

Novel Food Technology Approaches for Enhancing Nutritional Value and Shelf-life

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Abstract. In recent years, the demand for nutritious and shelf-stable food products has surged, driven by changing consumer preferences and the need for sustainable food systems. This paper explores novel food technology approaches aimed at enhancing both the nutritional value and shelf-life of food products. Various techniques such as encapsulation, fortification, fermentation, and high-pressure processing are discussed in detail, along with their applications and effects on food properties. Additionally, the paper delves into emerging technologies such as nanotechnology, 3D printing, and genome editing, highlighting their potential in revolutionizing the food industry. Furthermore, the challenges and opportunities associated with implementing these novel approaches are addressed, emphasizing the importance of considering factors such as safety, regulatory compliance, and consumer acceptance. Overall, this paper provides valuable insights into the innovative strategies available for developing healthier and more sustainable food products with extended shelf-life.

Keywords: Novel Food Technology, Nutritional Enhancement, Shelf-life Extension, Encapsulation, Fortification, Fermentation, High-pressure Processing, Nanotechnology, 3D Printing, Genome Editing.

I. Introduction

The modern food industry is undergoing a significant transformation driven by shifting consumer preferences towards healthier and more sustainable options. There is a growing awareness among consumers about the importance of nutrition and the impact of food choices on their health and well-being. Concurrently, the demand for convenient, shelf-stable food products remains high, necessitating innovative approaches to ensure both nutritional quality and extended shelf-life [1]. Historically, food processing techniques have primarily focused on enhancing shelf-life through methods such as canning, freezing, and dehydration. While these methods effectively inhibit microbial growth and preserve food quality, they often result in the loss of essential nutrients and sensory attributes. Consequently, there is a need for novel food technology approaches that not only extend shelf-life but also enhance the nutritional value of food products.

Encapsulation is one such technique that has gained prominence in recent years. It involves the entrapment of bioactive compounds, vitamins, or flavors within a protective matrix, which shields them from environmental degradation and ensures controlled release. Microencapsulation and nanoencapsulation are two common methods used to encapsulate nutrients, enabling their incorporation into various food matrices without compromising sensory properties [2]. Encapsulated ingredients can be added to a wide range of products, including beverages, baked goods, and supplements, thereby fortifying them with essential nutrients while extending their shelf-life. Fortification is another strategy employed to enhance the nutritional content of foods. It involves the addition of micronutrients such as vitamins, minerals, and amino acids to staple foods to address specific nutrient deficiencies in populations [3]. Fortification can be achieved through various techniques such as spray drying, extrusion, and coating, which ensure uniform distribution of nutrients throughout the food

matrix. By fortifying foods with essential nutrients, manufacturers can improve their nutritional profile without significantly altering taste or texture, thereby catering to the needs of health-conscious consumers.

Fermentation is a traditional food processing technique that has been used for centuries to preserve food and enhance its flavor and nutritional value. During fermentation, microorganisms such as bacteria, yeast, and mold convert carbohydrates and proteins into organic acids, alcohols, and other bioactive compounds. Fermented foods such as yogurt, cheese, and kimchi are not only rich in probiotics and enzymes but also boast enhanced nutrient bioavailability and shelf-life [4]. As such, fermentation represents a sustainable and cost-effective approach to improving the nutritional quality of food products while reducing food waste. High-pressure processing (HPP) is a non-thermal food preservation technique that involves subjecting foods to high pressures to inactivate microorganisms and enzymes. Unlike traditional thermal processing methods, HPP does not require high temperatures, thus minimizing nutrient degradation and preserving the sensory qualities of foods [5]. HPP has been successfully applied to a variety of products, including juices, meats, and ready-to-eat meals, extending their shelf-life while ensuring food safety and quality.

In addition to these established techniques, emerging technologies such as nanotechnology, 3D printing, and genome editing hold promise for revolutionizing the food industry. Nanotechnology enables the manipulation of materials at the nanoscale, allowing for the development of novel delivery systems for nutrients and bioactive compounds. 3D printing allows for the precise deposition of food ingredients layer by layer, enabling the customization of food products based on individual preferences and nutritional needs. Genome editing techniques such as CRISPR-Cas9 offer the potential to engineer crops with enhanced nutritional profiles and improved resistance to pests and diseases [6]. A novel food technology approaches offer exciting opportunities to enhance the nutritional value and shelf-life of food products. By leveraging techniques such as encapsulation, fortification, fermentation, and high-pressure processing, manufacturers can develop healthier and more sustainable food options to meet the evolving needs of consumers. Moreover, the advent of emerging technologies holds promise for further innovation in the food industry, paving the way for a future where nutritious and shelf-stable foods are accessible to all.

II. Encapsulation Techniques

Encapsulation techniques represent a versatile approach to enhance the nutritional value and shelf-life of food products by protecting sensitive ingredients from degradation and controlling their release. This section explores various encapsulation methods, including microencapsulation and nanoencapsulation, along with their applications and effects on food properties.

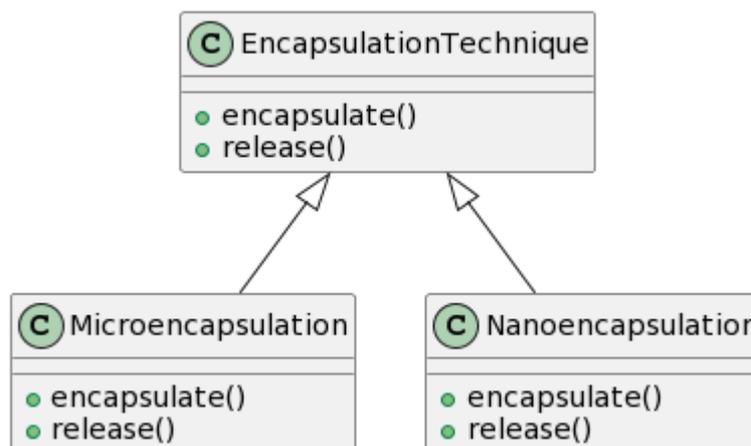


Figure 1. Encapsulation Techniques

A. Definition and Principles: Encapsulation involves the entrapping of bioactive compounds, vitamins, flavors, or other sensitive ingredients within a protective matrix, thereby shielding them from external factors

such as oxygen, moisture, and light. The encapsulating material forms a barrier around the core material, preventing its degradation and ensuring controlled release upon consumption. The choice of encapsulating material and method depends on factors such as the nature of the core material, desired release profile, and compatibility with the food matrix.

B. Microencapsulation: Microencapsulation is a widely employed technique wherein the core material is encapsulated within particles ranging from a few micrometers to several hundred micrometers in size. Common encapsulating materials include proteins, carbohydrates, lipids, and synthetic polymers, which are selected based on their compatibility with the core material and desired release properties. Microencapsulation can be achieved through various methods such as spray drying, coacervation, extrusion, and emulsification. These techniques enable the incorporation of sensitive ingredients such as vitamins, probiotics, and antioxidants into a wide range of food products, including beverages, dairy products, and functional foods.

C. Nanoencapsulation: Nanoencapsulation involves the encapsulation of bioactive compounds within nanoscale carriers, typically ranging from 1 to 100 nanometers in size. Nanoencapsulation offers several advantages over microencapsulation, including enhanced stability, bioavailability, and targeted delivery. Common nanocarriers used for encapsulation include liposomes, nanoparticles, and nanoemulsions, which can be fabricated using techniques such as solvent evaporation, homogenization, and self-assembly. Nanoencapsulation enables the delivery of hydrophobic and hydrophilic compounds with improved solubility and controlled release, making it particularly suitable for functional food applications and nutraceutical formulations.

D. Applications and Effects: Encapsulation techniques find numerous applications in the food industry, ranging from fortification and flavor masking to controlled release and targeted delivery. Encapsulated ingredients can be incorporated into a variety of food products, including beverages, baked goods, confections, and dietary supplements, to enhance their nutritional profile and sensory attributes. Additionally, encapsulation can improve the stability of sensitive ingredients during processing, storage, and digestion, thereby extending the shelf-life and bioavailability of food products. The encapsulation of probiotics, omega-3 fatty acids, and vitamins has been shown to improve their survival during gastrointestinal transit, ensuring their efficacy in promoting gut health and overall well-being.

III. Fortification Strategies

Fortification is a pivotal strategy employed in the food industry to address nutrient deficiencies and enhance the nutritional content of foods. This section explores various fortification techniques, the importance of fortification in public health, and its effects on food products.

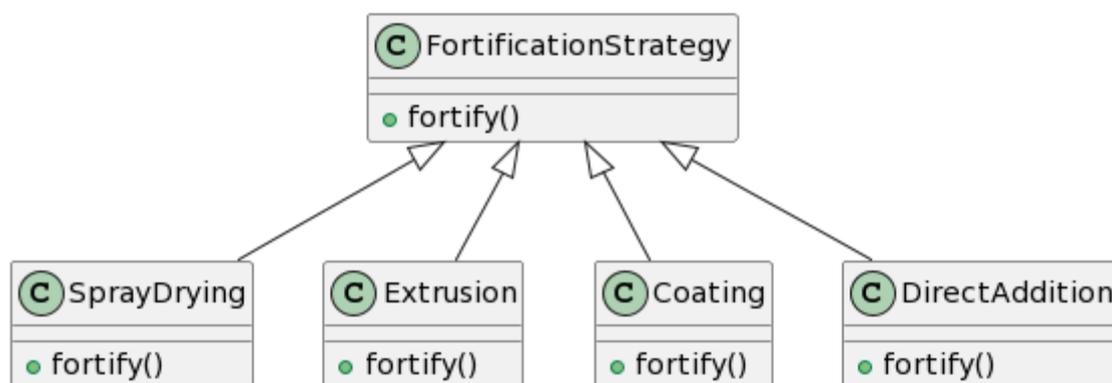


Figure 2. Fortification Strategies

Importance of Fortification: Fortification involves the addition of essential vitamins, minerals, and other nutrients to staple foods to improve their nutritional profile. This strategy plays a critical role in public health, particularly in regions where nutrient deficiencies are prevalent. Fortification programs aim to increase the intake of key nutrients such as vitamin A, iron, iodine, and folic acid, which are essential for growth, development, and overall health. By fortifying commonly consumed foods such as flour, rice, salt, and cooking

oil, manufacturers can reach large segments of the population and mitigate the risk of micronutrient deficiencies, thereby promoting health and well-being.

Fortification Techniques: Fortification can be achieved through various techniques, depending on the nature of the food matrix and the desired nutrient profile. Common fortification techniques include:

- **Spray Drying:** In spray drying, micronutrients are dissolved or suspended in a liquid carrier and then atomized into fine droplets using a spray nozzle. The droplets are rapidly dried using hot air, resulting in the formation of micron-sized particles that can be easily incorporated into dry food powders such as flour, powdered milk, and infant formula.
- **Extrusion:** Extrusion involves the simultaneous application of heat, pressure, and shear forces to food materials, resulting in the formation of a continuous flow of dough-like material. During extrusion, fortificant premixes containing vitamins, minerals, and other nutrients can be added to the food matrix, ensuring uniform distribution and stability.
- **Coating:** Coating is a technique wherein fortificant particles are coated with a thin layer of edible material to protect them from moisture, light, and oxidation. Coated fortificants can be incorporated into food products such as cereals, snacks, and confectionery items, providing a discrete and visually appealing means of fortification.
- **Direct Addition:** In some cases, fortificants can be directly added to food products without the need for specialized processing techniques. For example, iodized salt and vitamin-enriched cooking oils are commonly used to fortify staple foods in households and foodservice establishments.
- **Impact on Food Products:** Fortification has a significant impact on the nutritional content, sensory properties, and consumer acceptance of food products. When done correctly, fortification can increase the levels of key nutrients in foods without compromising taste, texture, or appearance. However, excessive fortification or improper formulation can lead to off-flavors, discoloration, or textural changes, which may negatively affect consumer perception. Therefore, careful consideration must be given to the selection of fortificants, their concentration levels, and the compatibility with the food matrix to ensure optimal results.
- **Regulatory Considerations:** Fortification programs are subject to regulatory oversight to ensure the safety, efficacy, and accuracy of fortified foods. Regulatory agencies such as the Food and Drug Administration (FDA) in the United States and the European Food Safety Authority (EFSA) in Europe establish guidelines and standards for fortification, including permissible levels of fortificants, labeling requirements, and monitoring procedures. Compliance with these regulations is essential to maintain consumer trust and safeguard public health.

IV. Fermentation Processes

Fermentation is a traditional food processing technique that has been utilized for centuries to preserve food, enhance flavor, and improve nutritional quality. This section explores the principles of fermentation, its role in food preservation, and its applications in enhancing the nutritional content and shelf-life of food products.

- **Role of Fermentation:** Fermentation is a metabolic process wherein microorganisms such as bacteria, yeast, and molds metabolize carbohydrates, proteins, and other organic compounds in the absence of oxygen. This anaerobic process results in the production of various end products, including organic acids, alcohols, gases, and bioactive compounds, which contribute to the characteristic flavor, texture, and aroma of fermented foods. Fermentation serves as a natural means of food preservation by creating an acidic environment that inhibits the growth of spoilage microorganisms and pathogens, thereby extending the shelf-life of perishable foods.
- **Microbial Fermentation:** Microbial fermentation involves the use of specific strains of bacteria, yeast, or mold cultures to ferment food substrates and produce desired end products. Different microorganisms impart unique sensory and nutritional characteristics to fermented foods, depending on factors such as fermentation conditions, substrates, and microbial strains. For example, lactic acid bacteria are commonly used in dairy

fermentation to produce yogurt, cheese, and kefir, while *Saccharomyces cerevisiae* is used in bread fermentation to leaven dough and generate carbon dioxide gas.

- **Effects on Nutritional Quality:** Fermentation can significantly impact the nutritional quality of foods by improving nutrient bioavailability, increasing protein digestibility, and synthesizing bioactive compounds. During fermentation, microbial enzymes break down complex carbohydrates, proteins, and lipids into simpler forms that are more easily digested and absorbed by the human body. Additionally, fermentation enhances the production of vitamins, amino acids, and antioxidants, contributing to the overall nutritional value of fermented foods. For example, fermentation of soybeans into tempeh increases the bioavailability of essential amino acids and vitamins while reducing antinutritional factors such as phytic acid and trypsin inhibitors.
- **Examples of Fermented Foods:** Fermented foods are an integral part of traditional diets worldwide and encompass a diverse range of products, including dairy products, fermented vegetables, sourdough bread, fermented beverages, and condiments. Examples of fermented foods from various cultures include sauerkraut from Germany, kimchi from Korea, miso from Japan, kombucha from China, and injera from Ethiopia. These fermented foods not only provide unique flavors and textures but also offer health benefits such as improved digestion, enhanced immune function, and gut microbiota modulation.
- **Challenges and Considerations:** Despite its numerous benefits, fermentation poses challenges related to food safety, quality control, and standardization. The microbial composition and fermentation kinetics can vary depending on factors such as temperature, pH, moisture, and substrate composition, leading to inconsistencies in product quality and sensory attributes. Additionally, certain fermented foods may pose risks of foodborne pathogens or spoilage microorganisms if not properly controlled during production and storage. Therefore, strict adherence to good manufacturing practices (GMPs), sanitation protocols, and microbial testing is essential to ensure the safety and quality of fermented foods.
- **Future Directions:** The growing interest in fermented foods and probiotics has spurred research into innovative fermentation techniques, microbial cultures, and functional ingredients to develop novel fermented products with enhanced health benefits and sensory properties. Advances in biotechnology, genomics, and fermentation engineering hold promise for optimizing fermentation processes, improving microbial starter cultures, and diversifying the range of fermented foods available to consumers. Additionally, there is a need for further studies to elucidate the mechanisms underlying the health-promoting effects of fermented foods and their role in preventing chronic diseases such as obesity, diabetes, and cardiovascular disorders.

V. High-Pressure Processing (HPP)

High-pressure processing (HPP) is a non-thermal food preservation technique that utilizes high pressures to inactivate microorganisms, enzymes, and pathogens while preserving the nutritional integrity and sensory attributes of food products. This section explores the principles of HPP, its applications in food processing, and its effects on food quality and safety.

- **Principles of High-Pressure Processing:** HPP involves subjecting foods to pressures ranging from 100 to 1000 megapascals (MPa) for a few seconds to several minutes. These elevated pressures disrupt the cellular structure of microorganisms and enzymes, leading to their inactivation and preventing spoilage and pathogen growth. Unlike thermal processing methods such as pasteurization and sterilization, HPP does not rely on high temperatures, thereby minimizing the detrimental effects of heat on food nutrients, flavors, and textures. Instead, HPP preserves the nutritional quality, color, and sensory characteristics of foods while ensuring microbiological safety.
- **Applications of High-Pressure Processing:** HPP has a wide range of applications in the food industry, including the preservation of fresh juices, meats, seafood, dairy products, and ready-to-eat meals. Fresh juices and beverages are commonly treated with HPP to extend shelf-life and maintain freshness without the need for heat pasteurization, which can degrade heat-sensitive vitamins and enzymes. Similarly, HPP is used to extend the shelf-life of refrigerated and frozen meats, poultry, and seafood by reducing the microbial load and delaying spoilage. In the dairy industry, HPP is employed to produce yogurt, cheese, and milk products with improved safety and quality. Additionally, HPP can be used to develop minimally processed convenience foods such as

salads, dips, and sauces, which retain their natural flavors and nutrients while meeting consumer demand for convenience and healthfulness.

- **Effects on Food Quality and Safety:** HPP has minimal effects on the sensory attributes and nutritional composition of foods compared to traditional thermal processing methods. Studies have shown that HPP preserves the color, texture, and flavor of fruits, vegetables, and meats while retaining their vitamins, antioxidants, and bioactive compounds. Furthermore, HPP effectively reduces the microbial load of foodborne pathogens such as Salmonella, Escherichia coli, and Listeria monocytogenes, ensuring the safety and microbiological stability of HPP-treated foods. However, it is important to note that HPP may not completely eliminate all microorganisms present in the food, particularly spore-forming bacteria, which may require additional control measures such as refrigeration or modified atmosphere packaging.
- **Commercial Applications and Future Trends:** HPP technology has gained widespread acceptance in the food industry due to its ability to deliver safe, minimally processed foods with extended shelf-life and superior quality. Major food manufacturers and retailers worldwide have adopted HPP for a variety of products, including fresh juices, guacamole, deli meats, and seafood. As consumer demand for clean-label, natural, and preservative-free foods continues to grow, HPP is expected to play an increasingly prominent role in meeting these market trends. Future developments in HPP technology may focus on optimizing processing parameters, scaling up production, and expanding the range of foods amenable to HPP treatment. Additionally, research efforts may explore synergistic combinations of HPP with other preservation methods such as mild heat treatments, natural antimicrobials, and packaging technologies to further enhance food safety and quality.

VI. Emerging Technologies

Emerging technologies in the food industry are revolutionizing the way we produce, process, and consume food. This section explores three innovative technologies: nanotechnology, 3D printing, and genome editing, and their potential applications in enhancing nutritional value and shelf-life of food products.

- **Nanotechnology:** Nanotechnology involves the manipulation of materials at the nanoscale, typically ranging from 1 to 100 nanometers. In the food industry, nanotechnology offers exciting opportunities to enhance the nutritional content, bioavailability, and functionality of food ingredients and additives. Nanoparticles can be used to encapsulate bioactive compounds such as vitamins, antioxidants, and omega-3 fatty acids, protecting them from degradation and improving their solubility and absorption in the body. Additionally, nanomaterials can be incorporated into food packaging materials to provide antimicrobial properties, extend shelf-life, and prevent spoilage. However, the safety and regulatory aspects of nanotechnology in food are still being studied, and further research is needed to ensure the responsible and sustainable use of nanomaterials in food production.
- **3D Printing:** 3D printing, also known as additive manufacturing, enables the precise deposition of food materials layer by layer to create customized food products with complex shapes and structures. In the food industry, 3D printing has applications in personalized nutrition, culinary arts, and food design. For example, 3D printers can fabricate personalized snacks, confections, and dietary supplements tailored to individual preferences and nutritional needs. Additionally, 3D printing allows for the creation of intricate food designs and textures that are not achievable through traditional manufacturing methods. However, challenges such as ingredient compatibility, printing speed, and regulatory compliance need to be addressed to realize the full potential of 3D printing in food production.
- **Genome Editing:** Genome editing technologies such as CRISPR-Cas9 offer precise and targeted modifications to the DNA of plants and animals, enabling the development of crops with enhanced nutritional profiles, improved yield, and resistance to pests and diseases. In the context of food production, genome editing can be used to develop "designer foods" with specific traits such as increased nutrient content, reduced allergenicity, and enhanced flavor. For example, researchers have used genome editing to develop rice varieties with higher levels of essential vitamins and minerals, offering potential solutions to malnutrition in regions where rice is a staple food. However, genome-edited foods raise ethical, regulatory, and consumer acceptance concerns, highlighting the need for transparent communication and informed decision-making regarding their use and commercialization.

- **Integration of Technologies:** The convergence of nanotechnology, 3D printing, and genome editing offers synergistic opportunities to create innovative food products with optimized nutritional value, sensory attributes, and shelf-life. For example, nanomaterials can be used as ink formulations in 3D printing to create functional food structures with controlled release properties. Similarly, genome editing can be combined with nanotechnology to develop crop varieties with improved nutrient uptake and bioavailability. By leveraging the complementary strengths of these emerging technologies, the food industry can address current challenges such as food insecurity, malnutrition, and food waste, while also paving the way for the development of sustainable and nutritious food systems.

The emerging technologies such as nanotechnology, 3D printing, and genome editing hold immense potential to transform the food industry and improve the nutritional value and shelf-life of food products. By embracing innovation and collaboration across disciplines, researchers, and stakeholders can harness the power of these technologies to develop novel food solutions that meet the evolving needs of consumers and contribute to a healthier, more sustainable future. However, it is essential to approach the adoption of these technologies with caution, considering factors such as safety, ethics, and societal impacts, to ensure responsible innovation and positive outcomes for both people and the planet.

VII. Challenges and Opportunities

While novel food technology approaches offer promising solutions for enhancing nutritional value and extending shelf-life, they also present various challenges and opportunities that need to be addressed for successful implementation. This section examines the key challenges and opportunities associated with the adoption of these innovative technologies in the food industry.

A. Challenges:

- **Safety Concerns:** One of the primary challenges is ensuring the safety of novel food products developed using innovative technologies. This includes assessing the potential risks associated with novel ingredients, processing methods, and unintended consequences of genetic modifications.
- **Regulatory Compliance:** Meeting regulatory requirements and standards for novel food products can be complex and time-consuming. Regulatory frameworks may vary between countries, requiring manufacturers to navigate multiple regulatory jurisdictions to bring their products to market.
- **Consumer Acceptance:** Consumer perception and acceptance of novel food products play a crucial role in their market success. Consumers may be hesitant to embrace unfamiliar technologies or ingredients, particularly if they perceive them as artificial or unnatural.
- **Cost and Scalability:** Developing and implementing novel food technologies can be costly, requiring significant investment in research, development, and infrastructure. Additionally, scaling up production to meet consumer demand while maintaining product quality and consistency presents logistical challenges.
- **Ethical and Societal Implications:** Ethical considerations surrounding the use of emerging technologies in food production, such as genome editing and nanotechnology, raise questions about environmental impact, equity, and access to technology.

B. Opportunities:

- **Health and Wellness:** Novel food technologies offer opportunities to improve public health outcomes by developing nutritious, functional foods that address specific dietary needs and health concerns, such as obesity, malnutrition, and chronic diseases.
- **Sustainability:** Many novel food technologies have the potential to enhance sustainability by reducing food waste, improving resource efficiency, and minimizing environmental impact throughout the food supply chain.
- **Innovation and Differentiation:** Adopting novel food technologies allows food companies to differentiate their products in the market, innovate with new flavors, textures, and formats, and respond to changing consumer preferences and trends.

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- **Global Food Security:** By improving the efficiency and resilience of food production, novel food technologies can contribute to global food security by ensuring a stable supply of nutritious food for a growing population.
 - **Collaboration and Knowledge Exchange:** Collaboration between stakeholders across the food industry, including researchers, manufacturers, policymakers, and consumers, fosters knowledge exchange, innovation, and responsible development and adoption of novel food technologies.

VIII. Conclusion

In conclusion, the pursuit of novel food technology approaches offers exciting possibilities for enhancing both the nutritional value and shelf-life of food products. Throughout this paper, we have explored various innovative techniques and technologies, including encapsulation, fortification, fermentation, high-pressure processing, nanotechnology, 3D printing, and genome editing, each contributing unique advantages to the food industry. Encapsulation techniques provide a means to protect sensitive ingredients, ensuring their stability and controlled release in food products. Fortification strategies address nutrient deficiencies and improve the nutritional profile of staple foods, supporting public health initiatives globally. Fermentation processes not only preserve foods but also enhance their flavor, texture, and nutritional content through the action of beneficial microorganisms. High-pressure processing offers a non-thermal method for food preservation while maintaining the sensory and nutritional qualities of foods. Furthermore, emerging technologies such as nanotechnology, 3D printing, and genome editing hold promise for revolutionizing food production, allowing for precise control over food composition, structure, and functionality. These technologies offer opportunities to develop customized, nutrient-rich foods that cater to individual preferences and dietary requirements. However, alongside these opportunities come challenges, including safety concerns, regulatory compliance, consumer acceptance, and ethical considerations. Addressing these challenges requires collaboration, transparency, and responsible innovation to ensure that novel food technologies are developed and deployed in a manner that prioritizes human health, environmental sustainability, and social equity. Looking ahead, continued research and development efforts, coupled with regulatory support and consumer education, will be essential for realizing the full potential of novel food technology approaches. By leveraging innovation and science, the food industry can meet the evolving needs and preferences of consumers while promoting a healthier, more sustainable future for all.

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