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Most recent and emerging technologies for enhancing the nutritional characteristics of food, challenges and future directions: A Review

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ABSTRACT

The rapid advancement of emerging technologies is transforming the food industry, especially in enhancing the nutritional qualities of food. These innovations have significant potential for tackling global nutritional deficiencies and promoting public health. Key technologies include precision fermentation, which enables the production of high-quality proteins and micronutrients while minimizing environmental impact. Additionally, gene editing techniques such as CRISPR allow for the development of crops with improved nutrient profiles and enhanced resistance to pests and diseases. Furthermore, advancements in nanotechnology enhance the fortification of foods with essential vitamins and minerals, improving their bioavailability and stability. Personalized nutrition, driven by big data and artificial intelligence, customizes dietary recommendations based on individual genetic profiles, optimizing

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Personalized Nutrition

Sustainable Food Systems

nutrient intake and health outcomes. This review article overviews these cutting-edge technologies and their applications in creating a more nutritious and sustainable food system.

1 Introduction

The global food industry is experiencing a significant transformation driven by the need to improve the nutritional quality of food while ensuring sustainability and addressing the challenges posed by a growing population. Innovative technologies are increasingly supplementing and, in some cases, replacing traditional food production and fortification (Alina et al. 2019). These emerging technologies have the potential to significantly enhance the nutritional characteristics of food, leading to better health outcomes on a global scale (Ivanov et al. 2021). Precision fermentation is particularly promising among these technologies, as it efficiently produces high-quality proteins and essential nutrients with a lower environmental impact than conventional agricultural practices. Additionally, gene editing tools such as CRISPR enable the development of crop varieties with improved nutrient profiles, higher yields, and better resistance to pests and diseases, thereby supporting food security and nutritional quality (Figure 1).

Nanotechnology represents a new frontier in food science, providing innovative solutions for nutrient fortification (Aguilar-Pérez et al. 2023). Using nanoparticles, we can enhance the bioavailability and stability of vitamins and minerals in food products. This ensures that essential nutrients are delivered to the body more effectively, addressing specific nutrient deficiencies and improving overall dietary health. Additionally, big data and artificial intelligence advancements are revolutionizing personalized nutrition (Cohen et al. 2023). This approach tailors dietary recommendations to individual genetic profiles, lifestyles, and health conditions, allowing for more precise and effective nutritional interventions. As a result, it promotes optimal health

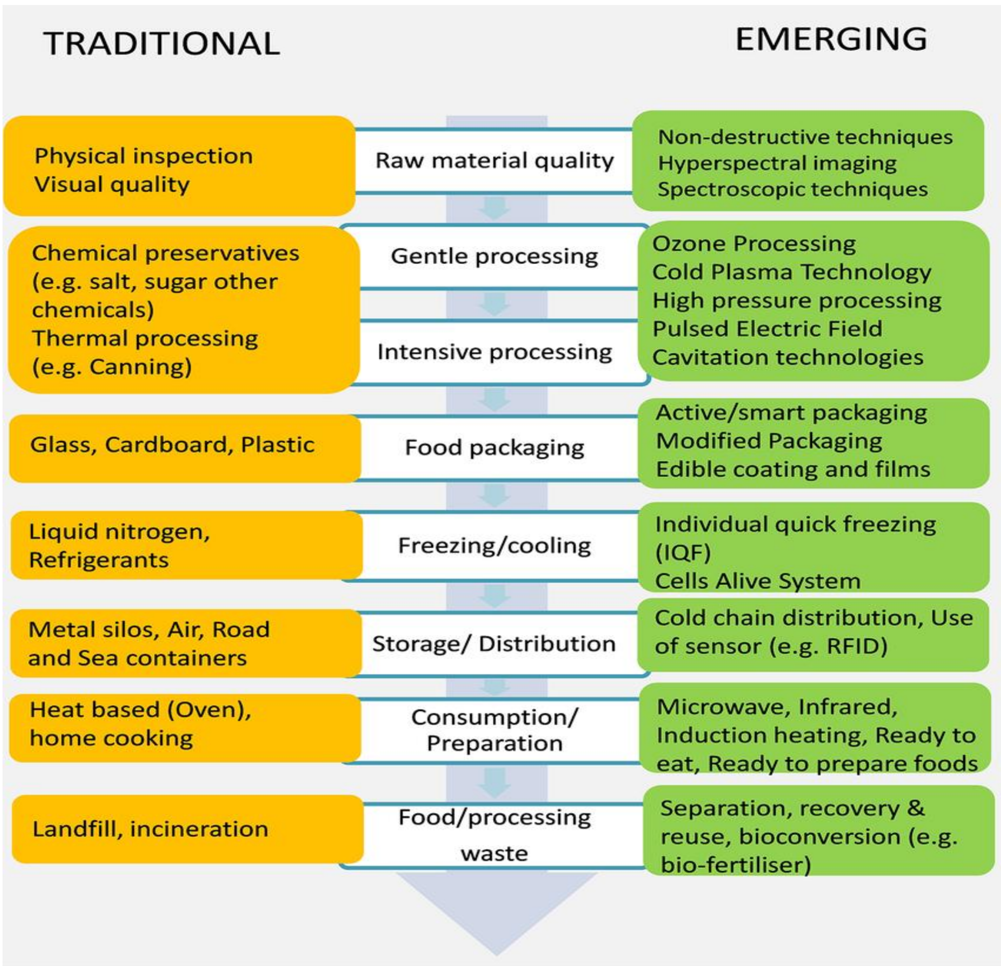

Figure 1 Difference between traditional and emerging technologies

and helps prevent diet-related diseases (Sahoo et al. 2021). This introduction paves the way for an in-depth exploration of these emerging technologies, focusing on their mechanisms, applications, and potential impacts on food nutrition (Sonnino 2016; Rizwan et al. 2018). By harnessing these innovations, the food industry can produce products that are not only more nutritious but also more sustainable and accessible, ultimately contributing to improved public health worldwide.

This study aims to investigate the mechanisms, applications, and potential impacts of emerging technologies such as precision fermentation, gene editing, nanotechnology, and personalized nutrition on enhancing the nutritional quality of food. This research aims to assess how these innovations can improve food sustainability, address global nutrient deficiencies, and contribute to public health by facilitating the production of more nutritious, accessible, and environmentally sustainable food products.

2 Overview of the importance of nutritional enhancement in food

Nutritional enhancement in food addresses widespread public health issues such as malnutrition, nutrient deficiencies, and diet-related chronic diseases. As global populations grow and dietary patterns change, ensuring that food provides adequate and balanced nutrients is increasingly important. Nutritionally enhanced foods can help alleviate deficiencies in essential vitamins and minerals, particularly in areas with limited access to a varied diet (Tontisirin et al. 2002). Moreover, with the rise of health-conscious consumers, there is a growing demand for foods that promote overall well-being, prevent diseases, and support optimal health. Improving the nutritional quality of food also has economic benefits by reducing healthcare costs associated with malnutrition and chronic diseases (Miller and Welch 2013). Therefore, utilizing advanced technologies to enhance the nutrient content of food is a vital strategy for promoting public health, supporting sustainable agricultural practices, and meeting the diverse nutritional needs of the global population.

3 The role of technology in addressing nutritional deficiencies and improving public health

Technology is essential for addressing nutritional deficiencies and enhancing public health by facilitating the development of foods with improved nutritional profiles and greater bioavailability of vital nutrients.

3.1 Most recent technologies

The latest technologies for improving the nutritional quality of food are continually pushing the boundaries of innovation. Here are some of the most advanced developments:

3.1.1 Cellular agriculture

This field includes techniques such as cultured meat and cultured dairy, where animal products are developed from cell cultures instead of being obtained from live animals (Eibl et al. 2021). Recent advancements have focused on enhancing the nutritional profile of these products by adjusting the growth medium to increase protein content and incorporating essential vitamins and minerals. In cellular agriculture, cultured meat and dairy products are created by growing animal cells in a controlled environment, reducing ethical and environmental concerns associated with traditional farming. The process typically begins with a small tissue sample taken from an animal, which is used to isolate and expand muscle or fat cells in a nutrient-rich culture medium. This method produces cell-based foods with minimal animal involvement, offering a sustainable and potentially healthier alternative to conventional meat production (Eibl et al. 2021; Merck KGaA 2023).

Recent efforts are aimed at optimizing the cell culture media, which consists of amino acids, growth factors, and micronutrients, to improve the nutritional quality of cultured meat. For instance, specific media formulations can enhance protein levels or add essential vitamins, resulting in products that are nutritionally superior to traditional meat. To refine flavor and texture, metabolomic profiling has been used to monitor nutrient flow and prevent the build-up of undesirable by-products, such as ammonia, which can impact taste and cell growth. Metabolomic studies also support scalability by identifying and managing the metabolic needs of different cell lines under various growth conditions, thereby enhancing both efficiency and product consistency (Buko 2023). Innovations in bioreactor technology and scaffold design facilitate the scalability and structuring of cultured meat. Bioreactors enable cells to expand on a larger scale, while edible scaffolds and 3D printing contribute to creating complex textures that mimic conventional meat. Leading companies and biopharma firms are collaborating to tackle challenges such as nutrient delivery, optimal texture, and scale-up solutions, advancing the commercial viability of cultured meat products (Merck KGaA 2023).

3.1.2 Microbiome engineering

Research into the role of the gut microbiome in nutrient absorption and overall health has led to the exploration of microbiome engineering (Foo et al. 2017). Scientists are investigating ways to modify gut microbiota to enhance nutrient metabolism and absorption, which could result in functional foods with improved nutritional benefits. Microbiome engineering takes advantage of the complex interactions between the gut microbiome and human physiology to boost nutrient absorption and metabolic health.

Studies have shown that specific gut bacteria, such as *Bifidobacterium* and *Lactobacillus*, play a vital role in producing essential vitamins like B and K, which are important for bone and cardiovascular health. By targeting these microbial populations, researchers aim to increase nutrient bioavailability, addressing global health issues like anemia and osteoporosis (Foo et al. 2017; Qadri et al. 2024). One promising strategy involves engineered probiotics specifically designed to enhance the absorption of key micronutrients like calcium and iron, thereby tackling malabsorption and related deficiencies. Evidence suggests that microbiome interventions may also help regulate lipid metabolism, which could lower the risk of obesity and metabolic disorders (Kau et al. 2011; Marsh et al. 2023). Another approach involves using synbiotics, which are combinations of prebiotics and probiotics to optimize gut flora composition. This method helps maintain a balanced microbiota by promoting beneficial bacteria while inhibiting harmful strains. Synbiotics have demonstrated potential in supporting immune health and metabolic function, underlining their long-term benefits for overall well-being (Bäckhed et al. 2004).

Recent studies featuring engineered microbiomes have shown promising results in clinical trials. For example, dietary interventions enriched with *Akkermansia muciniphila* have demonstrated significant improvement in glucose regulation among diabetic patients, highlighting the therapeutic potential of microbiome modulation in managing chronic diseases (Smith et al. 2013; Ridaura et al. 2013). Furthermore, innovative tools like CRISPR enable targeted gene editing within probiotic strains, enhancing their metabolic capabilities to produce specific nutrients or therapeutic compounds directly in the gut. This approach could transform personalized nutrition, allowing dietary interventions to be tailored to individual microbiome profiles and genetic predispositions (Bongers et al. 2014; Eibl et al. 2021).

3.1.3 3D food printing

3D food printing technology is still in its early stages, but it can potentially create customized food products with precise nutritional compositions (Mantihal et al. 2021). Researchers focus on printing food structures at the microscale, which allows for directly incorporating vitamins, minerals, and other nutrients into the printed food items. This groundbreaking technology enables precise creation of tailored food products that cater to specific nutritional needs. The process involves techniques such as extrusion-based printing, where semi-solid or gel-like food materials are deposited layer by layer to form complex three-dimensional structures. During printing, proteins, vitamins, minerals, and bioactive compounds can be integrated into the food matrix, resulting in functional foods that meet specific health or dietary requirements. For instance, nutrients like probiotics or dietary fibers can be included in 3D-printed foods to promote digestive health or enhance immune function (Zhang et al. 2018; Mantihal et al. 2021).

One significant advantage of 3D food printing is its ability to personalize food products for individuals with specific health conditions, dietary preferences, or nutritional needs. Foods can be formulated to have enhanced protein content, reduced sugar levels, or added micronutrients like calcium or iron, which are crucial for those with deficiencies. Ongoing research explores the printing of bakery products, snacks, and even meals enriched with essential nutrients, making this technology particularly useful in settings such as hospitals and eldercare facilities (Sun et al. 2018). However, this technology does face challenges. Printed food must maintain structural integrity, especially when subjected to post-printing treatments like baking or cooling. Material formulations are carefully selected to ensure the food retains its shape and texture while preserving the incorporated nutrients. For instance, formulations used in 3D printing should possess shear-thinning properties to facilitate extrusion and exhibit rapid recovery to maintain structural stability after deposition (Pulatsu et al. 2020). Researchers continue developing innovative approaches to improve the quality and stability of printed foods, focusing on controlling printed structures' consistency and ingredients' behavior during processing.

Ultimately, 3D food printing has the potential to revolutionize the food industry by providing solutions for food customization, nutrient fortification, and personalized dietary needs. This could be particularly impactful in addressing malnutrition, supporting health conditions, and reducing food waste using alternative, sustainable ingredients (Centre for Childhood Nutrition Research 2021).

3.1.4 Advanced plant breeding techniques

Advanced plant breeding techniques, particularly genome editing technologies like CRISPR-Cas9, enhance traditional breeding methods to develop crops with improved nutritional profiles (Lusser et al. 2011). Researchers can precisely edit plant genomes to increase essential nutrients such as vitamins, minerals, and antioxidants while maintaining desirable traits like yield and pest resistance. CRISPR-Cas9 revolutionizes crop development by allowing targeted modifications to the plant genome. Researchers can introduce or correct genetic variations that result in higher nutrient content by focusing on specific genes. For example, biofortified rice has been developed to contain increased vitamin A levels, and beans have been enhanced with higher iron content (Bortesi et al. 2016). In addition to improving nutrient levels, CRISPR technology facilitates targeted enhancements in nutrient bioavailability. Researchers have manipulated genes involved in phytate metabolism to increase the availability of minerals like iron and zinc in staple crops such as wheat and maize. This has significant implications for addressing global malnutrition, especially in developing regions with common nutrient deficiencies (Voss et al. 2015; Richetti et al. 2020). Another important advancement is using CRISPR to enhance crops' antioxidant properties. Antioxidants, like flavonoids and carotenoids, are vital for human health as they combat oxidative stress and reduce the risk of chronic diseases. Genetic editing has been used to engineer crops like tomatoes, apples, and kale to contain higher levels of these beneficial compounds, thereby improving the overall nutritional quality of the food consumed (Tang et al. 2017; He et al. 2020).

Furthermore, these advanced techniques are being applied to breed more resilient crops to climate change, ensuring food security while enhancing nutritional content. Crops that thrive in drought-prone or saline environments can be genetically modified to maintain high yields and nutrient levels, contributing to more sustainable and nutritionally rich food systems (Sarkar et al. 2020). In summary, enhanced nutritional content, improved agronomic traits, and increased resilience make advanced plant breeding techniques, particularly genome editing, a powerful tool for addressing global nutritional challenges and ensuring sustainable food production.

3.1.5 Blockchain technology for food traceability

Blockchain technology may not directly enhance nutritional characteristics, but it is increasingly being utilized to improve food traceability and transparency throughout the supply chain (Feng et al. 2020). By providing consumers with detailed information about food products' origins and nutritional content, blockchain empowers individuals to make more informed dietary choices.

It has emerged as a transformative tool in the food industry, particularly enhancing traceability and transparency within the supply chain. While its direct impact on improving nutritional content may be limited, blockchain is crucial in ensuring that consumers can access accurate and comprehensive information about food products' origin, handling, and nutritional profile. By creating a secure, decentralized digital ledger, blockchain allows real-time tracking of food items from farm to table. This ensures that all supply chain stages, from production and processing to distribution and retail, are transparent and verifiable. This technology helps reduce fraud and improve food safety, enabling consumers to make better choices regarding the nutritional value of the foods they purchase. For instance, consumers can trace the source of ingredients in their food, the production methods (such as organic or conventional), and details about any added preservatives, pesticides, or vitamins (Feng et al. 2020; Zohar et al. 2021). Beyond tracing the origin and quality of food, blockchain can also facilitate the communication of specific nutritional content in a verifiable and immutable manner. This is especially important in food fortification cases or when consumers seek to track micronutrient levels, such as vitamins, minerals, and antioxidants, in processed foods. For example, through blockchain, consumers could easily access verified information on the nutrient content of fresh produce or processed items, ensuring that their health-conscious choices are based on reliable data (Kshetri 2018; Arora et al. 2020).

Furthermore, blockchain technology can potentially reduce food waste by providing precise information on the shelf life of products and optimizing inventory management. This aspect indirectly supports healthier diets by increasing access to fresher, higher-quality foods while promoting sustainability by reducing spoilage and waste (Dai et al. 2021). Ultimately, integrating blockchain into food systems could bridge the gap between consumer demand for nutritional transparency and the complexities of current food supply chains, allowing consumers to make decisions based on taste, price, and verified nutritional information.

3.2 Emerging Technologies for Nutritional Enhancement in Food Systems

Recent advancements in food technology represent a significant shift towards improving the nutritional quality of our food supply. These innovations encompass various approaches, including genetic modifications, new food production methods, and systems designed to ensure transparency and traceability within the food supply chain. For instance, genome editing technologies like CRISPR-Cas9 enable precise enhancements in the nutritional content of crops, boosting essential nutrient levels such as vitamins and minerals (Bortesi et al. 2016). These tools can help address nutrient deficiencies in populations worldwide, ultimately contributing to improved health outcomes. In addition to genetic improvements, novel manufacturing processes like 3D food printing offer the potential to customize foods to meet specific nutritional needs. This can lead to personalized nutrition and enhance the bioavailability of key nutrients (Mantihal et al. 2021). Similarly, precision fermentation allows for the efficient production of high-quality proteins and micronutrients, enabling the creation of foods with tailored nutritional profiles and reduced environmental impacts (Malmud et al. 2021).

3.2.1 Precision Fermentation: A Technological Revolution in Food Production

Precision fermentation is an advanced biotechnological process that utilizes microorganisms such as bacteria, yeast, or fungi to produce specific compounds, ingredients, or food products under carefully controlled conditions. Unlike traditional fermentation, which typically relies on the natural metabolic pathways of microorganisms to generate products, precision fermentation allows for precise regulation of environmental factors, including temperature, pH, oxygen levels, and nutrient availability. This meticulous control results in higher yields and more consistent production of the desired compounds, making it a powerful tool in the food industry (Chai et al. 2022; Augustin et al. 2024).

The process begins with selecting genetically engineered microorganisms designed to produce specific products, such as proteins, fats, vitamins, or other essential nutrients. These microbes are cultivated in bioreactors, where conditions are optimized for their growth and production capabilities. By adjusting these parameters, scientists can achieve specific characteristics in the final product, including taste, texture, and nutritional content, that are tailored to meet market demands (Smetana et al. 2020; Schwenteck et al. 2021). One of the most promising applications of precision fermentation in the food industry is the production of high-quality proteins, such as dairy proteins (casein and whey) and meat proteins, without the need for animal farming. Companies like Perfect Day and Eat Just are pioneering this technology to create animal-free dairy products and cultured meat alternatives, maintaining traditional animal-based products' sensory properties and nutritional benefits while reducing their environmental footprint (Tziva et al. 2023).

Precision fermentation is increasingly used to produce functional ingredients such as prebiotics, probiotics, and bioactive compounds, which can be incorporated into food products to enhance health outcomes. Researchers have successfully employed precision fermentation to sustainably produce plant-based omega-3 fatty acids, typically found in fish. This approach helps to eliminate the need for ocean-based fishing, thereby reducing the strain on marine ecosystems (Smetana et al. 2020). Moreover, precision fermentation can enhance the bioavailability of nutrients, making them more easily absorbed by the human body. This is particularly important for fortifying foods with essential micronutrients such as vitamins, minerals, and amino acids, which can help address nutritional deficiencies and improve public health globally (Augustin et al. 2024).

3.2.2 Environmental and Nutritional Benefits

Precision fermentation provides numerous environmental advantages over conventional protein production methods. It requires fewer resources, including land, water, and energy, producing less waste and fewer greenhouse gas emissions (Teng et al. 2021). By removing the necessity for animal agriculture, precision fermentation also mitigates the environmental impacts associated with livestock farming, such as deforestation, water pollution, and habitat destruction (Hilgendorf et al. 2024).

This innovative biotechnological process addresses several global challenges, including food security, public health, and environmental sustainability, by offering efficient, sustainable, and nutrient-rich food production methods. Precision fermentation allows for the controlled cultivation of microorganisms (such as bacteria, yeast, or fungi) to produce specific nutrients or ingredients with high precision (Chai et al. 2022). One significant advantage of precision fermentation is its ability to enhance the nutritional quality of food. By genetically modifying microorganisms to produce crucial nutrients like essential amino acids, vitamins, and omega-3 fatty acids, this technology provides a sustainable alternative to traditional methods that depend on animal products (Smetana et al. 2020). For instance, omega-3 fatty acids, commonly sourced from fish, can be produced through precision fermentation, reducing dependence on marine ecosystems (Schwenteck et al. 2021).

Moreover, precision fermentation is vital in tackling food security. It enables the production of high-quality proteins without relying on conventional agricultural practices or animal farming, making it a scalable and efficient solution to meet the increasing global demand for protein (Tziva et al. 2023). Companies like Perfect Day and Eat Just are already harnessing precision fermentation to create dairy and meat products that match their animal-derived counterparts' nutritional profile and sensory qualities but with a significantly lower environmental footprint (Tziva et al. 2023). Regarding environmental sustainability, precision fermentation offers a more responsible method of food production than traditional animal farming. The livestock industry is a major contributor to greenhouse gas emissions, land degradation, and excessive water consumption. By producing food ingredients through fermentation, precision fermentation significantly reduces the overall environmental impact of agriculture (Smetana et al. 2020). Additionally, creating nutrient-rich food in controlled environments minimizes the need for large areas of land, which is essential for preserving biodiversity and curbing deforestation.

Lastly, precision fermentation promotes public health by facilitating food fortification with essential nutrients in highly bioavailable forms. This capability can potentially improve health outcomes, especially in regions where specific micronutrients, like Vitamin B12, are deficient in the diet. By producing these nutrients in a form that the body can absorb more quickly, precision fermentation helps tackle health challenges such as malnutrition and nutrient deficiencies (Augustin et al. 2024). As this technology continues to advance, its ability to produce nutrient-dense food while minimizing environmental impact positions it as a crucial player in the future of food production.

3.3 Gene Editing Techniques

3.3.1 CRISPR and Other Gene Editing Tools

CRISPR-Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats) is a groundbreaking gene editing tool that enables scientists to modify the DNA of organisms with high precision.

This system consists of a Cas9 enzyme guided by RNA molecules that target specific DNA sequences. This facilitates gene insertion, deletion, or modification with unmatched accuracy (Moon et al. 2019). Other gene editing tools, such as TALENs (Transcription Activator-Like Effector Nucleases) and zinc finger nucleases, operate similarly to CRISPR but utilize different mechanisms for protein-DNA recognition.

3.3.2 CRISPR-Cas9 in Food Enhancement

CRISPR-Cas9 has been widely utilized in food production to enhance the nutritional quality of both crops and livestock. By targeting specific genes, this technology allows for increased levels of essential nutrients such as vitamins, minerals, and proteins. For instance, CRISPR has been used to develop rice varieties with higher provitamin A (beta-carotene) levels, which helps combat vitamin A deficiencies in developing countries (Zhou et al. 2020). Additionally, it has been employed to boost the protein content of soybeans and to improve the drought resistance of crops like wheat, thereby enhancing yield and quality under adverse conditions (Huang et al. 2022). In livestock, CRISPR has facilitated the creation of animals with desirable traits, such as pigs that are resistant to diseases like Porcine Reproductive and Respiratory Syndrome (PRRS), which can lead to more sustainable meat production (Wang et al. 2020). Another application includes the production of leaner meats by modifying genes associated with fat metabolism in animals (Mao et al. 2020).

3.3.3 TALENs and Zinc Finger Nucleases in Food Quality

TALENs (Transcription Activator-Like Effector Nucleases) and zinc finger nucleases are potent tools for enhancing food quality through distinct gene-targeting mechanisms. These technologies have been utilized to create crops with improved resistance to pests and diseases. For instance, TALENs have been used to develop rice plants resistant to bacterial blight, a significant disease that can severely reduce crop yields (Bortesi et al. 2016). Similarly, zinc finger nucleases have been employed to produce crops with better nutritional profiles, such as potatoes with lower levels of acrylamide, a potentially harmful compound that can form during cooking (Laudadio et al. 2021). Additionally, these gene-editing technologies are making strides in improving food shelf life and minimizing spoilage by altering genes that control ripening and aging processes in fruits and vegetables. This progress has resulted in genetically modified crops with extended shelf life, which helps reduce food waste (Liu et al. 2021).

3.3.4 Development of Nutrient-Enriched Crops

Gene editing techniques can potentially create nutrient-enriched crops that target specific nutritional deficiencies in the human diet. Scientists can utilize CRISPR and other advanced tools to modify genes involved in the pathways that produce essential nutrients, thereby increasing the levels of vitamins, minerals, and other beneficial compounds in crops (Hammed et al. 2019). For instance, researchers have successfully engineered rice varieties with enhanced vitamin A, iron, and zinc levels to combat micronutrient deficiencies common in developing countries (Unnevehr et al. 2007; Bouis et al. 2019).

3.3.5 Examples of Genetically Enhanced Foods

Several genetically enhanced foods have been developed using gene editing techniques (Hefferon 2015). One notable example is the vitamin A-enriched "Golden Rice," which can potentially prevent blindness and other health issues caused by vitamin A deficiency (Tang et al. 2009). Another example includes soybean varieties engineered to contain increased levels of oleic acid, resulting in healthier cooking oils with improved nutritional profiles (Clemente and Cahoon 2009). Additionally, gene-edited crops are being developed with enhanced resistance to pests, diseases, and environmental stresses, improving yield and reducing agricultural losses (Zhang et al. 2018).

4 Regulatory and Ethical Considerations

Developing and commercializing genetically enhanced foods present significant regulatory and ethical considerations. Regulatory agencies, such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), assess the safety of gene-edited crops on a case-by-case basis, evaluating factors such as potential allergenicity, toxicity, and environmental impact (Zhang et al. 2018).

Ethical concerns include transparency, consumer acceptance, and equitable access to genetically modified organisms (GMOs). Furthermore, there is ongoing debate about the potential long-term effects of gene editing on biodiversity, ecosystem stability, and human health. This highlights the need for thorough risk assessment and regulatory oversight. Gene editing techniques offer unprecedented opportunities to develop nutrient-enriched crops and improve global food security. However, their widespread adoption depends on addressing regulatory challenges, building public trust, and navigating the complex ethical considerations surrounding genetic engineering in agriculture.

5 Nanotechnology

5.1 Overview of Nanotechnology in Food Science

Nanotechnology involves manipulating nanoscale materials, typically ranging from 1 to 100 nanometers. In food science, nanotechnology has emerged as a promising tool for enhancing food products' nutritional quality, safety, and shelf life (Zhang et al. 2018). Nanomaterials, such as nanoparticles, nanocapsules, and nanofibers, possess unique physical, chemical, and biological properties that can address various challenges in food processing, preservation, and delivery.

5.2 Techniques for Fortifying Foods with Vitamins and Minerals

Nanotechnology facilitates the efficient encapsulation and delivery of vitamins, minerals, and other bioactive compounds in food products (Li et al. 2023). Encapsulation techniques such as nanoemulsions, nanoliposomes, and nanofibers protect sensitive nutrients from degradation during processing and storage, allowing for controlled release and targeted delivery in the gastrointestinal tract (Miano and Rojas 2023a). This process enhances the bioavailability of nutrients, ensuring that they are effectively absorbed and utilized by the body.

Nanotechnology has become a key technology for fortifying foods with essential vitamins, minerals, and bioactive compounds, making them more bioavailable and effective in combating nutritional deficiencies. The use of nanotechnology in food fortification often involves advanced encapsulation techniques, including nanoemulsions, nanoliposomes, and nanofibers. These methods safeguard sensitive nutrients against degradation during food processing and storage, ensuring they reach their target locations in the gastrointestinal tract for optimal absorption. For example, nanoemulsions are colloidal water and oil dispersions stabilized by nanoscale surfactants, which can encapsulate hydrophobic vitamins like vitamins D and E. These emulsions enhance the solubility and bioavailability of such vitamins, allowing for more efficient absorption by the body (Li et al. 2023). Likewise, nanoliposomes, spherical vesicles made from lipids, encapsulate water-soluble and fat-soluble nutrients. During food processing, these liposomes protect nutrients from environmental factors, such as light and heat, and enable controlled nutrient release in the digestive system (Miano and Rojas 2023b).

Recent studies have shown that nanofibers, made from biopolymers or synthetic polymers, can further improve nutrient delivery. These nanofibers act as carriers for vitamins and minerals, providing slow-release properties and ensuring a consistent supply of nutrients over time. For instance, nanofibers have been successfully used to deliver vitamin C, enhancing its stability and bioavailability in food products (Gao et al. 2022). Another advantage of nanotechnology in fortification is its ability to target specific areas of the gastrointestinal tract, thereby optimizing nutrient absorption and minimizing waste. This is particularly beneficial for micronutrients like iron, zinc, and calcium, which are crucial for preventing deficiencies and improving overall health (Fang et al. 2020). Moreover, nanotechnology's role in food fortification extends beyond enhancing the bioavailability of vitamins and minerals; it also contributes to the development of functional foods, such as fortified beverages, dairy products, and snacks tailored to meet specific populations' nutritional needs. For instance, nanotechnology has been utilized to fortify plant-based milk alternatives with vitamin B12, a nutrient typically found in animal products, thus making these products more nutritious for vegans and vegetarians (Huang et al. 2022). In summary, nanotechnology advancements for food fortification have significant potential for improving public health, especially in regions with prevalent micronutrient deficiencies. By enhancing the bioavailability and stability of essential nutrients, nanotechnology can help create more efficient and sustainable methods of nutrient delivery, ensuring that these nutrients are effectively absorbed and utilized by the body.

5.3 Improving Bioavailability and Stability of Nutrients

Nanotechnology is essential for enhancing the bioavailability and stability of nutrients in fortified foods. Nanomaterials improve nutrient solubility, dispersibility, and absorption by reducing particle size and increasing surface area. This helps to address challenges related to poor water solubility and low bioavailability. Additionally, nanoencapsulation protects nutrients from environmental factors such as light, oxygen, and moisture, ensuring that fortified foods' nutritional quality and sensory attributes are preserved over time.

5.4 Enhancing Nutrient Solubility and Absorption

Nanomaterials, such as nanoparticles, nanoliposomes, and nanocrystals, have been shown to enhance the solubility and absorption of essential nutrients significantly. Due to their small size, typically less than 100 nanometers, nanoparticles have a much higher surface area-to-volume ratio than bulk materials. This characteristic makes them more reactive and efficient in dissolving in biological fluids, thereby increasing the rate at which nutrients are absorbed in the gastrointestinal tract. For instance, nanoencapsulated iron has been demonstrated to improve absorption in the body while reducing common side effects, such as gastric irritation, typically associated with conventional iron supplements (Sharma et al. 2022). Additionally, research has shown that nanoencapsulation of lipophilic nutrients, like vitamins A and E, enhances their solubility in water-based food matrices, making them more bioavailable (Huang et al. 2016; Huang et al. 2022).

5.5 Protection against Environmental Degradation

Nanotechnology enhances the bioavailability of nutrients and plays a crucial role in preserving their stability throughout food processing and storage. Sensitive compounds such as vitamins and antioxidants are prone to degradation when exposed to light, oxygen, and moisture, which can significantly reduce their nutritional value. Nanoencapsulation provides a protective barrier against these environmental factors. For example, nanoliposomes and nanoemulsions can shield sensitive nutrients from oxidation and photodegradation during food storage, thus extending their shelf life while maintaining their effectiveness (Singh et al. 2021). This preservation is crucial for functional foods, where the intended health benefits must remain intact until consumption. A study by Shadab et al. (2023) demonstrated that nanoencapsulated vitamin C maintained its stability over an extended period in various food products, including beverages, highlighting the effectiveness of nanotechnology in stabilizing sensitive nutrients. Similarly, researchers have successfully encapsulated omega-3 fatty acids in nanostructures to prevent oxidation and preserve their beneficial properties for longer periods, even in processing-intensive food products like margarine and salad dressings (Gao et al. 2020).

5.6 Targeted Nutrient Delivery

One of the most exciting applications of nanotechnology in food fortification is the ability to target specific gastrointestinal tract regions for nutrient delivery. This targeted release is especially beneficial for nutrients that need specific conditions for optimal absorption. For instance, certain nanocarriers are designed to release nutrients only when they reach the small intestine, which improves absorption efficiency and reduces nutrient loss during digestion. This method has been particularly advantageous for minerals like calcium and magnesium, often poorly absorbed when consumed in traditional forms (Fang et al. 2021).

5.7 Potential Health Implications and Safety Concerns

Nanotechnology offers various benefits for food fortification and nutrient delivery; however, there are concerns about its potential health implications and safety risks. Nanoparticles can interact with biological systems unpredictably, which may lead to unintended biological effects or toxicity. Additionally, the long-term effects of chronic exposure to nanomaterials through dietary intake are not fully understood, raising concerns about their safety for human consumption. Regulatory agencies, such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), are actively assessing the safety of nanotechnology products and are working to establish guidelines for their use in the food industry.

6 Examples of Personalized Nutrition Applications

6.1 Nutrigenomics

Nutrigenomics is a field of personalized nutrition that analyzes genetic variations to understand how individuals respond to different nutrients. By examining specific genes influencing nutrient metabolism, absorption, and utilization, nutrigenomics enables tailored dietary recommendations based on a person's genetic profile. This can include guidance on optimal intake of vitamins, minerals, and other nutrients to prevent deficiencies or lower the risk of diet-related diseases. Recent studies suggest that genetic variations can affect how individuals process fats, carbohydrates, and proteins, which allows for more targeted dietary interventions (Müller et al. 2022). For instance, people with specific genetic polymorphisms may benefit from a higher intake of omega-3 fatty acids or may respond better to dietary changes aimed at controlling blood sugar levels, providing valuable insights for personalized nutrition plans (Fenech et al. 2011).

6.2 Wearable Devices and Mobile Apps

Wearable devices and mobile applications have transformed personalized nutrition by tracking dietary intake, physical activity, and other health metrics. These devices use sensors and algorithms to collect data, which is then analyzed to offer personalized feedback and nutritional recommendations (Romero-Tapiador et al. 2023). For instance, apps monitoring food intake can notify users about nutrient imbalances or suggest healthier meal options tailored to their nutritional needs. Additionally, devices like fitness trackers that monitor physical activity and energy expenditure can recommend personalized adjustments to daily caloric intake, aiding goals such as weight management or muscle gain (Chen et al. 2022). By gathering data over time, these tools optimize nutrition and encourage long-term dietary behavior changes, helping users achieve their health goals (Yao et al. 2020).

6.3 Microbiome Analysis

The composition and function of the gut microbiota are essential for nutrition and overall health. Recent advances in microbiome analysis have allowed scientists to identify the specific strains of bacteria and other microorganisms in an individual's gut. This detailed analysis can be used to recommend personalized dietary interventions that promote a healthy gut microbiome, which is linked to improved digestion, immune function, and mental health. For example, individuals with a less diverse microbiome may benefit from a diet rich in fiber, probiotics, and prebiotics to help restore microbial balance. Some studies suggest that specific microbiome profiles are associated with conditions like obesity, diabetes, and irritable bowel syndrome (IBS). Tailored nutritional interventions can help reduce these risks (Zhao et al. 2021). Personalized microbiome-based recommendations may enhance nutrient absorption, reduce inflammation, and support mental health by influencing the gut-brain axis (Turnbaugh et al. 2021).

7 Benefits and Challenges

7.1 Benefits of Personalized Nutrition

One of the major benefits of personalized nutrition is its ability to improve dietary adherence. By offering individuals dietary recommendations tailored to their unique genetic makeup, lifestyle, and health goals, personalized nutrition encourages a more substantial commitment to making dietary changes. Research has shown that people are more likely to follow personalized nutrition advice than general dietary guidelines, which leads to better health outcomes (Ramos-Lopez et al. 2017). Moreover, personalized nutrition can help prevent chronic diseases such as obesity, diabetes, and cardiovascular disease by providing targeted interventions that address the root causes of these conditions. By optimizing nutrient intake, individuals can avoid deficiencies or excesses that could contribute to health issues. Personalized approaches also enhance overall well-being by supporting individual health goals, including managing stress, improving digestion, or boosting energy levels (Burgess et al. 2021).

7.2 Challenges of Personalized Nutrition

Despite its significant benefits, personalized nutrition faces several challenges. One major issue is access to the technologies and services that provide personalized nutritional recommendations. While advancements in wearable devices and mobile apps have made personalized nutrition more accessible, these tools are often expensive and not widely available in low-resource settings, leading to disparities in access to care (De Lauzon-Guillain et al. 2021). Additionally, privacy concerns are related to collecting and using personal health data, such as genetic and biometric information, for creating dietary recommendations. Ensuring this data's security and ethical use is crucial for gaining consumer trust and promoting widespread adoption (O'Neill et al. 2020). Another significant challenge is the complexity of interpreting genetic and biochemical data. Although technological advances have made genetic and microbiome analysis more accessible, converting this data into actionable dietary recommendations remains complicated. Furthermore, the variability in individual responses to dietary interventions means that personalized recommendations must be continuously adjusted (Roth et al. 2021). Finally, integrating personalized nutrition into existing healthcare systems and dietary guidelines presents additional difficulties. Many healthcare professionals do not have the training to interpret genetic or microbiome data, and there is a lack of consensus on how to incorporate personalized nutrition into clinical practice effectively (Patterson et al. 2022).

8 Other Emerging Technologies

8.1 Use of Biotechnology in Developing Functional Foods

Biotechnology plays a significant role in the development of functional foods, which are foods that provide additional health benefits beyond essential nutrition. Through genetic engineering, biotechnologists can enhance the nutritional content of foods, improve their sensory characteristics, and introduce bioactive compounds with potential health-promoting properties. For example, genetically modified crops can be engineered to produce antioxidants, omega-3 fatty acids, or other bioactive compounds that contribute to cardiovascular health, immune function, and cognitive function. Additionally, fermentation techniques can produce probiotic-rich foods that promote gut health and digestion.

8.2 Advances in Food Processing and Packaging for Nutrient Retention

Advances in food processing and packaging technologies aim to preserve the nutritional quality of foods throughout production, storage, and distribution (Garba 2023). High-pressure processing, pulsed electric field processing, and cold plasma treatment effectively retain foods' vitamins, minerals, and other nutrients while minimizing degradation caused by heat, light, and oxygen exposure. Additionally, innovative packaging materials and designs, such as barrier films, modified atmosphere packaging, and active packaging systems, create protective barriers that extend the shelf life of foods and help maintain their nutritional value.

8.3 Innovations in Food Fortification Methods

Food fortification adds vitamins, minerals, or other essential nutrients to foods to address specific nutritional deficiencies and improve public health. Recent innovations in food fortification methods include micronutrient encapsulation, nanoencapsulation, and biofortification techniques (Gharibzahedi et al. 2023). Micronutrient encapsulation involves enclosing vitamins and minerals within microcapsules or nanoparticles to protect them from degradation and enhance their stability in fortified foods. Nanoencapsulation further improves the bioavailability of nutrients by reducing particle size and increasing surface area. Biofortification involves breeding crops with higher nutrient levels using conventional breeding techniques or genetic engineering, resulting in nutrient-rich foods that provide additional health benefits (Yuraskina et al. 2024). The use of biotechnology in the development of functional foods, along with advances in food processing and packaging for nutrient retention, is driving the emergence of new technologies that enhance the nutritional quality of foods and promote public health. These innovations offer promising solutions for addressing nutritional deficiencies, improving dietary patterns, and preventing diet-related chronic diseases, contributing to a healthier and more sustainable food system.

9 Case Studies

A notable example of the successful use of precision fermentation technology is the production of animal-free dairy proteins by companies such as Perfect Day Foods and New Culture. These companies utilize fermentation methods to create dairy proteins,

Table 1 Case studies on emerging technologies for enhancing the nutritional quality of food

#	Case Study	Technology Used	Application	Impact on Public Health and Nutrition	References
1	Precision Fermentation in Dairy	Precision Fermentation	Animal-free dairy proteins (e.g., whey, casein) produced via engineered yeast or bacteria.	Sustainable, allergen-free, lactose-free alternatives rich in essential amino acids and vitamins.	Chai et al. (2022); Banovic and Grunert 2023; Augustin et al. (2024)
2	Non-Browning Mushrooms	CRISPR-Cas9	Gene-edited mushrooms that resist browning, improving shelf life.	Reduces food waste, maintains nutritional quality, promotes healthier diets.	Moon et al. (2019); Yang et al. (2020)
3	Vitamin-Fortified Crops	CRISPR-Cas9	Rice engineered with higher levels of vitamin A, iron, and zinc.	Addresses micronutrient deficiencies, especially in developing countries.	Liu et al. (2021); Zhang et al. (2018)
4	Cultured Meat Production	Precision Fermentation	Growing meat products (e.g., chicken, beef) from cultured cells, without animal slaughter.	Sustainable protein source, reduced environmental impact, cruelty-free alternatives.	Post et al. (2020); Ellis et al. (2022)
5	Nanoparticle Encapsulation of Nutrients	Nanotechnolfogy	Encapsulation of vitamins and minerals in nanoparticles for improved delivery in foods.	Enhanced bioavailability, stable nutrient release, and improved nutrient absorption in the body.	Li et al. (2023); Miano and Rojas (2023a)
6	Nutrient Delivery Systems	Nanotechnology	Nanoencapsulation of bioactive compounds to increase stability and bioavailability of nutrients.	Better nutrient absorption, prevents degradation of sensitive compounds during storage.	Jafari et al. (2021); Mehta et al. (2022)
7	Genetically Modified Soybean	Genetic Modification (GMO)	Soybeans engineered to contain higher omega-3 fatty acids.	Improves dietary intake of essential fatty acids, reduces cardiovascular disease risks.	Dewitt et al. (2020); Schläpfer et al. (2021)
8	Biofortified Golden Rice	Genetic Engineering	Rice engineered to produce beta-carotene (vitamin A precursor) to combat vitamin A deficiency.	Helps prevent blindness and malnutrition in regions with rice as a staple food.	Potrykus (2010); Yuan et al. (2022)
9	Sustainable Fish Protein (Algae)	Algae-based Protein Production	Microalgae used to produce protein-rich food products for human consumption.	Provides sustainable, plant-based protein alternative, rich in omega-3 fatty acids.	Wang et al. (2021); Wei et al. (2022)
10	Plant-Based Milk Alternatives	Precision Fermentation	Fermentation of plants like oats, soy, or peas to create nutrient-rich milk alternatives.	Provides plant-based, dairy-free milk options with added vitamins, minerals, and protein.	Huang et al. (2022); Mukherjee et al. (2021)
11	3D Printed Personalized Foods	3D Printing Technology	Customized food products created by printing at the microscale to include specific nutrients.	Precision in nutritional content, customized for individual dietary needs and preferences.	Mantihal et al. (2021); Gonzalez et al. (2022)
12	Gut Microbiome Modulation	Microbiome Engineering	Tailoring gut microbiome composition through food additives or probiotics to improve nutrient absorption.	Improves digestive health, enhances nutrient metabolism, and reduces the risk of chronic diseases like obesity and diabetes.	Foo et al. (2017); Bäckhed et al. (2004)

including whey and casein, without relying on cows. By genetically engineering microorganisms like yeast to produce these proteins, they provide a sustainable alternative to traditional dairy farming. This approach reduces the environmental impact of dairy production and offers products that are nutritionally equivalent to animal-derived products. The widespread adoption of precision fermentation for dairy protein production has the potential to lessen the environmental effects of animal agriculture and enhance consumers' access to high-quality protein sources around the world.

10 Challenges and Future Directions

10.1 Technical Challenges

10.1.1 Complexity of Technologies

Emerging technologies such as precision fermentation, gene editing, and nanotechnology involve complex processes and require specialized expertise. This complexity poses challenges in research, development, and implementation.

10.1.2 Scalability

Scaling up the production of innovative food products using advanced technologies can be difficult, especially in commercially maintaining consistent quality, safety, and cost-effectiveness.

10.1.3 Integration of Technologies

Successfully integrating multiple technologies into food production systems necessitates interdisciplinary collaboration and coordination. This involves addressing technical compatibility and optimizing efficiency and performance.

10.2 Regulatory Challenges

10.2.1 Safety Assessment

To ensure the safety of novel food products developed through emerging technologies, it is essential to have strong risk assessment frameworks and regulatory oversight. These measures will evaluate potential health risks, allergenicity, toxicity, and environmental impacts.

10.2.2 Labeling and Transparency

Implementing clear labeling requirements and transparency standards for genetically modified or technologically enhanced foods is crucial. This will help inform consumer choices and build trust in food innovation.

10.3 Ethical Challenges

10.3.1 Equity and Access

It is crucial to address disparities in access to advanced food technologies and ensure that the benefits are distributed equitably among diverse populations. This is an important ethical consideration that requires attention.

10.3.2 Environmental and Social Impacts

It is essential to anticipate and mitigate emerging food technologies' potential environmental and social impacts. This includes land use, biodiversity, and changes in socioeconomic dynamics, all vital for ethical and sustainable food production.

11 Future Trends and Potential Developments in Food Technology

11.1 Personalized Nutrition

Advances in genomics, digital health technologies, and artificial intelligence will lead to the growth of personalized nutrition services. These services will provide tailored dietary recommendations based on individual genetic, metabolic, and lifestyle factors.

11.2 Cellular Agriculture

The development of cultured meat, seafood, and other animal-derived products using cell culture techniques will continue to progress. This approach offers sustainable and cruelty-free alternatives to traditional animal agriculture.

11.3 Sustainable Packaging

Innovations in biodegradable and recyclable packaging materials and smart packaging technologies that monitor freshness and extend shelf life will help reduce food waste and lessen environmental impact.

11.4 Blockchain Technology

Adopting blockchain technology for supply chain traceability and transparency will improve food safety and quality assurance. This advancement will enable consumers to make informed choices and verify the authenticity of food products.

Conclusion

Emerging technologies such as precision fermentation, gene editing, nanotechnology, and personalized nutrition are transforming the food industry by providing innovative solutions to global challenges like malnutrition, food insecurity, and sustainability. These advancements allow for the development of nutrient-rich foods, including fortified products, animal-free proteins, and non-browning produce. They also enhance bioavailability, food safety, and shelf life. Integrating these technologies leads to more sustainable food systems that minimize environmental impact and reduce food waste. Looking to the future, these technologies offer significant potential for changing food production and distribution, positively affecting public health and environmental preservation. However, we must address technical complexity, ethical concerns, and equitable access challenges to harness their benefits fully. Collaboration across sectors, ongoing research, and a dedication to sustainability will ensure that emerging technologies contribute to a more nutritious, sustainable, and equitable global food system.

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