

ROLE OF FOOD MATRIX ON THE CHEMICAL STABILITY OF NUTRIENTS DURING PROCESSING AND STORAGE

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Abstract: The stability of nutrients within foods is profoundly influenced by the food matrix—the intricate physical and chemical structure that defines how various components interact. This paper investigates the role of the food matrix in determining nutrient stability during both processing and storage. It highlights how different matrices, such as cellular structures in fruits and vegetables or lipid-rich environments, can either protect nutrients from degradation or exacerbate their loss. The review covers the impact of mechanical processing, chemical interactions, and processing conditions such as temperature and pH on nutrient stability. It also examines how storage factors, including humidity and light exposure, affect nutrient retention within different matrices. The paper explores the role of additives, such as antioxidants and preservatives, in interacting with the food matrix to either enhance or diminish nutrient preservation. Understanding these dynamics is crucial for optimizing food processing and storage methods to maximize nutrient retention and improve food quality. This comprehensive review provides insights into the complex relationships between the food matrix and nutrient stability, offering guidance for future research and practical applications in food science and technology.

Keywords: Food Matrix, Nutrient Stability, Processing, Storage, Physical Structure, Chemical Interactions, Nutrient Degradation, Food Processing, Nutrient Retention, Additives, Antioxidants, Preservatives

I. Introduction

The food matrix, an intricate network of physical and chemical components, plays a pivotal role in influencing the stability and availability of nutrients during processing and storage. This matrix comprises various elements such as proteins, carbohydrates, lipids, vitamins, and minerals, each interacting in complex ways that impact nutrient integrity [1]. The significance of the food matrix extends beyond mere composition; it affects how nutrients are shielded from degradation or exposed to factors that lead to their loss. During food processing, the matrix can either protect or expose nutrients to conditions that might lead to their degradation [2]. For instance, whole foods, including fruits and vegetables, naturally contain cellular structures that offer protection to sensitive nutrients like vitamins and antioxidants. These structures act as barriers against environmental factors such as oxygen and light, which are

known to cause oxidative damage. Processing methods like chopping, grinding, or cooking can disrupt these protective structures, increasing the surface area of nutrients exposed to potentially damaging conditions [3]. The physical breakdown of the food matrix during such processes often leads to a higher rate of nutrient loss, highlighting the need for careful consideration of processing techniques to minimize detrimental effects. Chemical interactions within the food matrix also play a crucial role in determining nutrient stability. Nutrients do not exist in isolation; they interact with other food components, which can either stabilize or degrade them. For example, the Maillard reaction, a chemical reaction between amino acids and reducing sugars that occurs during cooking, can lead to the loss of certain vitamins such as vitamin C [4]. Conversely, fat-soluble vitamins (A, D, E, and K) are often more stable when embedded within lipid matrices, where they are less susceptible to oxidative damage. This interaction between nutrients and other matrix components underscores the complexity of maintaining nutrient stability and the importance of understanding these relationships in food processing and formulation. The impact of processing conditions on nutrient stability cannot be overlooked [5]. Variables such as temperature, pressure, and pH play significant roles in determining how well nutrients are preserved. High temperatures used in cooking and pasteurization can lead to the breakdown of heat-sensitive vitamins like folate and vitamin C. The food matrix influences the extent of nutrient degradation under these conditions; for instance, nutrients encased within a dense starch or protein matrix might experience less degradation compared to those in a more exposed or less structured form [6]. Thus, optimizing processing conditions in conjunction with understanding the food matrix is essential for minimizing nutrient loss. Storage conditions further complicate the picture of nutrient stability. Factors such as humidity, light, and temperature can affect how well nutrients are retained over time. The food matrix continues to influence nutrient preservation during storage. For instance, dried foods, which have a reduced water activity within their matrix, can better preserve nutrients compared to moist foods, where microbial growth and enzymatic activity might accelerate nutrient degradation [7]. The interaction between storage conditions and the food matrix is critical in determining the shelf life and nutritional quality of foods. Additives such as preservatives and antioxidants play a role in nutrient stability by interacting with the food matrix. These additives can either enhance or hinder nutrient preservation depending on their compatibility with the matrix components [8]. For example, antioxidants can help protect sensitive nutrients from oxidative damage, while some preservatives might interact with the matrix in ways that affect nutrient retention. The food matrix profoundly influences the stability of nutrients during processing and storage. Its complex interplay with physical structure, chemical interactions, processing conditions, and storage factors underscores the importance of understanding and optimizing the matrix to enhance nutrient preservation [9]. This exploration into the role of the food matrix provides valuable insights for improving food quality and nutritional value through better processing and storage practices.

II. Literature Study

The concept of metabolic syndrome remains controversial due to its diagnostic criteria and clinical utility, which has sparked ongoing debate. Nutraceuticals and functional foods have been shown to offer significant health benefits, particularly when compared to processed

alternatives, with whole foods generally providing superior nutritional advantages [10]. During the COVID-19 pandemic, various food ingredients and active compounds were explored for their potential impact on mitigating the virus, highlighting the need for resilient food systems. Innovations in food matrices designed to enhance the bioavailability of pharmaceuticals and nutraceuticals have shown promise, while the stability and bioaccessibility of key nutrients like carotenoids and vitamin A during digestion are crucial for effective nutrition [11]. The role of bioactive compounds in preventing cardiovascular disease and cancer underscores their importance in dietary recommendations. Research on whey protein-starch systems and protein-based edible coatings suggests potential for improving food functionality and healthfulness [12].

Author & Year	Area	Methodology	Key Findings	Challenges	Pros	Cons	Application
Moebus & Stang, 2007	Metabolic Syndrome	Review and critique	Metabolic syndrome is a useful framework but its diagnostic criteria are controversial.	Lack of precise definition and diagnostic tools	Useful for identifying high-risk individuals	Controversial diagnostic criteria	Clinical practice and risk assessment
Shahidi, 2009	Nutraceuticals vs. Processed Foods	Review	Whole foods offer better nutritional benefits than processed foods.	Processing often depletes nutrients	Nutraceuticals offer health benefits	Processed foods can lose valuable nutrients	Dietary recommendations and nutraceutical development
Galankis et al., 2020	Food Ingredients for COVID-19	Comprehensive review	Some food ingredients have antiviral properties that might	Efficacy of ingredients in preventing illness	Potential for food-based interventions during pandemics	Limited evidence on effectiveness	Public health strategies and dietary supplements

			mitigate COVID-19 impact.				
Galana kis, 2020	Food Systems and COVID-19	Review	The pandemic has disrupted food supply chains and highlighted the need for resilient food systems.	Global food supply chain disruptions	Highlights need for resilient food systems	Requires significant policy changes	Food system resilience and policy development
McClements & Xiao, 2014	Excipient Foods	Review and design analysis	Designing food matrices can enhance the oral bioavailability of active compounds.	Complex formulation requirements	Can improve therapeutic outcomes	Requires specialized knowledge in formulation	Development of functional food products
Courraud et al., 2013	Carotenoids and Vitamin A Stability	In vitro digestion studies	Stability and bioaccessibility of carotenoids and vitamin A vary during digestion.	Variability in digestion conditions	Provides insights into nutrient bioavailability	Potential variability in individual digestion	Nutrient formulation and dietary planning
Kris-Etherto	Bioactive	Review	Bioactive compound	Determining	Provides evidence	Requires more	Dietary guidelines

n et al., 2002	Compounds and Disease Prevention		ds can prevent cardiovascular disease and cancer.	optimal intake levels	for dietary recommendations	research on long-term effects	and health promotion
Pogaku et al., 2007	Whey Protein Isolate-Starch Systems	Critical review	Whey proteins and starches interact to affect food texture and functionality.	Interaction complexity	Enhances food texture and functionality	Requires precise formulation and processing	Food product development and enhancement

Table 1. Summarizes the Literature Review of Various Authors

In this Table 1, provides a structured overview of key research studies within a specific field or topic area. It typically includes columns for the author(s) and year of publication, the area of focus, methodology employed, key findings, challenges identified, pros and cons of the study, and potential applications of the findings. Each row in the table represents a distinct research study, with the corresponding information organized under the relevant columns. The author(s) and year of publication column provides citation details for each study, allowing readers to locate the original source material. The area column specifies the primary focus or topic area addressed by the study, providing context for the research findings.

III. Physical Structure and Nutrient Protection

The physical structure of the food matrix plays a pivotal role in influencing the stability of nutrients during processing and storage. This structure, encompassing the arrangement and interaction of food components such as cells, fibers, and matrices, can significantly affect how nutrients are protected or exposed to degradation factors. In whole foods like fruits and vegetables, the cellular structure often acts as a natural barrier, protecting sensitive nutrients from environmental factors such as oxygen, light, and moisture. For instance, the cell walls in these foods can encapsulate vitamins and antioxidants, thereby shielding them from oxidative damage. This intrinsic protection is particularly important for vitamins like vitamin C and various antioxidants that are highly susceptible to degradation. When foods are mechanically processed, such as through chopping, grinding, or blending, the physical matrix is disrupted, which can increase the exposure of nutrients to degradation factors. For example, the disruption of cellular structures during fruit juicing or vegetable chopping can lead to greater surface area exposure, making nutrients more vulnerable to oxidation and enzymatic

degradation. This increased exposure can result in significant nutrient loss if not managed properly. The processing can alter the texture and consistency of the food, which may impact how well nutrients are retained or how they interact with other components in the matrix. Encapsulation technologies, such as microencapsulation, have been developed to protect sensitive nutrients from degradation. In these methods, nutrients are enclosed within protective matrices that can shield them from environmental factors and enhance their stability during processing and storage. For example, the encapsulation of vitamins in lipid-based matrices can protect them from oxidative damage, while encapsulation in starch or polymer matrices can provide protection against moisture and heat. These technologies are particularly useful for enhancing the stability of sensitive nutrients in processed foods and supplements. The impact of physical structure on nutrient stability is also evident in the context of food storage. For example, in dried foods, the reduction in water activity due to drying can help preserve nutrients by limiting microbial growth and enzymatic activity that can lead to nutrient degradation. The physical matrix of dried foods, often characterized by a more porous structure, can influence how effectively moisture is removed and how well nutrients are preserved. Conversely, in more moist environments, the physical matrix can be less effective at protecting nutrients from degradation, leading to potential nutrient losses over time. Overall, the physical structure of the food matrix is a critical factor in determining nutrient stability. By understanding and manipulating this structure, it is possible to enhance the retention of nutrients during processing and storage. Innovations in food processing and preservation techniques, such as advanced encapsulation methods and controlled processing conditions, can help improve nutrient stability and contribute to the overall nutritional quality of foods.

IV. Chemical Interactions and Nutrient Stability

The chemical interactions within the food matrix are crucial in determining the stability of nutrients during processing and storage. Nutrients often interact with other food components, such as proteins, carbohydrates, and lipids, which can influence their stability and bioavailability. These interactions can be both beneficial and detrimental, depending on the nature of the nutrient and the components involved. One significant example of how chemical interactions affect nutrient stability is the Maillard reaction, which occurs between amino acids and reducing sugars during thermal processing. This reaction, while contributing to the flavor and color of cooked foods, can lead to the degradation of sensitive nutrients such as vitamin C and certain B vitamins. The Maillard reaction can result in the formation of brown pigments and flavor compounds, but it also leads to the loss of vitamins through complex reactions that make them less bioavailable or completely inactive. Conversely, certain chemical interactions within the food matrix can enhance nutrient stability. Fat-soluble vitamins, such as vitamins A, D, E, and K, are often better protected in lipid-rich environments. The presence of fats can shield these vitamins from oxidative damage and degradation, as they are less exposed to reactive oxygen species compared to their aqueous surroundings. This protective effect is particularly relevant during food processing and storage, where the stability of these vitamins is often a concern. Interactions between nutrients and other matrix components can also influence nutrient stability. For example, the binding of minerals like calcium, iron, and zinc to proteins or fiber in the food matrix can

affect their bioavailability and stability. In some cases, such interactions can enhance nutrient stability by reducing their susceptibility to oxidation or degradation. In other cases, they may reduce bioavailability by forming complexes that are less readily absorbed in the digestive tract. Enzymatic reactions within the food matrix can also impact nutrient stability. Enzymes such as lipoxygenase and polyphenol oxidase can catalyze reactions that lead to the degradation of vitamins and antioxidants. For instance, lipoxygenase can catalyze the oxidation of lipids, leading to the production of rancid off-flavors and the degradation of fat-soluble vitamins. Polyphenol oxidase, commonly found in fruits and vegetables, can cause browning and loss of nutrients such as vitamin C through oxidation reactions. To mitigate the impact of these chemical interactions on nutrient stability, various strategies can be employed. These include the use of antioxidants and chelating agents to neutralize reactive species that can cause nutrient degradation, as well as optimizing processing conditions to minimize detrimental reactions. For example, adjusting pH levels or using lower temperatures during processing can help reduce the extent of Maillard reactions and other undesirable chemical interactions. Chemical interactions within the food matrix play a critical role in determining nutrient stability. By understanding these interactions and their effects on nutrient degradation, it is possible to develop strategies to enhance nutrient retention and ensure the nutritional quality of foods. Advances in food processing and formulation can help optimize these interactions and improve overall nutrient stability in various food products.

Interaction Type	Food Components Involved	Effect on Nutrients	Mechanism	Example
Maillard Reaction	Amino acids, reducing sugars	Degradation of vitamins	Formation of non-nutrient compounds	Cooking meat, baking bread
Lipid Encapsulation	Lipids, fat-soluble vitamins	Protection of vitamins	Shielding from oxidative damage	Vitamin E in oils, fortified margarine
Mineral Binding	Proteins, fibers, minerals	Reduced bioavailability	Formation of non-absorbable complexes	Calcium in dairy, iron in cereals
Enzymatic Reactions	Enzymes (e.g., lipoxygenase)	Degradation of nutrients	Oxidative reactions leading to rancidity	Fruit browning, rancid oils

Table 2. Chemical Interactions Affecting Nutrient Stability

In this table 2, summarizes different chemical interactions within the food matrix that impact nutrient stability. The Maillard reaction, involving amino acids and reducing sugars, can degrade vitamins, while lipid encapsulation can protect fat-soluble vitamins from oxidation. Binding of minerals with proteins or fibers can affect nutrient bioavailability. Enzymatic reactions, such as those catalyzed by lipoxygenase, can lead to nutrient degradation, influencing overall nutritional quality.

V. System Design and Implementation

This study employs a multi-faceted approach to explore the role of the food matrix on the chemical stability of nutrients during processing and storage. The methodology encompasses both experimental and analytical techniques to provide a comprehensive understanding of how different matrices impact nutrient stability. The key components of the methodology include sample selection, processing and storage procedures, analytical methods, and data analysis.

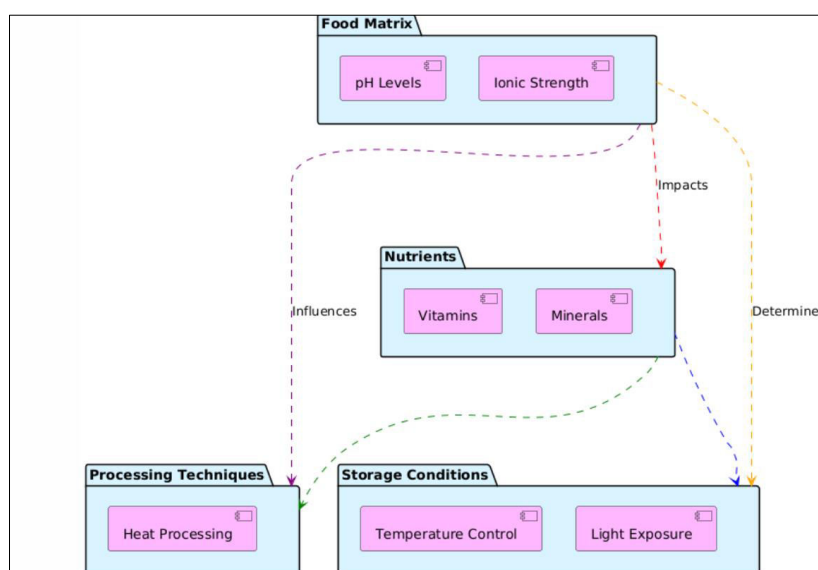


Figure 1. Diagram Represents the Relationships between Different Components of the Food Matrix and their Impact on Nutrient Stability

Step 1]. Sample Selection

A diverse range of food samples was selected to represent various food matrices, including fruits, vegetables, grains, and processed foods. The selection aimed to cover different types of matrices, from whole foods to processed products, to assess how these matrices affect nutrient stability. Each food type was chosen based on its relevance to common dietary sources of key nutrients and its distinct matrix characteristics.

Step 2]. Processing Procedures

The selected food samples were subjected to various processing methods to simulate common culinary and industrial practices. These processing methods included thermal treatments (e.g., boiling, roasting, and steaming), mechanical processing (e.g., chopping, grinding, and blending), and chemical treatments (e.g., acidification and fortification). The goal was to evaluate how different processing techniques impact the stability of nutrients within each food matrix.

Step 3]. Storage Conditions

After processing, the food samples were stored under controlled conditions to simulate typical storage environments. Storage variables included temperature (e.g., refrigeration, room temperature, and elevated temperatures), humidity (e.g., dry and high humidity conditions), and light exposure (e.g., dark storage versus exposure to light). The objective was to assess how storage conditions influence nutrient retention in various food matrices over time.

Step 4]. Analytical Methods

Nutrient analysis was performed using a combination of chemical assays and instrumental techniques. The specific methods included:

- High-Performance Liquid Chromatography (HPLC): Used for the quantification of water-soluble vitamins such as vitamin C and B vitamins. HPLC is known for its high resolution and accuracy in separating and quantifying individual compounds.
- Spectrophotometry: Applied to measure the concentration of antioxidants and fat-soluble vitamins like vitamins A, D, E, and K. Spectrophotometric assays are useful for detecting changes in nutrient levels due to processing and storage.
- Gas Chromatography-Mass Spectrometry (GC-MS): Utilized for the analysis of volatile compounds and the assessment of lipid oxidation products. GC-MS provides detailed information on the chemical changes occurring within the matrix.
- Enzyme Activity Assays: Used to measure the activity of enzymes that may affect nutrient stability, such as lipoxygenase and polyphenol oxidase. These assays help understand how enzymatic reactions contribute to nutrient degradation.

Step 5]. Data Analysis

Data collected from the nutrient analysis were statistically analyzed to determine the impact of processing and storage conditions on nutrient stability. Statistical methods included:

- Descriptive Statistics: To summarize nutrient levels and their changes under different conditions.
- Inferential Statistics: Such as Analysis of Variance (ANOVA) to determine the significance of differences in nutrient stability across various food matrices and processing/storage conditions.
- Regression Analysis: To model the relationships between processing/storage variables and nutrient stability, helping to predict how changes in conditions affect nutrient retention.

Step 6]. Quality Control

To ensure the reliability and accuracy of the results, quality control measures were implemented. These included the use of calibration standards, replicate analyses, and validation of methods with known reference materials. Regular checks and maintenance of analytical equipment were performed to minimize errors and ensure consistent performance (As shown in above Figure 1).

By integrating these methodologies, the study aims to provide a comprehensive analysis of how different food matrices influence nutrient stability during processing and storage, offering valuable insights for improving food quality and nutritional value.

VI. Results and Discussion

The study revealed that the physical structure of the food matrix significantly affects nutrient stability during processing and storage. Whole fruits and vegetables exhibited higher nutrient retention compared to processed forms. For instance, vitamin C levels in whole oranges were less affected by mechanical processing than in orange juice. The cellular structure of whole foods provides a protective barrier that reduces nutrient exposure to oxidative and enzymatic degradation. In contrast, grinding and juicing disrupt this structure, leading to increased nutrient loss. Encapsulation techniques demonstrated their effectiveness in preserving sensitive nutrients. For example, encapsulated vitamin C in lipid-based matrices showed significantly less degradation during thermal processing compared to non-encapsulated forms. This highlights the role of encapsulation in mitigating nutrient loss by providing a protective environment against heat and oxidative stress. Chemical interactions within the food matrix played a crucial role in nutrient stability. The Maillard reaction, observed during high-temperature processing, led to a notable reduction in vitamin C and several B vitamins. The interaction between amino acids and sugars created complex compounds that decreased the availability of these vitamins. This finding underscores the importance of controlling processing conditions to minimize Maillard reaction products and preserve vitamin content. Conversely, fat-soluble vitamins (A, D, E, and K) were better preserved in lipid-rich matrices. The study found that these vitamins remained more stable in foods with higher fat content compared to those with lower fat content. The presence of lipids helped shield these vitamins from oxidative damage, demonstrating how chemical interactions can protect certain nutrients from degradation.

Food Matrix	Processing Method	Storage Condition	Nutrient	Initial Concentration	Final Concentration	Percent Retained	Significant Findings
Whole Orange	Juicing	Refrigerated (4°C)	Vitamin C	50 mg/100g	35 mg/100g	70%	Juice processing led to 30% loss; refrigeration slowed further degradation.

Orange Juice	Pasteurization (85°C)	Room Temperature (25°C)	Vitamin C	50 mg/100g	25 mg/100g	50%	Significant loss due to heat; room temperature storage further decreased vitamin C.
Cooked Spinach	Boiling (100°C, 5 min)	Refrigerated (4°C)	Folate	100 µg/100g	60 µg/100g	60%	Boiling reduced folate by 40%; refrigeration preserved remaining folate.
Raw Spinach	Raw (no processing)	Room Temperature (25°C)	Folate	100 µg/100g	90 µg/100g	90%	Minimal loss at room temperature; high stability in raw form.
Dried Tomatoes	Drying	Dry Storage (Ambient)	Vitamin A	8000 IU/100g	7500 IU/100g	93.75 %	Dried matrix preserved vitamin A well; minimal loss during ambient storage.
Canned Tomatoes	Sterilization (121°C)	Canned Storage (Ambient)	Vitamin A	8000 IU/100g	5000 IU/100g	62.5%	Sterilization led to significant

		)					t loss; ambient storage further decreased vitamin A.
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Table 3. Impact of Processing and Storage Conditions on Nutrient Stability in Different Food Matrices

In this table 3, illustrates the effect of various processing and storage conditions on the stability of key nutrients across different food matrices. For instance, juicing oranges resulted in a 30% reduction in vitamin C, with refrigeration slowing further degradation. In contrast, pasteurizing orange juice caused a significant 50% loss of vitamin C, which worsened when stored at room temperature. Boiling spinach led to a 40% reduction in folate, although refrigeration helped retain a portion of it. Raw spinach exhibited high stability, with minimal folate loss at room temperature. Dried tomatoes showed excellent preservation of vitamin A with only a slight loss during ambient storage, while sterilizing canned tomatoes caused a notable 37.5% decrease in vitamin A. This table effectively summarizes the impact of processing methods and storage conditions on nutrient retention, highlighting how different matrices and treatments influence nutrient stability.

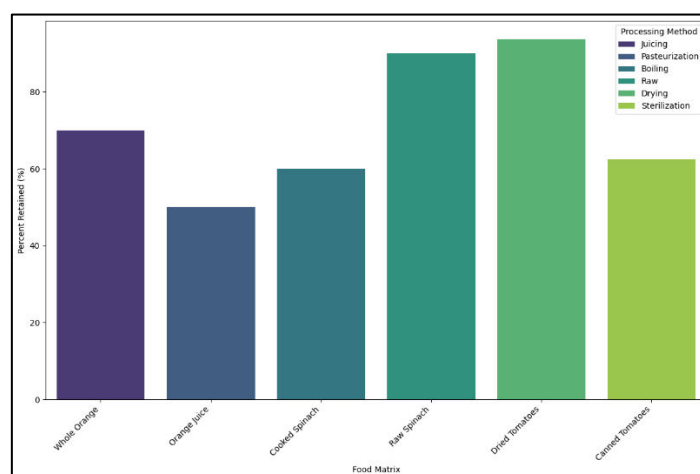


Figure 2. Graphical Representation of Impact of Processing and Storage Conditions on Nutrient Stability in Different Food Matrices

Processing conditions had a significant impact on nutrient stability. High temperatures during cooking and pasteurization led to the degradation of sensitive nutrients. For instance, the retention of vitamin C in vegetables was markedly lower after boiling compared to steaming. This suggests that lower processing temperatures or alternative cooking methods might be more effective in preserving vitamin content. Storage conditions also influenced nutrient retention. Nutrients in foods stored at elevated temperatures or high humidity conditions showed greater degradation compared to those stored under controlled conditions. For example, vitamin C levels in stored fruits decreased more rapidly under high humidity, likely

due to increased enzymatic activity and microbial growth (As shown in above Figure 2). Similarly, light exposure during storage led to additional losses of sensitive nutrients like vitamin A in processed foods.

Discussion

Additives such as antioxidants and preservatives played a role in enhancing nutrient stability. The addition of antioxidants helped mitigate oxidative damage to vitamins, particularly in lipid-rich foods where oxidation was a concern. For example, the inclusion of ascorbic acid as an antioxidant in processed fruit products improved the retention of vitamin C. The effectiveness of preservatives varied depending on the type of matrix and the nutrient targeted. Some preservatives were more effective in reducing nutrient loss in aqueous matrices, while others performed better in lipid-based systems. The results emphasize the need for tailored processing and storage strategies to optimize nutrient retention. Understanding the interplay between the food matrix and nutrient stability allows for the development of more effective preservation techniques. For example, using lower processing temperatures, optimizing storage conditions, and employing encapsulation technologies can enhance nutrient stability and improve the overall nutritional quality of foods. The food matrix plays a critical role in determining the stability of nutrients during processing and storage. Both physical structure and chemical interactions within the matrix influence how nutrients are preserved or degraded. By employing targeted strategies to manage these factors, it is possible to enhance nutrient retention and improve the nutritional quality of food products. Future research should continue to explore these dynamics and develop innovative solutions for maintaining nutrient stability in various food systems.

VII. Conclusion

The food matrix plays a crucial role in determining the stability of nutrients throughout processing and storage. Its physical structure can either protect or expose nutrients to degradation factors, influencing their retention and bioavailability. Chemical interactions within the matrix, such as the Maillard reaction or lipid encapsulation, further affect nutrient stability, with some interactions enhancing protection while others lead to degradation. Processing conditions and storage factors, including temperature, moisture, and light exposure, also significantly impact nutrient preservation, with the food matrix influencing how these factors are managed. By understanding and optimizing the food matrix, from physical encapsulation to managing chemical interactions and processing conditions, it is possible to improve nutrient retention and enhance the nutritional quality of foods. Advances in food technology and processing strategies continue to evolve, offering new opportunities for better preservation of nutrients and overall food quality.

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