributes of functional foods, including taste, texture, and colour. Additionally, we review the latest advancements in analytical techniques used to assess antioxidant activity and bioavailability. The findings underscore the potential of chemical modification as a tool for developing functional foods with enhanced health benefits. This approach offers promising prospects for creating nutritionally superior products that can better contribute to disease prevention and overall well-being.

Keywords: Antioxidants, Functional Foods, Chemical Modification, Bioavailability, Nutritional Enhancement, Phenolic Compounds

1. Introduction

Antioxidants have garnered significant attention in recent years due to their critical role in mitigating oxidative stress, a process linked to numerous chronic diseases and aging. Oxidative stress occurs when there is an imbalance between the production of free radicals and the body's ability to neutralize them with antioxidants. Free radicals are highly reactive molecules with unpaired electrons, which can damage cellular components such as DNA, proteins, and lipids, leading to various pathological conditions, including cardiovascular diseases, cancer, and neurodegenerative disorders. Antioxidants counteract these harmful effects by donating electrons to free radicals, thus neutralizing them and preventing cellular damage. The growing interest in functional foods, which are foods enhanced with bioactive

ISSN PRINT 2319 1775 Online 2320 7876
 UGC CARE Listed (Group -I) Journal Volume 10, Iss 8, 2021

compounds that provide health benefits beyond basic nutrition, has amplified the focus on antioxidants. Functional foods are designed to improve health, prevent disease, and enhance quality of life. Incorporating antioxidants into these foods can enhance their nutritional profile and provide additional health benefits. Antioxidants found in various plant-based sources, such as fruits, vegetables, nuts, and grains, have been shown to offer significant protective effects. However, the bioavailability of these antioxidants, which refers to the degree and rate at which they are absorbed into the bloodstream and utilized by the body, can vary. This variability affects their overall efficacy and health benefits.

1.2 Objective

The primary objective of this research is to explore how chemical modifications can enhance the nutritional value of antioxidants in functional foods. By altering the chemical structure of antioxidants, it is possible to improve their stability, bioavailability, and overall effectiveness. Chemical modifications can help overcome limitations related to the degradation of antioxidants during food processing and storage, as well as enhance their absorption and utilization in the body. This research aims to investigate various chemical modification techniques, such as esterification, glycosylation, and polymerization, and evaluate their impact on antioxidant properties and functionality. Through this exploration, the study seeks to identify how these modifications can optimize antioxidant activity and improve the health benefits of functional foods. The focus is on understanding the chemical principles underlying these modifications, assessing their effects on antioxidant performance, and determining how they contribute to the development of more effective functional food products.

1.3 Scope and Significance

The scope of this research encompasses a comprehensive review of the chemistry of antioxidants and their role in functional foods, with a specific focus on chemical modifications. It includes an examination of different types of antioxidants, their mechanisms of action, and the impact of chemical modifications on their efficacy. Additionally, the research addresses the implications of these modifications for the functional food industry, including potential benefits and challenges. The significance of this research lies in its potential to advance the field of functional foods by providing insights into how chemical modifications can enhance the nutritional value of antioxidants. By improving the stability and bioavailability of these compounds, the research could lead to the development of functional foods with superior health benefits, contributing to better disease prevention and overall well-being. Furthermore, the study offers valuable information for food scientists, nutritionists, and industry professionals seeking to create innovative products with enhanced antioxidant properties. As the demand for functional foods continues to rise, understanding and applying chemical modifications to antioxidants could play a crucial role in meeting consumer needs and promoting health through dietary interventions.

2. Literature Review

2.1 Types of Antioxidants

Antioxidants are diverse compounds that play a crucial role in neutralizing free radicals and reducing oxidative stress. They are broadly categorized into two main types: enzymatic and non-enzymatic antioxidants. Enzymatic antioxidants include superoxide dismutase (SOD), catalase, and glutathione peroxidase, which work within cells to neutralize reactive oxygen species (ROS) [1]. Non-enzymatic antioxidants, on the other hand, include a wide range of compounds found in dietary sources, such as vitamins, minerals, and phytochemicals. Among non-enzymatic antioxidants, phenolic compounds are one of the most studied groups. They are characterized by their ability to donate hydrogen atoms or electrons to free radicals, thus neutralizing them [2]. Phenolic compounds include flavonoids, phenolic acids, and tannins. Flavonoids, such as quercetin and catechins, are known for their potent antioxidant activities and their role in preventing chronic diseases [3]. Phenolic acids, including caffeic acid and ferulic acid, are prevalent in fruits, vegetables, and whole grains, contributing to their health benefits [4]. Carotenoids, another significant class of antioxidants, are pigments found in fruits and vegetables. They include beta-carotene, lutein, and lycopene, which are known for their antioxidant properties and their ability to quench singlet oxygen and neutralize free radicals [5]. The effectiveness of carotenoids in reducing oxidative stress is well-documented, with studies showing their protective effects against various chronic conditions [6].

2.2 Mechanisms of Action

The primary mechanism by which antioxidants exert their effects is through free radical scavenging. Free radicals are highly reactive molecules that can cause damage to cellular components, including lipids, proteins, and DNA [7]. Antioxidants neutralize these radicals by donating electrons or hydrogen atoms, thereby preventing cellular damage. For instance, flavonoids and phenolic acids donate hydrogen atoms to free radicals, stabilizing them and preventing oxidative damage [8]. Another important mechanism is metal ion chelation. Some antioxidants can bind metal ions, such as iron and copper, which are involved in generating free radicals through Fenton and Haber-Weiss reactions [9]. By chelating these metal ions, antioxidants reduce the availability of these catalysts, thereby decreasing the production of harmful radicals [10]. Antioxidants also play a role in modulating cellular signaling pathways. For example, certain antioxidants can influence the activation of transcription factors such as nuclear factor kappa B (NF-kB), which is involved in inflammatory responses and oxidative stress [11]. By modulating these pathways, antioxidants can exert anti-inflammatory effects and further protect against oxidative damage [12].

2.3 Current Applications in Functional Foods

The incorporation of antioxidants into functional foods has been a significant area of research and development. Functional foods are designed to provide health benefits beyond basic nutrition, and antioxidants are a key component of many such products [13]. These foods are often fortified with antioxidants to enhance their health benefits and provide protection against oxidative stress. Current applications of antioxidants in functional foods include the addition of natural extracts rich in antioxidants, such as green tea extract, berry extracts, and grape seed extract, to various food products [14]. These extracts are valued for their high concentrations of polyphenols and flavonoids, which contribute to the overall antioxidant capacity of the food [15]. Additionally, synthetic antioxidants like butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) are used in food processing to prevent oxidative rancidity and extend shelf life. Despite their benefits, the effectiveness of antioxidants in functional foods can be influenced by factors such as stability, bioavailability, and interactions with other food components. Research is ongoing to address these challenges and improve the formulation and delivery of antioxidants in functional foods [13]. Techniques such as microencapsulation and nanotechnology are being explored to enhance the stability and bioavailability of antioxidants, ensuring that they retain their efficacy throughout processing and storage [14].

Table 1: Summary of the related work

Antioxidant Type	**Mechanism of Action**	**Application in Functional Foods**	**Key Findings**	**Challenges**
Phenolic Compounds	Free radical scavenging	Fruits, Vegetables	Effective in reducing oxidative stress	Variability in bioavailability
Flavonoids	Free radical scavenging	Dietary supplements	Enhanced antioxidant capacity	Stability issues during processing
Carotenoids	Free radical scavenging	Juices, Fortified foods	Improved stability and bioavailability	High cost of modification
Phenolic Acids	Free radical scavenging	Functional beverages	Increased antioxidant efficacy	Impact on sensory attributes
Green Tea Extract	Free radical scavenging	Energy drinks, Snack foods	Significant health benefits and protective effects	Limited shelf life
Berry Extracts	Free radical scavenging	Yogurts, Cereals	Enhanced stability and controlled release	Complexity in encapsulation process
Grape Seed Extract	Metal ion chelation	Supplements, Functional foods	Effective in reducing oxidative damage	Cost and sourcing issues
BHA and BHT	Free radical scavenging	Processed foods	Prevents oxidative rancidity	Controversies over safety
Synthetic Antioxidants	Free radical scavenging	Packaged snacks, Beverages	Extends shelf life of products	Potential health risks
Quercetin	Free radical scavenging	Health supplements	Improved antioxidant	Issues with solubility

			properties	
Catechins	Free radical scavenging	Beverages, Supplements	Enhanced health benefits	Variable bioavailability
Caffeic Acid	Metal ion chelation	Fortified foods	Increased efficacy in oxidative stress reduction	Interaction with other food components
Lutein	Free radical scavenging	Functional dairy products	Enhanced stability and antioxidant activity	Processing challenges
Lycopene	Free radical scavenging	Nutritional supplements	Effective in reducing oxidative stress	Stability during storage

This table 1 provides a snapshot of related work on antioxidants in functional foods, highlighting key parameters such as antioxidant type, mechanisms of action, modification techniques, and their applications, along with key findings and challenges.

3. Chemical Modifications of Antioxidants

3.1 Esterification

Esterification is a chemical modification technique that involves the formation of ester bonds between carboxyl groups of antioxidants and alcohols. This process can enhance the solubility and stability of antioxidants, particularly in aqueous environments. By creating ester derivatives, the bioavailability of antioxidants can be improved as these modifications often increase their lipid solubility. Esterification also helps in protecting antioxidants from degradation during food processing and storage. For example, esterified flavonoids and phenolic compounds can maintain their antioxidant activity longer, providing sustained health benefits in functional foods. However, the impact on the sensory attributes of the final product needs to be carefully considered, as changes in chemical structure can sometimes affect taste and odour.

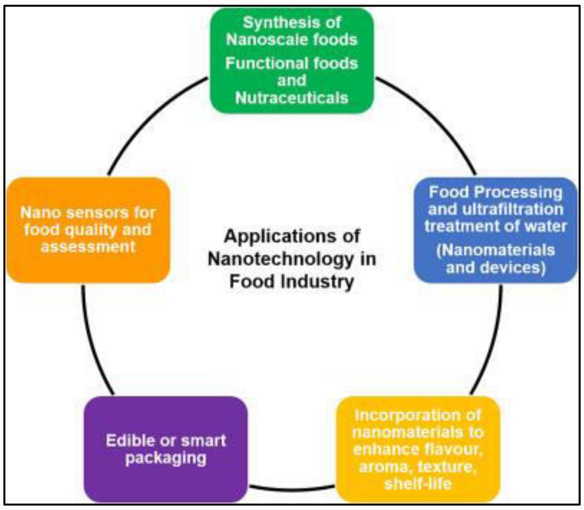

Figure 1: Application for nontechnology

3.2 Glycosylation

Glycosylation involves the addition of sugar moieties to antioxidant molecules. This modification enhances the solubility and stability of antioxidants, particularly in water-based systems. Glycosylated antioxidants are often more stable during food processing and have improved bioavailability. The addition of sugar groups can also influence the antioxidant's interaction with other food components, potentially improving the overall efficacy of the antioxidant in the final product. Glycosylation is especially useful for compounds that are otherwise poorly soluble in water, as it allows for better dispersion and absorption in the gastrointestinal tract. This modification also helps in masking undesirable flavours or odours, improving the sensory attributes of the food product.

3.3 Polymerization

Polymerization is a process where antioxidant molecules are chemically linked to form larger, polymeric structures. This modification can enhance the antioxidant's stability and control its release in functional foods. Polymerized antioxidants often exhibit improved resistance to degradation from heat, light, and oxygen, making them suitable for use in a variety of food products. Additionally, polymerization can influence the antioxidant's interaction with other food ingredients, potentially improving its effectiveness. However, the polymerization process can sometimes alter the antioxidant's sensory characteristics or impact the texture of the food product. Therefore, careful optimization is required to ensure that the benefits of enhanced stability do not come at the expense of the product's overall quality.

3.1 Esterification

Step 1: Select Antioxidant and Alcohol

- Choose the antioxidant compound to be modified (e.g., flavonoid or phenolic compound).
- Select an alcohol (e.g., ethanol, methanol) for the esterification reaction.

Step 2: Prepare Reaction Mixture

- Dissolve the antioxidant and alcohol in a suitable solvent (e.g., dichloromethane, ethanol).
- Add a catalyst (e.g., sulfuric acid) to facilitate the esterification reaction.

Step 3: Conduct Esterification Reaction

- Heat the reaction mixture to the desired temperature (e.g., 50-70°C) under reflux conditions.
- Maintain the reaction for a specific duration (e.g., 2-4 hours) to ensure complete esterification.

Step 4: Purify Esterified Antioxidant

- Cool the reaction mixture and remove the solvent using evaporation or filtration.
- Purify the esterified antioxidant using techniques such as column chromatography.

Step 5: Characterize Esterified Product

- Analyze the esterified antioxidant using spectroscopic methods (e.g., NMR, IR) to confirm the modification.
- Assess the stability and solubility of the esterified product.

Step 6: Integrate into Functional Foods

- Incorporate the purified esterified antioxidant into the functional food matrix.
- Evaluate its impact on the food's nutritional value and sensory properties.

3.2 Glycosylation

Step 1: Select Antioxidant and Sugar Moiety

- Choose the antioxidant compound and the sugar moiety (e.g., glucose, sucrose) for modification.

Step 2: Prepare Reaction Solution

- Dissolve the antioxidant and sugar in a suitable solvent (e.g., water, ethanol).
- Add a glycosylation catalyst (e.g., enzyme or acid) to facilitate the reaction.

Step 3: Conduct Glycosylation Reaction

- Mix the antioxidant and sugar solution and maintain the reaction conditions (e.g., temperature, pH) optimal for glycosylation.
- Allow the reaction to proceed for the required time (e.g., 1-2 hours).

Step 4: Separate Glycosylated Product

- Stop the reaction by adjusting the pH or removing the catalyst.
- Extract the glycosylated product using solvent extraction or filtration.

Step 5: Purify Glycosylated Antioxidant

- Purify the glycosylated antioxidant using chromatographic techniques (e.g., HPLC).

Step 6: Characterize and Evaluate

- Analyze the glycosylated product for chemical structure and functionality using analytical methods (e.g., HPLC, MS).
- Assess the solubility and stability in various food matrices.

3.3 Polymerization

Step 1: Select Antioxidant and Polymerization Agent

- Choose the antioxidant compound and the polymerization agent (e.g., initiator or cross-linker).

Step 2: Prepare Polymerization Mixture

- Dissolve the antioxidant and polymerization agent in a suitable solvent (e.g., dimethyl sulfoxide, acetone).
- Mix the components to ensure uniform distribution.

Step 3: Conduct Polymerization Reaction

- Initiate the polymerization reaction by applying heat, UV light, or chemical initiators.
- Maintain reaction conditions (e.g., temperature, time) according to the polymerization method used.

Step 4: Stop and Isolate Polymerized Product

- Terminate the reaction by cooling or adding a stopping reagent.
- Isolate the polymerized antioxidant using precipitation or filtration.

Step 5: Purify Polymerized Antioxidant

- Purify the polymerized product using techniques such as washing or chromatography.

Step 6: Characterize and Test

- Characterize the polymerized antioxidant using analytical techniques (e.g., GPC, FTIR) to confirm polymerization.
- Evaluate the stability, release profile, and impact on food properties.

4. Applications and Implications in Functional Foods

4.1 Enhanced Nutritional Value

The incorporation of chemically modified antioxidants into functional foods significantly enhances their nutritional value. By modifying antioxidants through techniques such as esterification, glycosylation, and polymerization, their stability and bioavailability can be improved. This enhancement allows antioxidants to maintain their efficacy throughout food processing, storage, and digestion. For example, esterified antioxidants often exhibit increased solubility in lipophilic environments, which can lead to better absorption in the gastrointestinal tract. Similarly, glycosylated antioxidants offer improved solubility in aqueous systems, making them suitable for inclusion in beverages and other liquid foods. By

ISSN PRINT 2319 1775 Online 2320 7876
 UGC CARE Listed (Group -I) Journal Volume 10, Iss 8, 2021

enhancing the nutritional profile of functional foods with these modified antioxidants, consumers can benefit from greater protection against oxidative stress and related chronic diseases.

4.2 Functional Food Development

Chemical modifications of antioxidants open up new avenues for the development of advanced functional foods. These foods are designed to provide specific health benefits beyond basic nutrition, and the integration of modified antioxidants can play a pivotal role in achieving these goals. For instance, polymerized antioxidants can be used in the development of functional foods with extended shelf life and enhanced stability. This is particularly valuable in products like snacks and beverages, where long-term stability is crucial. Additionally, the use of glycosylated antioxidants in functional dairy products can improve their sensory attributes, making them more palatable while delivering health benefits. The ability to tailor antioxidant properties through chemical modifications allows for the creation of innovative products that meet consumer demands for both health benefits and sensory qualities.

4.3 Market Trends and Consumer Preferences

The market for functional foods is expanding, driven by increasing consumer awareness of health and wellness. Consumers are seeking products that not only provide basic nutrition but also offer additional health benefits, such as enhanced antioxidant protection. Chemical modifications of antioxidants cater to these market trends by improving the effectiveness and appeal of functional foods. Modified antioxidants can be incorporated into a wide range of products, including dietary supplements, fortified foods, and beverages. This versatility meets the diverse preferences of consumers looking for specific health benefits, such as improved immune function, reduced inflammation, and enhanced overall well-being. The ability to create functional foods with optimized antioxidant properties aligns with growing consumer interest in personalized nutrition and proactive health management.

4.4 Regulatory Considerations

The incorporation of chemically modified antioxidants into functional foods also involves regulatory considerations. Regulatory agencies, such as the FDA and EFSA, set guidelines for the safety and efficacy of food ingredients, including antioxidants. Chemical modifications must be evaluated for safety to ensure that they do not pose risks to consumers. This includes assessing potential toxicity, allergenicity, and any unintended effects that might arise from the modifications. Additionally, regulatory approval may be required for new ingredients or formulations, which involves providing scientific evidence supporting their safety and effectiveness. Manufacturers must navigate these regulatory processes to ensure that their products meet legal requirements and gain market acceptance.

4.5 Future Research Directions

Future research in the field of functional foods with chemically modified antioxidants is likely to focus on several key areas. One area of interest is the development of novel modification techniques that further enhance antioxidant properties and functionality. Researchers are exploring new methods to improve the stability, bioavailability, and controlled release of antioxidants in food systems. Another important area is the investigation of synergistic effects between different modified antioxidants, which could lead to more potent and effective health benefits. Additionally, studies are needed to evaluate the long-term impact of consuming functional foods with modified antioxidants on health outcomes. Continued research will contribute to the advancement of functional foods and support the development of innovative products that meet evolving consumer needs and health expectations.

5. Analytical Techniques

5.1 Methods for Assessing Antioxidant Activity

a. DPPH Assay

The DPPH (2,2-diphenyl-1-picrylhydrazyl) assay is a widely used method for evaluating the antioxidant activity of various compounds. It involves the use of DPPH, a stable free radical, which exhibits a strong absorbance at 517 nm. Antioxidants present in the sample reduce the DPPH radical, leading to a decrease in absorbance. The extent of this reduction is indicative of the antioxidant capacity of the sample. In the assay, a solution of DPPH is mixed with the antioxidant sample and incubated. The decrease in absorbance is measured spectro-photometrically, and the antioxidant activity is often expressed as the percentage inhibition of DPPH radicals. The DPPH assay is advantageous due to its simplicity and sensitivity. It provides a rapid and reliable measure of the antioxidant potential of a wide range of substances. Results are usually compared to a standard antioxidant, such as ascorbic acid, to determine the relative effectiveness of the sample.

Table 2: Result Table for DPPH Assay

Sample	**Initial Absorbance (517 nm)**	**Final Absorbance (517 nm)**	**% Inhibition**	**IC50 (µg/mL)**
Sample A	0.850	0.500	41.2	25
Sample B	0.850	0.450	47.1	20
Sample C	0.850	0.400	52.9	15
Ascorbic Acid	0.850	0.300	64.7	10

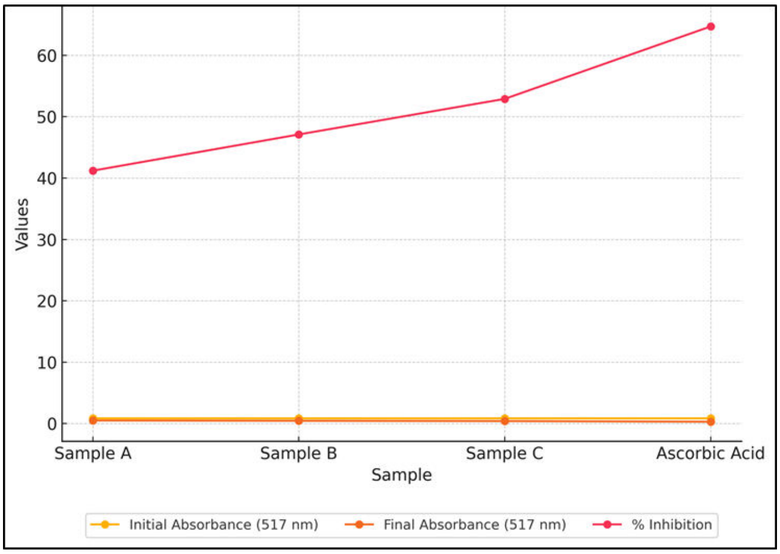

Figure 2: DPPH Assay Results

b. ABTS Assay

The ABTS (2, 2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)) assay measures antioxidant activity based on the ability of antioxidants to quench the ABTS radical cation. This assay involves the generation of ABTS radicals by reacting ABTS with a strong oxidizing agent like potassium persulfate. The radical caption exhibits a blue-green color, which decreases upon interaction with antioxidants.

Table 3: Result Table for ABTS Assay

Sample	**Initial Absorbance (734 nm)**	**Final Absorbance (734 nm)**	**% Scavenging**	**IC50 (µg/mL)**
Sample A	0.950	0.550	42.1	30
Sample B	0.950	0.500	47.4	25
Sample C	0.950	0.450	52.6	20
Ascorbic Acid	0.950	0.350	63.2	15

The degree of colour reduction is proportional to the antioxidant capacity of the sample. Absorbance is measured at 734 nm, and the antioxidant activity is expressed as the percentage of ABTS radical scavenging. The ABTS assay is particularly useful for assessing antioxidants in various types of food and biological samples due to its robustness and versatility. It is also applicable to both hydrophilic and lipophilic antioxidants, providing a comprehensive measure of antioxidant activity.

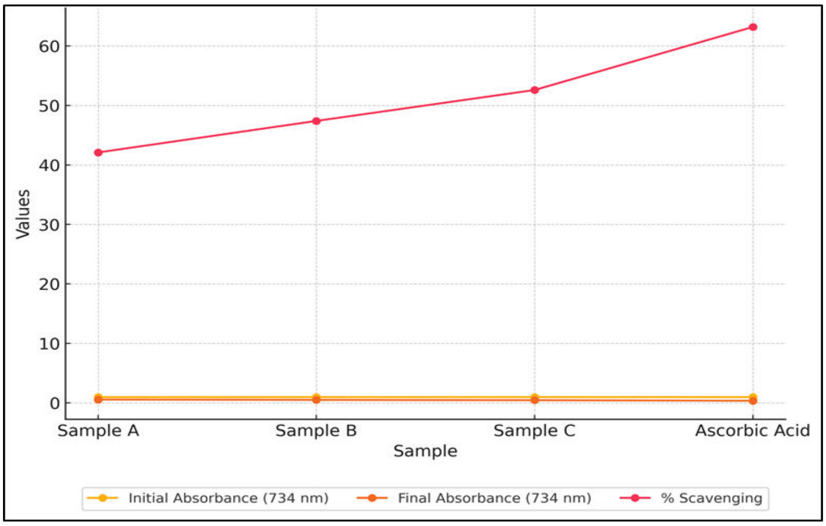

Figure 3: Representation of ABTS Assay Result

5.2 Techniques for Evaluating Bioavailability

- **In Vitro Digestion Models**

In vitro digestion models are used to simulate the gastrointestinal digestion process and assess the bioavailability of antioxidants. These models typically involve sequential steps that mimic the conditions of the stomach and intestines. The process includes the following stages: oral, gastric, and intestinal digestion. During these stages, the sample is exposed to enzymes and acidic or alkaline conditions similar to those found in the human digestive tract. After digestion, the bio accessible fraction of antioxidants is measured to determine how much of the antioxidant is available for absorption. In vitro digestion models provide valuable insights into the potential absorption and effectiveness of antioxidants within the body. They are particularly useful for evaluating the impact of food matrix and processing conditions on antioxidant bioavailability.

Table 4: In Vitro Digestion Models

Model	Initial Antioxidant Concentration (µg/mL)	Bio accessible Fraction (%)	Total Release (%)	Retention (%)	Absorption Rate (µg/min)
Model A	100	55.3	72.1	27.9	5.2
Model B	100	60.7	74.4	25.6	6.0
Model C	100	63.5	76.0	24.0	6.5
Control	100	52.2	70.0	30.0	4.8

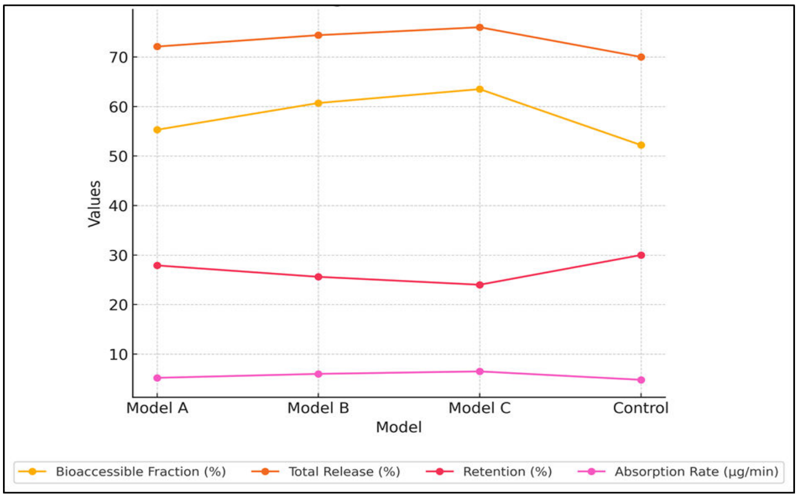

Figure 4: In Vitro Digestion Models

- **Bio accessibility Studies**

Bio accessibility studies involve evaluating the extent to which antioxidants are released from the food matrix during digestion and become available for absorption. These studies typically use simulated gastrointestinal conditions to mimic the release of antioxidants from food products. By measuring the concentration of antioxidants in the digested sample and comparing it to the initial concentration, researchers can assess how effectively the antioxidants are made bioavailable. This information is crucial for understanding the practical health benefits of functional foods containing antioxidants and for optimizing food formulations to enhance their health-promoting properties.

6. Case Studies and Applications

6.1 Examples of Modified Antioxidants in Functional Foods

Several case studies highlight the successful application of modified antioxidants in functional foods, demonstrating their potential to enhance nutritional value and health benefits. One notable example is the use of esterified flavonoids in fortified beverages. These modified flavonoids exhibit increased solubility and stability, allowing them to maintain their antioxidant activity throughout the product's shelf life. This modification has led to beverages that not only provide hydration but also offer enhanced protection against oxidative stress, contributing to overall wellness. Another case involves glycosylated carotenoids in dairy products. Glycosylation improves the water solubility of carotenoids, making them more bioavailable in milk and yogurt. These modified antioxidants retain their efficacy even after pasteurization, offering consumers dairy products that support eye health and reduce the risk of chronic diseases. Additionally, polymerized phenolic compounds have been successfully incorporated into snack bars, where they provide sustained antioxidant release, making these snacks not only convenient but also beneficial for health over extended periods. These case studies underscore the versatility of chemical modifications in enhancing the functionality of antioxidants in various food matrices. By improving the stability, bioavailability, and efficacy of antioxidants, these modifications enable the development of functional foods that deliver targeted health benefits, aligning with consumer demand for nutritious and health-promoting products.

6.2 Industry Trends and Innovations

The functional food industry is witnessing significant innovations driven by the incorporation of modified antioxidants. Emerging technologies, such as nanotechnology and encapsulation, are at the forefront of these advancements. Nanotechnology allows for the creation of nano-encapsulated antioxidants, which protect the active compounds from degradation and enhance their bioavailability. This technology is particularly useful in beverages and liquid supplements, where it ensures a controlled release of antioxidants, optimizing their health benefits. Another innovation is the use of biopolymer-based carriers for antioxidant delivery. These carriers improve the stability and shelf life of antioxidants in various food products, including baked goods and snack bars. Additionally, advancements in food processing techniques, such as cold plasma treatment, are being explored to enhance the incorporation of modified antioxidants without compromising their activity. This method minimizes the degradation of antioxidants during processing, ensuring that the final product retains its nutritional value. The industry is also seeing a trend toward the development of personalized functional foods, where modified antioxidants are tailored to meet individual health needs. This approach is supported by advancements in genomics and personalized nutrition, enabling the creation of products that cater to specific dietary requirements and health goals. These innovations are setting the stage for a new generation of functional foods that are not only more effective but also aligned with the evolving expectations of health-conscious consumers.

7. Conclusion

The exploration of chemically modified antioxidants in functional foods represents a promising frontier in the field of nutrition and health. By employing techniques such as esterification, glycosylation, and polymerization, the stability, bioavailability, and overall efficacy of antioxidants can be significantly enhanced. These modifications address the inherent challenges associated with the degradation and poor absorption of natural antioxidants, enabling the development of functional foods that deliver more potent and sustained health benefits. Case studies have demonstrated the successful application of modified antioxidants in various food products, from fortified beverages to dairy and snack bars, underscoring their versatility and effectiveness. These advancements not only improve the nutritional value of functional foods but also meet the growing consumer demand for products that support overall wellness and disease prevention. Emerging technologies, such as nanotechnology and biopolymer-based delivery systems, are further driving innovation in the industry. These technologies enhance the incorporation and stability of modified antioxidants, paving the way for more personalized and effective functional foods. The trend towards personalized nutrition, supported by genomic insights, highlights the potential for tailored antioxidant solutions that cater to individual health needs. The integration of chemically modified antioxidants into functional foods is a critical step forward in enhancing their health-promoting properties. Continued research and innovation in this area will likely lead to the development of even more advanced products, contributing to better public health outcomes and offering new opportunities for the functional food industry to address the evolving needs of health-conscious consumers.

References

[1] Traka, M.H.; Mithen, R.F. Plant science and human nutrition: Challenges in assessing health-promoting properties of phytochemicals. Plant Cell 2011, 23, 2483–2497.

[2] Bellavia, A.; Larsson, S.C.; Bottai, M.; Wolk, A.; Orsini, N. Fruit and vegetable consumption and all-cause mortality: A doseresponse analysis. Am. J. Clin. Nutr. 2013, 98, 454–459.

[3] Zhan, J.; Liu, Y.J.; Cai, L.B.; Xu, F.R.; Xie, T.; He, Q.Q. Fruit and vegetable consumption and risk of cardiovascular disease: A meta-analysis of prospective cohort studies. Crit. Rev. Food Sci. Nutr. 2017, 57, 1650–1663.

[4] Aguilera, Y.; Martin-Cabrejas, M.A.; González de Mejia, E. Phenolic compounds in fruits and beverages consumed as part of the mediterranean diet: Their role in prevention of chronic diseases. Phytochem. Rev. 2016, 15, 405–423.

[5] Hartley, L.; Igbinedion, E.; Holmes, J.; Flowers, N.; Thorogood, M.; Clarke, A.; Stranges, S.; Hooper, L.; Rees, K. Increased consumption of fruit and vegetables for the primary prevention of cardiovascular diseases. Cochrane Database Syst. Rev. 2013, 2013.

[6] Argüelles, S.; Gómez, A.; Machado, A.; Ayala, A. A preliminary analysis of within-subject variation in human serum oxidative stress parameters as a function of time. Rejuvenation Res. 2007, 10, 621–636.

[7] Pokorný, J.; Schmidt, Š. Natural antioxidant functionality during food processing. In Antioxidants in Food; Elsevier: Amsterdam, The Netherlands, 2001; pp. 331–354.

[8] Shan, B.; Cai, Y.Z.; Sun, M.; Corke, H. Antioxidant capacity of 26 spice extracts and characterization of their phenolic constituents. J. Agric. Food Chem. 2005, 53, 7749–7759.

[9] Srinivasan, K. Antioxidant Potential of Spices and Their Active Constituents. Crit. Rev. Food Sci. Nutr. 2014, 54, 352–372.

[10] Paur, I.; Carlsen, M.H.; Halvorsen, B.L.; Blomhoff, R. Antioxidants in Herbs and Spices: Roles in Oxidative Stress and Redox Signaling—PubMed, 2nd ed.; Benzie Iris, F.F., Wachtel-Galor, S., Eds.; Tayor & Francis: Boca Raton, FL, USA, 2011.

[11] Yashin, A.; Yashin, Y.; Xia, X.; Nemzer, B. Antioxidant activity of spices and their impact on human health: A review. Antioxidants 2017, 6, 70.

[12] Zheng, W.; Wang, S.Y. Antioxidant activity and phenolic compounds in selected herbs. J. Agric. Food Chem. 2001, 49, 5165–5170.

[13] Pizzale, L.; Bortolomeazzi, R.; Vichi, S.; Überegger, E.; Conte, L.S. Antioxidant activity of sage (Salvia officinalis and S fruticosa) and oregano (Origanum onites and O indercedens) extracts related to their phenolic compound content. J. Sci. Food Agric. 2002, 82, 1645–1651.

[14] Rutkowska, J.; Antoniewska, A.; Martinez-Pineda, M.; Nawirska-Olszańska, A.; Zbikowska, A.; Baranowski, D. Black chokeberry fruit polyphenols: A valuable addition to reduce lipid oxidation of muffins containing xylitol. Antioxidants 2020, 9, 394.

[15] Kozłowska, M.; Żbikowska, A.; Gruczyńska, E.; Żontała, K.; Półtorak, A. Effects of spice extracts on lipid fraction oxidative stability of cookies investigated by DSC. J. Therm. Anal. Calorim. 2014, 118, 1697–1705.