Future Foods: INNOVATIONS IN FOOD PROCESSING TECHNOLOGIES

This book presents a comprehensive exploration of recent innovations, emerging trends, and future directions in food processing technologies. It brings together insights from researchers, academicians, and industry experts to address sustainable food systems, advanced processing techniques, and the evolving role of technology in ensuring food safety, quality, and nutrition for a healthier tomorrow.

KEY FEATURES

- Covers recent advancements in food processing technologies
- Highlights sustainable and healthy food innovations
- Discusses food safety, quality and preservation methods
- Explores novel ingredients, functional foods and alternative proteins
- Contributions from experts in academia, industry and research
- Useful for students, researchers, food technologists and industry professionals

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SWAMI VIVEKANANDA UNIVERSITY

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Edited by Dr. Manisha Maity

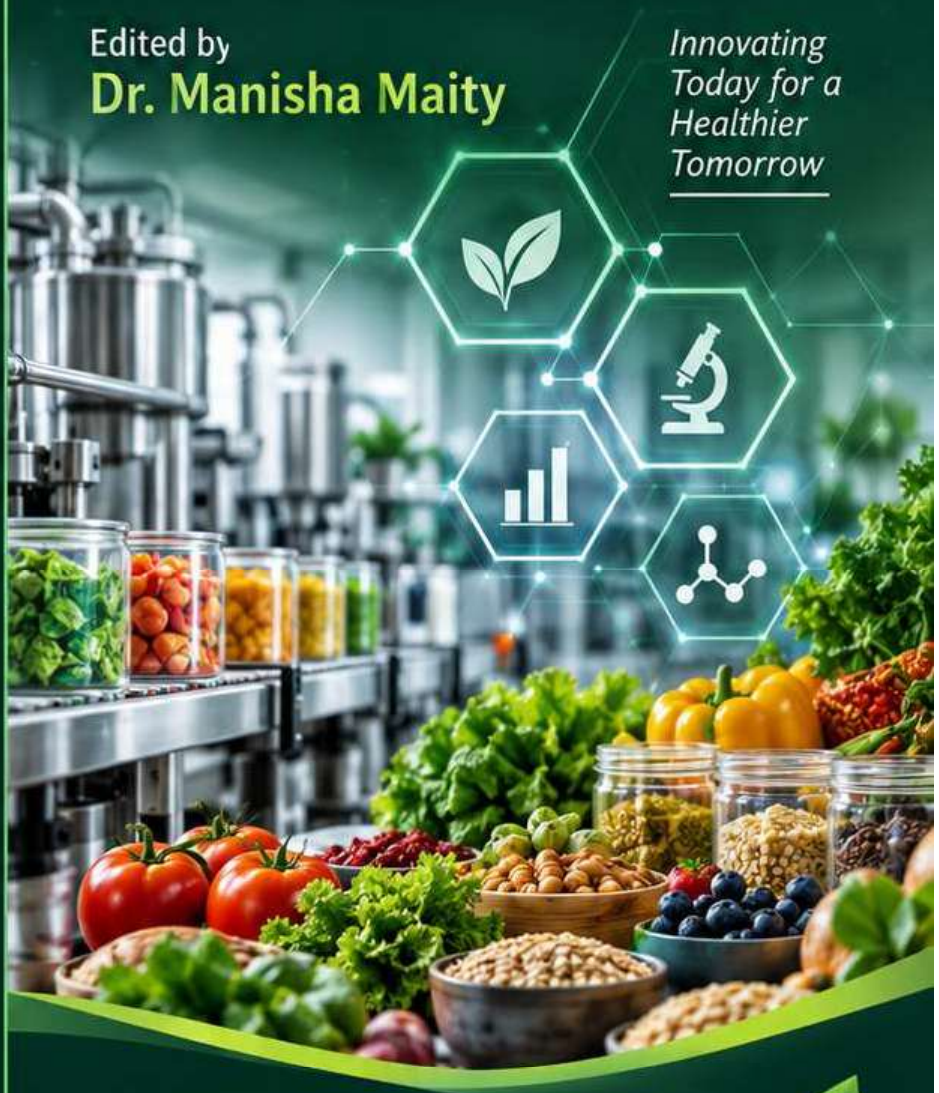
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SUSTAINABLE FOODS | ADVANCED PROCESSING | FUNCTIONAL FOODS | FOOD SAFETY & QUALITY | A HEALTHIER TOMORROW

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Innovating Today for a Healthier Tomorrow



SWAMI VIVEKANANDA UNIVERSITY

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CHAPTER-I

A Review on the Development of New Food Products Using Waste Through Food Fortification

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Abstract

Food is the instrument of nourishment; nutrition is the act of doing it. Food is a basic thing for survival. But we all have to know that up to one-third of the food is being wasted, never consumed, with adverse environmental consequences. In India, the management of food waste is an emergent concern for environmental health. Food waste encompasses both edible and inedible parts of food, such as vegetable peelings, fruit peelings, discarded vegetables and fruits, leftover food, tea leaves, eggshells etc. The issue of food waste is a new and important topic for the changes in India's traditional systems of food consumption. There are different sources of food waste - food processing industrial wastes like cereal, grain, vegetable and fruit, beverages, dairy product industry, the processed food industry; institutional food wastes like military service areas, hospitals, nursing homes, college canteen; residential food wastes that are kitchen wastes; commercial food wastes like a hotel, cafeteria, restaurant etc. Food waste is always a cheap source of bioactive compounds mainly fibres, phytonutrients, carbohydrates, proteins, polysaccharides Food waste is generally associated with nutrient wastage and today interventions mainly address nutrition quality and food sustainability. The present review work aims to gather knowledge on the nutrients present in various waste products and their uses for food fortification.

Keywords: Food waste, valuable substances, food fortification, food sustainability, utilisation in industry

Introduction

Fortification of staple foods nowadays a very successful strategy for the prevention of different micronutrient deficiencies. Micronutrient deficiency is always a great threat to society because it has a great impact on mortality and morbidity. Dietary inadequacy mainly happens due to a deficit intake of iron, vitamin A, Iodine, Vitamin D-like nutrients, etc. (Mejia and Bower, 2015). Morbidity and disability, these risk factors are associated with Micronutrient deficiencies, resulting in substantial disease burden (viz. years lived with disability and years of life lost) and economic losses (Chowdhury et al., 2022). As per NFHS-5, anaemia was found among 57.2 per cent of non-pregnant women, 52.2 per cent of pregnant women and 67.1 per cent of children (in the age group 6-59 months). Recently, as per the

comparison table burden of anaemia is rising, so fortification of staple food i.e., Rice with iron has been announced (Press Information Bureau, 2021). Anaemia affects approximately 1.8 billion people worldwide, of whom 60% suffer from iron deficiency anaemia. It is a global burden that affects adults' physical activity, productivity and their economic well-being (Jalal et al., 2023). The COVID-19 Pandemic also enhanced food and nutrition insecurity, particularly in low and middle-income groups, women and children, resulting in 2.1 million anaemic pregnant women and 2.1 million children born to women with low BMI in 2020-2022 compared to 2019 (Osendarp et al., 2021).

Table: 1. Per cent prevalence of anaemia in India from National Family Health Survey-2 to National Family Health Survey-5

Age group	NFHS-2	NFHS-3	NFHS-4	NFHS-5
Children age 6-35 months	74.3	78.9	66.8	
Children age 6-59 months		69.5	58.6	67.1
Non-pregnant women age 15-49		55.2	53.2	57.2
Pregnant women age 15-49 yr	49.7	57.9	50.4	52.2
All women age 15-49 yr		55.3	53.1	57.0
Men age 15-49 yr		24.2	22.7	25.0

(Source: International Institute for Population Sciences, 2022)

Micronutrient deficiency, also called 'hidden hunger, affects the proper functioning of the body and also affects the morbidity and mortality risk in children, as well as hidden hunger influences the individual's working capacity, productivity, etc. (Chauhan, 2019). Micronutrient deficiency, such as hidden hunger, occurs when a child consumes a smaller amount of essential vitamins and minerals, and the absorption level also falls below levels necessary for growth and development. Although progress has been made in addressing micronutrient deficiency in recent years, improvements in South Asia are going too slowly to achieve the Millennium Development Goal (MDG) target. If current trends continue SDG2 (achieving zero hunger) will be missed by 2030 (Ritchie et al., 2018).

Vitamin A deficiency causes night blindness in children globally. If milk or milk-based products are fortified with β-carotene, then it would be very beneficial for the children (Ahmed et al., 2023). Prevalence of Vitamin A deficiency disorder happens due to low amounts of vitamin A because of food insecurity and lack of awareness, therefore, to ensure regular intakes of vitamin A among the vulnerable groups through horticultural intervention to produce foods rich in the micronutrient, thus improving availability, access and utilization of locally available vitamin A/β-carotene-rich foods including non-conventional leafy vegetables with high β-carotene content. Other than that, fortification of one or more commonly consumed foods with vitamin A may be cost–effective for vitamin A deficiency (Vijaywaraghavan et al., 2018).

For the eradication of micronutrient deficiency, there are many intervention programs organised by the Government in which fortification is the most effective way. Through fortification, micronutrient-enriched food is provided to the target group of society. Besides this, there are other programs like supplementation, Status quo, food coupons, etc. (Chauhan, 2019). WHO and FAO have also endorsed four main strategies for improving dietary intake.

Bio fortification is the process in which the nutritional content of staple crops is changed through various agronomic technologies, including the application of micronutrient fertiliser to the crops, conventional plant breeding and/or genetic modification (Romana et al., 2023).

The aim of the present study is to know about the beneficial nutritional content of various waste food and the perfect use of this nutritional component for food fortification that can combat malnutrition in various target groups.

Different types of Food Fortification and their effects

Market-driven fortification is an opportunity for food manufacturers to contribute to the combat against the major global public health problem of micronutrient deficiencies (MND). Any market-driven fortification initiative should be based on the best available documented evidence of MND in the target population, with careful consideration given to the relevance of micronutrient fortification of the food product to existing deficiencies in the target population, the expected nutrition or health benefits, and how they are to be communicated(Klassen and Barclay., 2018). In Brazil, there is market-driven fortification done in packaged foods targeted at children. The main groups which selected for fortification are milk and milk products, sugars, sugary products and snack items, and the nutrients used as fortificants are vitamin A, B Complex, D, Calcium, Iron and Zinc (Martins et al., 2024).

In the Bangladesh market, driven fortification is going to be very cost-effective. They implemented home-based fortification in 164 sub-districts. Home fortification with micronutrient powder reduces the prevalence of Fe deficiency anaemia among children 6-59 months (Ahmed et al., 2020).

A larger proportion of the population can be reached via commercially processed food and value-added products. A multifaceted approach of fortifying more than one food vehicle is a good strategy for society (Mannar and Hurrell, 2018).

Target fortification appears to promote growth in very low birth weight preterm infants without any detrimental effects. In this study, breast milk was fortified to prevent postnatal growth failure in preterm infants (Morlachhi et al., 2016). Target fortification has also been done to meet the recommended dietary intake in preterm infants, it is seen that fortified human milk consumption increases the protein to energy ratio (Macedo et al., 2018). Another study on target fortification is to fortify breast milk with carbohydrate (8.8g), protein (3 g), and fat (4.4g), and it is fed to healthy very low birth weight babies at least 3 weeks, which improves health and clinical routine (Rochow et al.,2013). Infant and young children in 5 countries were selected for the targeted fortification. They have consumed fortified food or food supplements through the nutrition intervention program (Friesen et al., 2017).

The FACT (Fortification Assessment Coverage Toolkit) is a survey instrument that was designed to assess coverage and utilization of fortified foods in both population-based (i.e. staple foods and condiments) and targeted (e.g., complementary foods for infants and

young children) fortification programs, independently of any routine monitoring systems that the program may have(Neufeld et al., 2017).

Large-scale food fortification initiatives have been reaching increasingly larger segments of populations in low- and middle-income countries. Large-scale food fortification and bio-fortification should be part of nutrition intervention programs that aim to prevent and control micronutrient deficiencies. There are remaining technical and food system challenges, especially in relation to improving coverage and quality of delivery and measuring progress of national programs (Osendarp et al., 2018). Iron fortification of a staple food is very useful for the anaemia control program. NaFeEDTA is recommended for the mass fortification of high-phytate cereal flours and sauces with high peptide content (e.g. fish sauce, soy sauce), and ferrous bisglycinate, micronised ferric pyrophosphate and ferric ammonium citrate have been used to fortify liquid milk and dairy products to enhance the iron absorption and bioavailability of the iron in the body (Garsia-Casal et al., 2014).

Vitamin D deficiency is mainly prevented by three processes -sunshine exposure, food fortification, and supplementation - the latter seems to be the most effective and practical in the ageing population. Biofortification of animal feed with vitamin D could improve its content in eggs or meat. Additionally, the increase in the vegan population will require an increase in the use of plant-based vitamin D (Giustina et al., 2023). Fortification can be an effective NTD prevention strategy in populations with limited access to folic acid foods and/or supplements. Folic acid fortification has achieved the most success in the USA in the twenty-first century. More than 1,300 NTDs are prevented annually in the USA through the mandatory FA fortified food (Crider et al., 2023). Patients who are highly malnourished or have lower energy intake patterns obtain the highest benefit from food fortification, so those who have a higher risk of malnutrition and weight loss, food fortification should be included in more than one meal (Morillla-Herrrea et al., 2016).

Fortification for the prevention of the effects of climate change

In recent Climate change has great potential to increase the risk of micronutrient malnutrition in vulnerable populations because increasing atmospheric carbon dioxide and rising temperature reduce the overall yield of major staple crops, fruits, vegetables, and nuts, rather than affecting the micronutrient content of the foods themselves. Strategies are taken to reduce the risk of micronutrient malnutrition, such as post-harvest fortification of foods, micronutrient supplementation, and biofortification of staple crops with zinc and iron (Semba et al., 2022).

Food waste for fortification

For fortification, using food waste is a newer trend. Food waste has a good nutritional value because constituents present in the food waste are of premium quality since they were intended for human consumption. Loss and waste of highly perishable foods, such as fruits, vegetables, and animal-based products, lead to losses of important nutrients (Georganas et al., 2020). Food waste and nutrition are intrinsically linked in terms of environmental health and public health (Brennan and Browne, 2021).

Food waste is a by-product of various industrial, agricultural, household and other food sector activities, and is rising day by day due to an increase in such activities. Various studies have indicated that different kinds of food waste obtained from fruits, vegetables, cereal and other food processing industries can be used as a potential source of bioactive compounds and

nutraceuticals, which have significant applications in treating various diseases like cancer, obesity, diabetes, bone-related issues, etc. Different secondary metabolites, minerals and vitamins have been extracted from food waste, using various extraction approaches. The vegetable waste includes trimmings, peelings, stems, seeds, shells, bran and residues remaining after extraction of juice, oil, starch and sugar. Bioactive phytochemicals like sterols, tocopherols, carotenes, terpenes and polyphenols extracted from tomato by-products contain significant amounts of antioxidant activities. The bioactive compounds present in mango peel are phenolic compounds, carotenoids, vitamin C and dietary fibre. It has been well recognised that these compounds contribute to lowering the risk of cancer, cataracts, Alzheimer's disease and Parkinson's disease (Kumar et al.,2017). Fruit waste also affects our environmental circumstances. If we use fruit waste in the fortification process, then it would reduce the carbon footprint and greenhouse gas emissions. In fruit wastes, there are many kinds of phytochemicals present, like dietary fibre, flavonoids, phenolic compounds, and antioxidants. if this product can be extracted from the waste, then we can develop some value-added fortified products (Nirmal et al.,2023). Worldwide, a large amount of food wastes are produced. So, we have to reduce the European level food waste is being taken very seriously; they have targeted to reduce the amount of food waste by the year 2030. food waste like peel and pomace of fruits (apple, banana, orange, and kiwi) and vegetables (potato, cabbage, and carrots), which are very common in waste generated at the housing level (Ghinea et al., 2018).

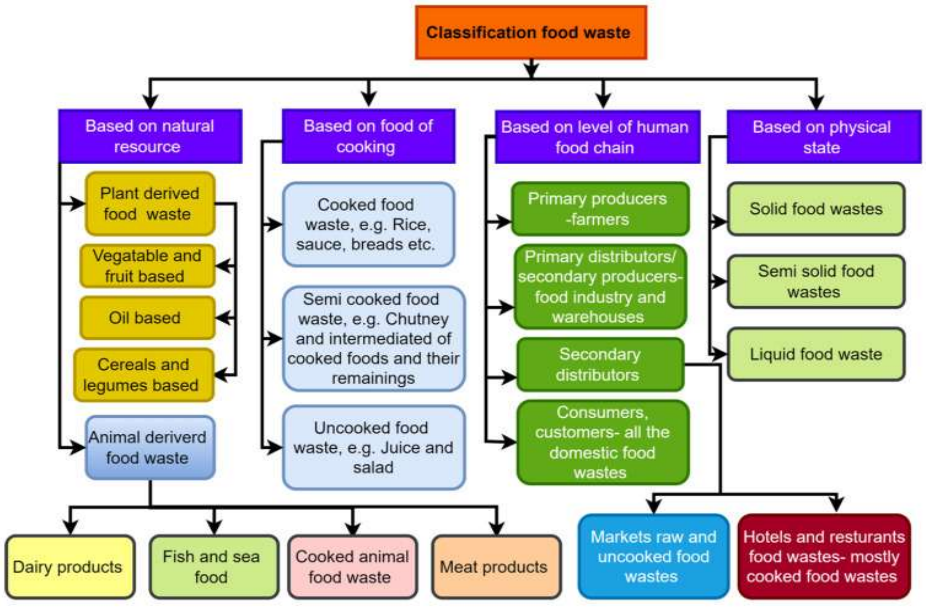
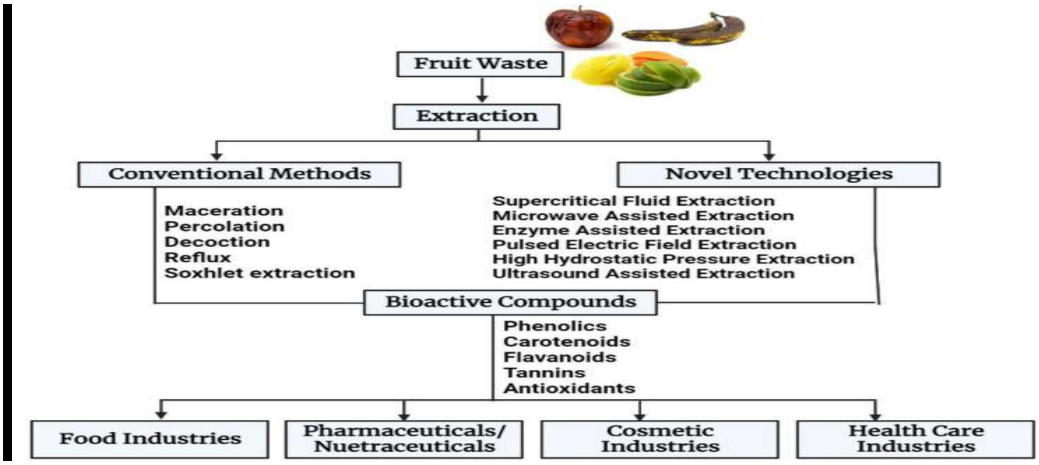


Fig:1. Overview of classification of Food Wastes (Nath et al., 2023)

Sustainable practices to reduce Food waste

The Definition of Food waste encompasses both edible and inedible parts of food, such as vegetable peelings, fruit peelings, discarded vegetables and fruits, leftover food, tea leaves, egg shells, etc. The issue of food waste is a new and of novel topics for the changes of India's traditional systems of food consumption (Kashyap, 2024).



A **Fig: 2. A schematic representation of fruit waste valorisation (**Nirmal et al.,2023**)**

Fruit wastes are naturally enriched with vitamins, minerals and other bioactive compounds. Compelling evidences justify and designates peels and relative extracts of numerous fruits as nutraceuticals and functional food (Morina and Shehaj, 2022). The fruit processing industry nowadays contributes to the increasing amount of food waste by-products. Fruit pomace is used much more because it contains different bioactive compounds, dietary fibres to encourage to design of novel food products. Advantages of fruit pomace addition include improved nutritional properties of products: total phenolic content, total flavonoid content, antioxidative activity and dietary fibre level (Piasecka and Górska, 2020).

Nutraceuticals are present in different food wastes

Nutraceuticals present in different food wastes have many beneficial roles for human health. Food product development, such as bakery products like biscuits, cookies, macaroni, noodles etc., by using fruit and vegetable wastes has been of great interest to researchers since most of them are rich in bioactive compounds and have potential health benefits to be applied in food and pharmaceutical products (Comunian et al., 2021). The bioactive compounds present in mango fruit wastes like peels include phenolic compounds, carotenoids, vitamin C and dietary fibre. It has been well recognised that these compounds contribute to lowering the risk of cancer, cataracts, Alzheimer's disease and Parkinson's disease. Wastes from the alcoholic beverages production industry include biodegradable solids, namely stems, skins, and seeds. Bioactive compounds from winery by-products have been shown to improve health-promoting activities both in vitro and in

vivo.

These compounds act as effective agents for prevention of degenerative processes through their incorporation into functional foods, nutraceuticals, and cosmetics. These are commonly utilized for the production of pharmaceuticals and as food additives to increase the functionality of foods (Kumar et al., 2017).

Table: 2. Different bioactive compounds found in food waste

Types of waste	Fruit/ Vegetable wastes	Bioactive compounds	References
Pomace	Apple	Quercetin, Glycosides, Hydroxycinnamates etc.	Chaudhary and Dangi, 2022
Peel	Banana	Carotenoids (palmitate or caprate, xanthophylls, laurate)	Ishikiriyama et al., 2024
Peel	Mango	Polyphenols, Tocopherols, Flavonol glycosides	Ismail et al., 2024
Pomace	Grapes	Catechins, anthocyanins, flavonol glycosides	Wandzel et al., 2024
Pomace	Carrot	Carotenoids (α and β)	Umair et al., 2021
Peel	Red Beet	L-tryptophan, p-coumaric and ferulic acids, cyclodopa glucoside derivatives	Szymanski et al., 2023
Peel	Potato	Glycoalkaloids, Dietary Fibre	Khanal et al., 2024

Food fortification is a cost-effective strategy to prevent micronutrient deficiency, and it also helps to improve health, economical benefits and social benefits. Food fortification that is large-scale food fortification, biofortification and point–of–use or home fortification, has significant benefits to reduce the prevalence of nutritional and economic benefits (Olson et al.,2021). Food fortification is an effective strategy to counteract nutrient deficiencies and has been applied for along time, especially in industrialised countries, where foods have been fortified with vitamins A, B, and D, iodine, and iron. “Designer foods” is a concept that defines regular foods, which, besides their traditional nutritional value, contain some compound that provides additional health benefits. They are also referred to as “functional” or “fortified” foods and have a long history of use in East Asia in traditional medicine to reduce the risk of various diseases. The use of designer foods avoids the need for changing dietary habits, and adequate amounts of nutrients can be delivered regularly, thereby improving the diet and preventing deficiencies (Patel et al.,2022).

Conclusion

This systematic review confirmed that food waste can be successfully used as a fortification ingredient in plant food products, dairy products, and meat products as well. High content of dietary fibres, various bioactive compounds, and phytochemicals present in food wastes, which improves the nutritional quality of food products. The increased antioxidant activity is one of the main targets for food fortification. But for every food product development, sensory evaluation may sometimes give some drawbacks. In recent times, Climate Change, i.e. extreme weather events, has the capacity to affect the quality and accessibility of micronutrient-rich food.

Food fortification through food waste is a novel approach to achieve the Sustainable Development Goal, to prevent micronutrient deficiency, and to prevent hidden hunger. The future scope of the study is to extract dietary fibre, calcium, phytochemicals, etc. from food wastes that may be collected from the underutilised part of food and then used as a fortificant to fortify different milk products, different cereals and cereal Products, etc.

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CHAPTER-II

Food Waste to New Food Products Development: Technologies, Nutritional Potential, and Sustainability Perspectives

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Abstract

Food waste represents a major global challenge with significant environmental, economic, and nutritional implications. Large quantities of edible and nutrient-rich food by-products generated during agricultural production, processing, distribution, and consumption are discarded annually. Recent advances in food science and technology have shifted focus toward the valorization of food waste into value-added food products, aligning with circular economy and sustainable development goals. Food wastes such as fruit and vegetable peels, seeds, pomace, cereal bran, dairy by-products, and fish residues are rich sources of dietary fibre, proteins, bioactive compounds, antioxidants, and micronutrients. Innovative processing techniques—including drying, fermentation, extrusion, encapsulation, and bioconversion—enable the transformation of these wastes into functional ingredients and novel food products such as bakery items, beverages, snacks, supplements, and fortified foods. This review critically examines sources and composition of food waste, emerging technologies for food waste valorization, applications in new food product development, nutritional and functional benefits, safety and regulatory considerations, and future research directions. Harnessing food waste for product development not only reduces environmental burden but also enhances food security, nutritional quality, and economic sustainability.

Keywords: Food waste valorization; By-products; Functional foods; Circular economy; Sustainable food systems; Food product development

1. Introduction

Food waste has emerged as one of the most pressing global sustainability issues, with approximately one-third of food produced for human consumption lost or wasted each year. This loss occurs across the food supply chain—from agricultural harvesting and food processing to retail and household consumption. Beyond ethical concerns related to food insecurity, food waste contributes substantially to greenhouse gas emissions, land degradation, water depletion, and economic losses. Consequently, transforming food waste into valuable food products has gained attention as a sustainable solution. Food waste and by-products often retain significant nutritional and functional value. Advances in food processing, preservation, and biotechnology have enabled their incorporation into new food formulations. This review focuses on the potential of food waste as a resource for new food product development, highlighting technological innovations, nutritional benefits, and

sustainability impacts (Gustavsson et al., 2011; UNEP, 2024; Ansari et al., 2024; Sarker et al., 2023).

2. Sources and Types of Food Waste

Food waste can be broadly categorized based on its origin:

2.1 Agricultural and Post-Harvest Waste

Agricultural and post-harvest waste arises primarily during harvesting, handling, storage, and transportation of raw produce. This category includes damaged or overripe fruits and vegetables, crop residues, and produce rejected due to non-uniform size, shape, or cosmetic defects despite being nutritionally sound. Such wastes are abundant in carbohydrates, dietary fibre, vitamins, and bioactive phytochemicals, including polyphenols and carotenoids. Inadequate storage facilities, mechanical damage, pest infestation, and poor post-harvest management significantly contribute to these losses, particularly in developing countries. Valorization of agricultural and post-harvest waste into food ingredients or functional products offers a sustainable approach to reduce losses while harnessing their retained nutritional and functional potential (Yadav et al., 2024; Sarker et al., 2024; Ansari et al., 2024; Bekavac et al., 2025).

2.2 Food Processing By-Products

Food processing by-products are generated in substantial quantities during industrial operations such as milling, juicing, oil extraction, dairy processing, and fish processing. Common examples include fruit peels and pomace, seeds, cereal bran, oilseed cakes, whey, and fish trimmings. These by-products are often concentrated sources of proteins, dietary fibre, essential fatty acids, minerals, and bioactive compounds such as polyphenols and antioxidants. Despite their rich composition, they are frequently underutilized or disposed of as waste. Advances in food processing and extraction technologies have enabled their transformation into functional ingredients for bakery products, beverages, snacks, and nutraceuticals, thereby enhancing resource efficiency and promoting circular food systems (Yadav et al., 2024; Sarker et al., 2023; Ansari et al., 2024; Bekavac et al., 2025).

2.3 Retail and Household Food Waste

Retail and household food waste originates from unsold products, expired foods, over-preparation, and consumer leftovers. Factors such as inaccurate demand forecasting, improper storage, bulk purchasing, and lack of consumer awareness significantly contribute to this category of waste. Although retail and household food waste is highly heterogeneous and poses greater challenges related to safety, quality, and traceability, controlled recovery and segregation systems can enable its partial utilization. When managed under strict hygienic and regulatory frameworks, selected fractions of this waste can be redirected for food redistribution, ingredient recovery, or secondary processing, thereby reducing landfill burden and contributing to sustainable waste management strategies (Sarker et al., 2023; Ansari et al., 2024; UNEP, 2024; Sezer et al., 2021).

3. Nutritional and Bioactive Potential of Food Waste

Food waste and by-products have been increasingly recognized as valuable reservoirs of nutrients and bioactive compounds with significant potential for food product development.

Fruit and vegetable peels, often discarded during processing, are particularly rich in dietary fibre, vitamins, antioxidants, and phenolic compounds that exhibit strong anti-inflammatory and antioxidative properties. Seeds and kernels recovered from fruits and vegetables provide high-quality proteins, health-promoting lipids, and essential micronutrients, Sarkering them suitable for incorporation into functional foods. Cereal bran, a major milling by-product, is an excellent source of insoluble dietary fibre, B-complex vitamins, and minerals that support digestive health and metabolic regulation. Dairy by-products such as whey contain high biological value proteins and bioactive peptides with immunomodulatory and antihypertensive effects. Similarly, fish processing waste is rich in omega-3 fatty acids, collagen, and minerals, contributing to cardiovascular health and joint function. Efficient recovery and utilization of these nutrients not only enhance the nutritional profile of newly developed food products but also support sustainable and circular food systems (Sarker et al., 2023; Yadav et al., 2024; Ansari et al., 2024; Bekavac et al., 2025; Yadav et al., 2024).

4. Technologies for Food Waste Valorization

4.1 Physical Processing Techniques

Physical processing methods such as drying, milling, extrusion, and micronization are commonly employed to convert food waste into stable, shelf-ready ingredients. Drying reduces moisture content, inhibits microbial growth, and extends storage life, while milling and micronization produce fine powders that can be easily incorporated into bakery products, snacks, beverages, and supplements. Extrusion processing further modifies the physicochemical properties of food waste materials, improving texture, digestibility, and functionality, Sarkering these techniques cost-effective and suitable for large-scale applications (Sarker et al., 2023; Ansari et al., 2024; Dey et al., 2021; Hossain et al., 2025; Dutta et al., 2022).

4.2 Chemical and Enzymatic Methods

Chemical and enzymatic processing techniques are widely used to recover high-value bioactive compounds from food waste. Solvent extraction and mild chemical treatments enable the isolation of polyphenols, dietary fibres, pigments, and proteins. Enzymatic hydrolysis, using specific enzymes such as proteases, cellulases, and amylases, enhances nutrient bioavailability, improves digestibility, and modifies functional properties like solubility, emulsification, and water-holding capacity. These methods allow targeted recovery of nutraceutical components while maintaining nutritional quality (Bekavac et al., 2025; Yadav et al., 2024; Hossain et al., 2025; Ansari et al., 2024).

4.3 Fermentation and Bioconversion

Fermentation and bioconversion processes employ beneficial microorganisms to enhance the nutritional and functional profile of food waste substrates. Microbial fermentation reduces anti-nutritional factors, increases mineral bioavailability, and enriches products with probiotics, organic acids, vitamins, and bioactive metabolites. This approach not only improves sensory attributes and safety but also supports the development of functional foods and beverages with added health benefits (Hossain et al., 2025; Sarker et al., 2023; Ansari et al., 2024; Faria et al., 2023; Sabater et al., 2020).

4.4 Encapsulation and Novel Processing

Encapsulation techniques are used to protect sensitive bioactive compounds from degradation and to enable their controlled release in the human gastrointestinal tract. Micro- and nano-encapsulation improve the stability, bioavailability, and application range of recovered nutrients. In addition, emerging non-thermal technologies such as ultrasound, pulsed electric fields, and high-pressure processing enhance extraction efficiency, preserve heat-sensitive compounds, and reduce processing time and energy consumption, Sarkering them promising tools for sustainable food waste valorization (Yadav et al., 2024; Hossain et al., 2025; Ansari et al., 2024; Bekavac et al., 2025).

5. Applications in New Food Product Development

5.1 Bakery and Cereal Products

Food waste–derived ingredients such as fruit peels, vegetable powders, oilseed cakes, and cereal bran are widely utilized in bakery and cereal-based products to enhance their nutritional quality. Incorporation of these materials into bread, biscuits, chapati, cookies, and breakfast cereals significantly increases dietary fibre, antioxidant capacity, and micronutrient content. Additionally, such fortification improves functional properties like water-holding capacity and shelf life, while contributing to the development of healthier, value-added products without compromising consumer acceptability when optimized levels are used (Yadav et al., 2024; Sarker et al., 2023; Hossain et al., 2025; Bekavac et al., 2025).

5.2 Beverages and Functional Drinks

Food processing by-products such as fruit pomace, peels, and dairy whey are increasingly used in the formulation of functional beverages. These materials serve as natural sources of polyphenols, vitamins, minerals, and bioactive peptides. Their incorporation into juices, smoothies, fermented drinks, and probiotic beverages enhances antioxidant activity, gut health benefits, and overall nutritional value. Fermentation further improves sensory attributes and bioavailability of nutrients, Sarkering waste-based beverages attractive functional alternatives (Sarker et al., 2023; Hossain et al., 2025; Ansari et al., 2024).

5.3 Snacks and Convenience Foods

Waste-derived flours, fibres, and protein-rich residues are effectively utilized in snacks and convenience foods, including extruded snacks, nutrition bars, and ready-to-eat products. These ingredients contribute to improved fibre content, protein quality, and functional properties such as texture and satiety. The use of food waste in snack formulations aligns with consumer demand for sustainable, nutrient-dense, and clean-label products while reducing production costs and environmental impact (Dey et al., 2021; Hossain et al., 2025; Ansari et al., 2024; Grasso, 2020).

5.4 Nutraceuticals and Supplements

Bioactive compounds extracted from food waste—such as polyphenols, dietary fibres, omega-3 fatty acids, collagen, and bioactive peptides—are widely formulated into nutraceuticals and dietary supplements. These are developed as capsules, powders, tablets, and functional ingredients aimed at promoting antioxidant activity, metabolic health, gut health, and cardiovascular protection. The valorization of food waste for nutraceutical

applications offers high economic value and supports the growing market for preventive and functional health products (Bekavac et al., 2025; Yadav et al., 2024; Ansari et al., 2024).

6. Safety, Quality, and Regulatory Considerations Despite its potential, food waste utilization faces challenges related to microbial safety, chemical contamination, allergenicity, and consumer perception. Strict quality control, standardized processing, and compliance with food safety regulations are essential. Regulatory frameworks vary across regions, necessitating clear guidelines for waste-derived food ingredients (Sarker et al., 2023; Ansari et al., 2024; DeLorenzo et al., 2019).

7. Environmental and Economic Implications Valorization of food waste contributes to waste reduction, lower carbon footprints, and improved resource efficiency. Economically, it creates opportunities for cost-effective raw materials, new markets, and employment, particularly in small-scale and community-based enterprises (Sarker et al., 2023; Ansari et al., 2024; UNEP, 2024; Ong et al., 2018).

8. Challenges and Future Perspectives

Key challenges include scalability, supply chain consistency, consumer acceptance, regulatory barriers, and technological costs. Future research should focus on advanced processing technologies, life-cycle assessment, sensory optimization, and policy support to promote food waste-based product development.

Table 1. Food Waste Valorization: Sources, Processing Technologies, Nutritional Potential, and Sustainability Perspectives

Section/Category	Key Technologies/Methods	Nutritional/Functional Potential	Sustainability Perspectives	References
Introduction & Global Issue	N/A (overview of waste sources: agricultural, processing, retail/household)	Retained nutrients in by-products (e.g., fibre, vitamins, bioactives)	Reduces GHG emissions, land/water depletion; promotes circular economy	UNEP (2024)
Agricultural & Post-Harvest Waste	Harvesting/handling optimization; valorization into ingredients	Rich in carbohydrates, fibre, vitamins, polyphenols, carotenoids	Minimizes losses in developing countries; resource recovery for food systems	Osei-Kwarteng et al. (2024)
Food Processing By-Products	Milling, juicing, extraction; transformation into functional ingredients	Proteins, fibre, fatty acids, minerals, polyphenols, antioxidants	Enhances efficiency; circular systems via upcycling	Idrishi et al. (2022)
Retail & Household Waste	Recovery/segregation systems; redistribution/secondary processing	Heterogeneous but recoverable nutrients under safety controls	Reduces landfill; supports waste management strategies	Cox et al. (2010)
Nutritional & Functional Potential	Recovery of bioactives from peels, seeds, bran, whey, fish waste	Anti-inflammatory/antioxidant properties; proteins, lipids, peptides for health benefits	Supports sustainable nutrition; circular food systems	Olaniran et al. (2024)
Physical Processing	Drying, milling, extrusion,	Improves digestibility, texture; stable powders for	Cost-effective, large-scale;	Thamilnesan and Cheng

Methods	micronization	incorporation	energy-efficient	(2025)
Chemical & Enzymatic Processing	Solvent extraction, enzymatic hydrolysis (proteases, cellulases, amylases)	Isolates polyphenols, fibres; enhances bioavailability, solubility	Targeted recovery; maintains quality	Streimikyte et al. (2022)
Fermentation & Bioconversion	Microbial fermentation; probiotic enrichment	Reduces anti-nutritional factors; adds vitamins, metabolites, probiotics	Improves safety/sensory; bio-based functional foods	Vermelho et al. (2025)

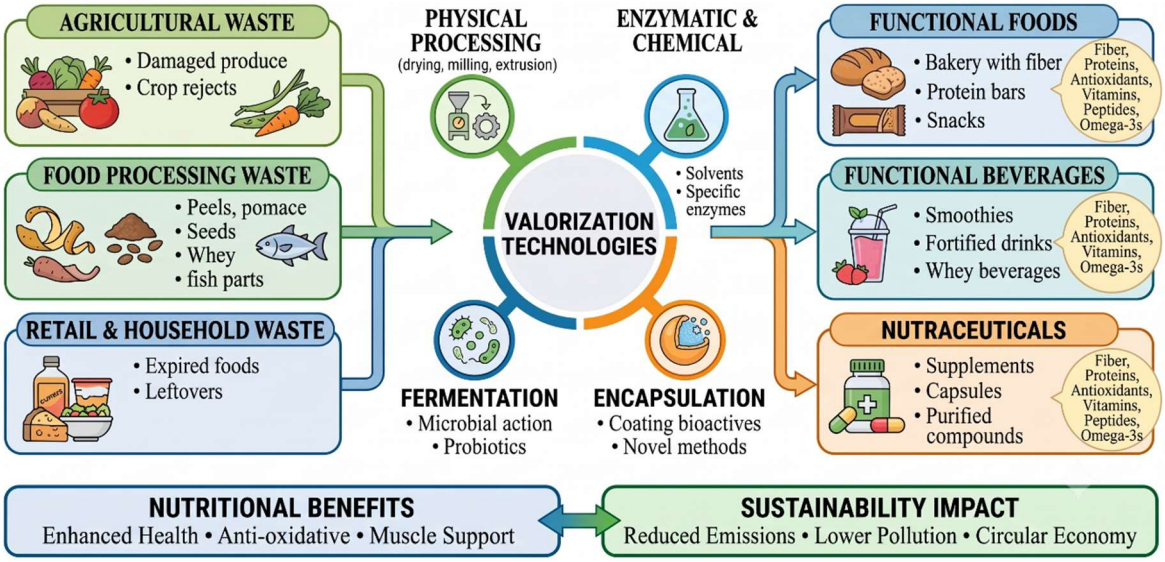


Figure 1. Schematic representation of food waste and by-product valorization pathways, processing technologies, functional food applications, and associated nutritional and sustainability impacts.

Conclusion

Transforming food waste into new food products presents a promising pathway toward sustainable food systems. By leveraging advanced technologies and nutritional potential, food waste can be converted into safe, functional, and value-added products. Integrating food waste valorization into mainstream food production supports environmental sustainability, nutritional security, and circular economy goals.

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CHAPTER-III

Nutritional Composition and Antidiabetic Potential of Bamboo Shoots: A Comprehensive Review

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Abstract

Diabetes mellitus is a major global health challenge characterized by chronic hyperglycemia and associated metabolic complications. Dietary strategies emphasizing low-glycemic, fiber-rich, and bioactive-containing foods are central to diabetes prevention and management. Bamboo shoots, the young edible culms of various bamboo species, are traditional vegetables widely consumed in Asia and increasingly recognized for their nutritional and therapeutic potential. Bamboo shoots are low in calories, rich in dietary fiber, and contain bioactive compounds such as phenolics, phytosterols, and antioxidants that may beneficially influence glucose metabolism, insulin sensitivity, lipid profiles, and oxidative stress. This review comprehensively examines the nutritional composition of bamboo shoots, their functional properties, and the mechanistic and clinical evidence supporting their role in diabetes management. The review highlights their potential as a functional food for glycemic control while identifying research gaps and future directions.

Keywords: Bamboo shoots; diabetes mellitus; dietary fiber; glycemic control; functional foods; antioxidants

Introduction

One of the non-communicable diseases with the fastest global growth is diabetes mellitus, especially type 2 diabetes mellitus (T2DM). Dietary and lifestyle changes continue to be the mainstays of diabetes management and prevention. Vegetable, dietary fibre, and bioactive compound-rich diets are often linked to better glycaemic control and a lower risk of complications from diabetes (Espinola et al., 2026; Son et al., 2026; Tang et al., 2025).

Traditional Asian cuisines have traditionally used bamboo shoots, which are generated from young bamboo culms that belong to the Poaceae family, as vegetables. Bamboo shoots have been utilised in traditional medicine for gastrointestinal and metabolic problems in addition to their culinary uses. They are a promising functional food for managing diabetes because of their high fibre content, low glycaemic load, and physiologically active chemicals (Liu et al., 2026; Wang et al., 2020).

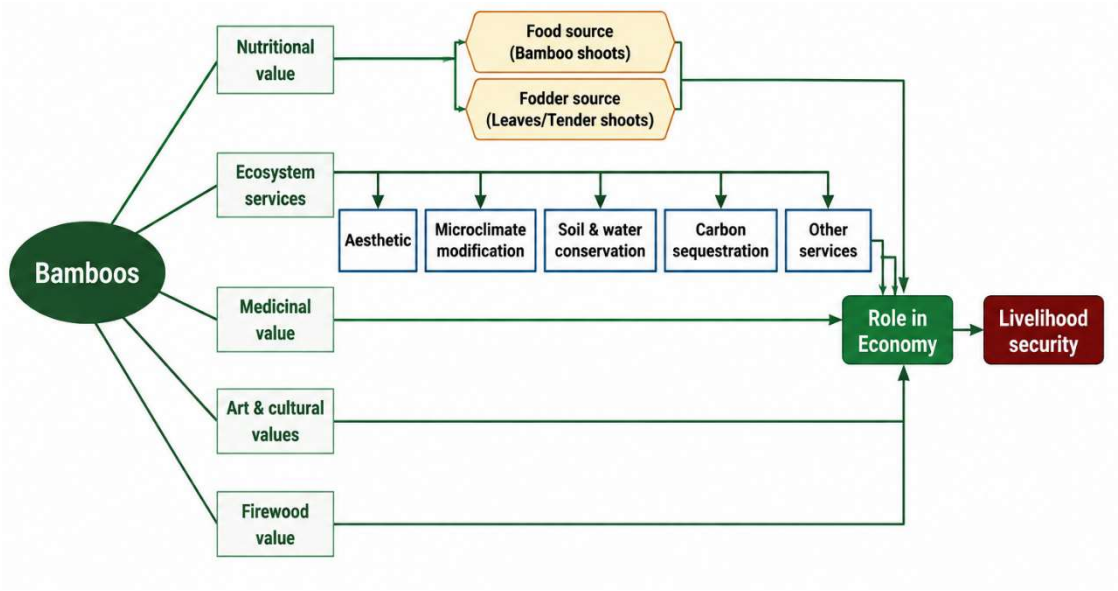


Figure 1: Importance and scope of edible bamboos in India (Sarkar et al., 2025)

Botanical Description and Edible Bamboo Species

A member of the Bambusoideae subfamily, bamboo is a perennial grass that grows quickly. Early in the growing process, before lignification, edible bamboo shoots are collected. *Phyllostachys edulis*., *Dendrocalamus asper*, *Dendrocalamus strictus*, *Bambusa bambos* and *Bambusa vulgaris*, are common edible species. Processing techniques, age, and species all affect the nutritional makeup (Sarkar et al., 2025).

Nutritional Composition of Bamboo Shoots

Bamboo shoots are nutritionally valuable yet low in energy, making them suitable for diabetic diets (Sarkar et al., 2025).

Macronutrients

Due to its high moisture content, particularly rich in dietary fiber, moderate amounts and are low in fat it can digest carbohydrates easily (Wang et al., 2020; Singl et al., 2013; Satya et al., 2009; Kumbhare & Bhargava, 2007).

Dietary Fiber

One of the most important nutritional aspects of bamboo shoots is dietary fibre. There are both soluble and insoluble fibres, which are essential for slowing down stomach emptying, decreasing the absorption of glucose, and enhancing insulin sensitivity (Tang et al., 2025).

Table1: Nutrient Contents in 100 g Fresh Bamboo Shoots

Nutrient	Range / Value	Reference
Macronutrients		
Protein (%)	1.80–25.84	(Singl et al., 2013; Satya et al., 2009; Kumbhare & Bhargava, 2007)
Amino acid (%)	3.11–3.98	(Nirmala et al., 2007)
Oxalic acid (mg/100 g)	157–462	(Singl et al., 2013)
Ascorbic acid content (%)	3.30–5.20	(Nirmala et al., 2007)
Carbohydrate (%)	2.00–9.94	(Singl et al., 2013)
Calories (kcal/100 g)	14.00–27.00	(Singl et al., 2013)

Crude fiber (%)	23.10–35.50	(Nirmala et al., 2007; Singl et al., 2013)
Fat (%)	0.30–3.97	(Singl et al., 2013)
Ash (%)	0.80–3.70	(Nirmala et al., 2007; Satya et al., 2009)

Vitamins and Minerals

Potassium, calcium, magnesium, phosphorus, iron, and zinc can all be found in bamboo shoots. Additionally, they supply the B complex vitamins, including niacin, riboflavin, and thiamin, which are critical for the metabolism of carbohydrates.

Table2: Nutrient Contents in 100 g Fresh Bamboo Shoots

Micronutrients – Vitamins		
Nutrient	**Range / Value**	**Reference**
Vitamin A (I.U.)	20.00	(Yamaguchi, 1983)
Thiamine (Vitamin B1) (%)	0.05	(Rajyalakshmi & Geervani, 1994).
Riboflavin (Vitamin B2) (%)	0.01	(Rajyalakshmi & Geervani, 1994).
Niacin (Vitamin B3) (mg/100 g)	0.20–14.92	(Duke & Atchley, 1986; Kumbhare, 2003)
Pyridoxine (Vitamin B6) (mg/100 g)	0.53–1.70	(Kumbhare, 2003)
Vitamin C (%)	3.00–23.00	(Nirmala et al., 2007)
Vitamin E (%)	0.61–0.91	(Kim et al., 2007)
α-Tocopherol (mg/100 g)	0.26	(Kim et al., 2007)
γ-Tocopherol (mg/100 g)	0.42	(Kim et al., 2007)
β-Carotene (µg/100 g)	1.90	(Kim et al., 2007)
Lutein (µg/100 g)	35.60	(Kim et al., 2007)
Mineral		
Nutrient	**Range / Value**	**Reference**
Calcium (mg/100 g)	0.36–1,900	(Nirmala et al., 2007)
Magnesium (mg/100 g)	5.38–140	(Nirmala et al., 2007; Bhargava et al., 1996; Nirmala et al., 2007)
Phosphorus (mg/100 g)	40–1,000	(Bhatt et al., 2005; 44, 62, 64, 67)
Potassium (mg/100 g)	20–1,400	(Bhatt et al., 2005; Nirmala et al., 2007; Bhargava et al., 1996; Nirmala et al., 2007)
Sodium (mg/100 g)	8.22–400.00	(Nirmala et al., 2007; Bhargava et al., 1996; Nirmala et al., 2007)
Iron (mg/100 g)	0.10–3.37	(Nirmala et al., 2007; Yamaguchi, 1983; Gopalan et al., 1987)
Selenium (mg/100 g)	0.0003	(Nirmala et al., 2007)
Zinc (mg/100 g)	0.57–1.01	(Nirmala et al., 2007)
Antioxidant activity (%)	13.97–46.00	(Satya et al., 2009, Yang et al., 2005)

Bioactive Compounds in Bamboo Shoots

Bamboo shoots contain various bioactive constituents that contribute to their antidiabetic potential (Ka'arayeno & Cita, 2026).

Phenolic Compounds and Antioxidants

Bamboo shoots' phenolic acids and flavonoids have antioxidant properties that assist reduce oxidative stress, which is a major contributing factor to the development of diabetes and its consequences (Techamahasaranont et al., 2026; Satya et al., 2009, Yang et al., 2005).

Phytosterols

By decreasing intestinal cholesterol absorption, phytosterols in bamboo shoots may help improve lipid profiles and minimise cardiovascular risk in people with diabetes (Manogaran et al., 2026).

Other Functional Components

Dietary silica, lignans and bioactive peptides are also present in bamboo shoots that may support metabolic health and vascular function.

Mechanisms Linking Bamboo Shoots to Glycemic Control

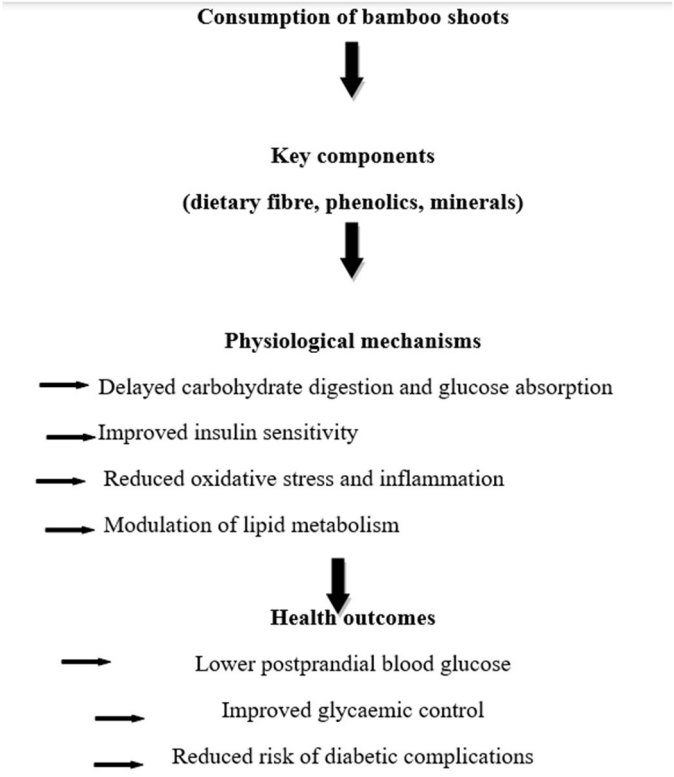


Figure 2. Schematic representation of mechanisms by which bamboo shoots may benefit diabetes management

Role of Bamboo Shoots in Diabetes Management

Glycaemic Index and Control of Blood Sugar

Because of their high fibre content and low accessible carbohydrate content, bamboo shoots have a low glycaemic index. Frequent inclusion in meals may enhance overall glycaemic management and reduce postprandial glucose rises (Espinola et al., 2026).

Sensitivity to Insulin

Bamboo shoots' bioactive phytochemicals and minerals like magnesium may improve peripheral tissues' absorption of glucose and insulin signalling pathways (Phuseerit et al., 2026).

Cardiometabolic Health and Lipid Profile

People with diabetes are more likely to develop dyslipidaemia. Bamboo shoots may help lower blood cholesterol and triglyceride levels since they are low in fat and contain fibre and phytosterols (Bajwa et al., 2022).

Satiety and Weight Control

Bamboo shoots' high fibre content and low-calorie density encourage fullness and may help reduce weight, which is a crucial part of managing type 2 diabetes (Bajwa et al., 2022).

Evidence from Experimental and Clinical Studies

Bamboo stalk extracts have been shown to exhibit hypoglycemic, hypolipidemic, and antioxidant properties in animal experiments. Diets including bamboo shoots may be linked to better metabolic profiles, according to a small number of human observational studies. Nevertheless, there are still few well-designed RCTs in diabetes populations (Bajwa et al., 2022).

Antinutritional Factors, Safety, and Processing

Cyanogenic glycosides found in fresh bamboo stalks have the potential to emit hydrogen cyanide if improperly treated. These substances are successfully reduced by conventional processing techniques like boiling, fermenting, and soaking, making bamboo shoots safe to eat. Processing must be done correctly, especially for vulnerable groups like people with long-term illnesses (Chongtham et al., 2022).

Limitations and Research Gaps

Bamboo shoots with diabetes have little clinical data, despite encouraging nutritional and experimental findings. Standardised formulations, dose response relationships, long-term safety, and clinical efficacy in diabetic patients should be the main subjects of future research.

Conclusion

Bamboo shoots are a low-calorie, fiber-rich vegetable that offer substantial potential advantages for managing diabetes. Their commendable nutritional profile, coupled with bioactive components, aids in glycemic control, improves insulin sensitivity, enhances lipid metabolism, and bolsters antioxidant defenses. Including appropriately processed bamboo shoots in balanced diets may represent an effective dietary approach for those living with diabetes. However, comprehensive clinical trials are essential to validate their therapeutic benefits and to formulate dietary guidelines.

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CHAPTER-IV

The Role of Food Processing Technologies in the Development of Innovative Food Products

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Abstract

The productivity of the food sector depends on its ability to introduce new products and formulations that create added value. Food processing technologies play a key role in this product innovation . These technologies can enhance a product's safety, stability, sensory and nutritional attributes, thereby making it possible to develop formats that target new consumer needs (e.g., clean label, fortified, tailored flavour, environmental sustainability). This paper examines which food processing technologies are currently the most relevant for product innovation. Analysis of successful innovation cases indicates that the strategic innovation potential of processing technologies can be better exploited when firms adopt a framework to understand and select these technologies, as well as to anticipate their concomitant change in product concept or value proposal. A second but less explored layer highlights the role played by food processing technologies—such as encapsulation and extrusion, circulation fields, and modulation of temperature, humidity, and time—in developing innovative food products with an enhanced degree of sustainability while maintaining product quality and safety. These examples illustrate how food processing technologies can enable significant functionality and convenience improvements in food products and contribute to innovation more broadly throughout the food value chain .

Keywords

Processing technologies ,Innovative food products,sensory characteristics and sustainability.

1. Introduction

Food processing technologies—tools that transform raw ingredients into safe, nutritious, and enjoyable food—enable innovation across the broader food system. Such innovation encompasses development of new products as well as reformulation of existing products to improve quality while preserving safety and extending shelf life. A diverse portfolio of processing technologies is available, classified by preservation (thermal and non-thermal), transformation (fermentation, extrusion, coating, milling), and enhancement (encapsulation, 3D printing). Each category supports different types of innovation. For instance, thermal processing underpins ready-to-eat and long-shelf-life food products, while extrusion and additive manufacturing enable entirely new semi-finished shapes and formats. Processing technologies can thus significantly shape food product development decisions.

Academic and industry research on food processing technology primarily emphasizes several key areas, including process design, engineering, quality control, and safety standards. Industry practice, in a parallel manner, centers its attention on producing well-defined food products that not only meet but consistently exceed high-quality expectations while focusing on efficient process engineering. Unfortunately, there are only a limited number of frameworks available to effectively guide the exploration of innovation opportunities that are closely associated with processing technology; as a result, the full potential for innovation, which could significantly enhance food processing techniques and products, often goes underestimated and underutilized. As the scope of available products and concepts continues to expand and evolve, gaining access to a comprehensive and diverse portfolio of processing technologies will become absolutely vital for successfully pursuing and capitalizing on new opportunities within the food industry. (Ester Betoret Valls et al., 2011)

2. Overview of Food Processing Technologies

Food processing technologies can be grouped into three major categories: Preservation technologies aim at extending the shelf life of food products; transformation technologies relate to changing physical state or availability of certain nutrients, flavors and nutrients of food products; enhancement technologies include technologies that enrich foods with value-added nutrients, flavors, bioprotectants, functional ingredients, preservatives, and/or emulsifiers. The innovation lens focuses on how food-processing technologies contribute to the creation of new food products. Relevant questions pertain to the mechanisms through which processing choices influence food innovation; the food-processing technologies with the greatest impact on productivity; and the trade-offs between risks and opportunities associated with the use of such technologies (Ester Betoret Valls et al., 2011).

Food processing technologies are categorized into thermal (e.g., pasteurization, frying, cooking); non-thermal (e.g., high-pressure processing, ohmic heating, microwaving, information processing, ultraviolet-irradiation, cold sterilization, irradiation, infomatics); fermentation (e.g., bioenergetics, enzymes, starter cultures, ethanol fermentation); extrusion (e.g., scattered drying, sugar-functional groups, sugar drying, heat-moisture conditioning, annealing, crystallization, calcium carbonate); encapsulation (e.g., conversion, liquid brine, mass fraction); coating (e.g., cryoprotectant, hydrocolloid, surface-laminating); and milling (e.g., comminution, bile astringent, calcium carbonate). Each category generically refers to a set of equipment that performs a similar role with respect to food transformation (Picart-Palmade et al., 2019).

3. Mechanisms Linking Processing Technologies to Product Innovation

Food processing technologies exert a powerful influence on product innovation across categories, shaping composition, functionality, and value propositions (Voytovych & Polyak, 2019). Techniques such as fermentation, extraction, and emulsification direct product features toward new attributes related to healthfulness, sustainability, and sensory experience. Complex interplay among multiple technologies frequently occurs, enabling value-adding combinations of attributes, such as fortification alongside clean labeling or plummeting fat reduction coupled with enhanced flavor.

Processing contemplations also intertwine with the evolving regulatory environment. Food legislation increasingly constrains the permissible set of product claims, necessitating an awareness of applicable regulations and formal approvals when designing innovative value propositions (Jarzębowski & Bezat-Jarzębowska, 2019). For instance, protein or fiber

enrichment of an offering does not inherently confer a health-related classification, yet a health claim—often strategically pivotal for consumer perception of the proposition—may become unattainable without complementary functionality. Conversely, food enrichment with certain vitamins transforms the product into a dietary supplement with extended procedural requirements. Determination of the appropriate label or classification to pursue therefore remains of utmost importance, especially for a high-stakes or costly concept.

4. Case Studies of Innovative Products Enabled by Processing Techniques

The Japanese company MUSEP, together with the European Union "Innovation and Technology Transfer from Japan" programme, developed a system for converting brown rice into a food product with high nutritional value, thus considerably extending its shelf life. The system uses the drive of a dinner plate to move the rolling materials uniformly, hollowing out the rice and providing a means for extracting the undesired organics such as malcolm or feston. Disasters, conflicts, climatic situations, such as floods and the COVID-19 pandemic, cause food supply insecurities to be one of the global concerns that require urgent action. Various food products are being developed and launched in the market to enhance sustainability aspect within the food industry (Brooks et al., 2021).

The expanding health concern promotes oat-based beverages product category in recent years. During the commercialization of oat milk product, the major barrier in the European market is the formation of off-flavour. In the production of oat milk, oats are processed as a cereal-based product and are subjected to hydrothermal treatment before the actual extraction step in order to deactivate enzymes and improve microbial quality. Steam is used as a heating medium in oat milk formulations to achieve high-quality production. The high hydrostatic pressure treatment is then applied as a sterile method (Ester Betoret Valls et al., 2011).

5. Food Safety, Quality, and Regulatory Considerations

Food safety and quality constitute major concerns for food manufacturers. Adoption of such technologies carries safety risks or product quality deterioration. Control measures should be carefully applied to microbial safety and allergen management along the supply chain. In many cases, addressing challenges through advanced techniques such as computer vision harassment, spectroscopic analysis, or non-destructive measurement can help minimize alteration of the original qualities or prevent unnecessary food waste (Hribar et al., 2018). Further, stringency of regulatory approvals for new processing techniques varies by region, and product-specific approval simplifies the route from laboratory to market adoption. Processing-led innovation may also affect product definition, concept, or branding, thus prompting food laws, standards, and labeling requirements modification (Picart-Palmade et al., 2019). Risk assessment frameworks and validation threads to protect food products, cover intermediate products, and demonstrate safety increase focus.

6. Market Dynamics and Consumer Perception of Processed Innovations

Innovations in food processing technologies that result in high levels of preservation, characterization, and transformation have shifted the global market from low to high added-value products. Cereal and meat-based novel food formulations represent a high proportion of the science- and technology-driven innovations for food and nutrition sustainability and coexist in the optimization of palatability; safety, health, convenience, clean label, and multi-functionality value proposition; and price–brand positioning. Widespread acceptance or fitness-for-use demands for advanced preservation technologies such as superheated steam,

CIR, HPP, and lactate fermentation differ among consumer packs (colder food chain) and IPP (ambient stability).

Consumers' evaluation and the market performance of food product innovations driven by processing technologies on the global, EU, and national levels strongly rely on the ability of innovative technologies to overcome strict barriers related to CHEN factors—cHanging staple; changing ethologies and numbers of consumers; rising conscientiousness on health. environmental sustainability, and nutrition led by the Green Deal; and Nutricare Revolution (Spada et al., 2024).

The food industry continues to face various barriers impeding the introduction of innovative products and manufacturing technologies. The numerous and extended physical–chemical and bio–bio interactions occurring during the transition from formulation to the finished packaged product have not yet been reduced or systematically characterized. As a result, the "one format suitable all" paradigm of mixing advanced food processing technologies with innovative food concepts has become insufficient to systematically formulate a multitude of innovative high-value-added food products.

7. Sustainability Implications of Processing-Driven Innovation

Food processing is notoriously energy-intensive, with trucks and equipment consuming significant amounts of energy, water, and producing waste. Yet many of the innovations are more convenient, often offering extended shelf life and greater safety (Knorr et al., 2020). Further, sustainability attributes have not been a priority for many consumers since price and quality take priority (Brooks et al., 2021). At the same time, efforts to improve sustainability are increasing, such as zero-discard technologies, entering ultra-high vacuum conditions, various alternatives to freezing, and even refining using cleaning agents such as liquid CO2. Processing-driven innovative approaches can meet needs for development of more sustainable food ingredients, some options are preparing ingredients concentrated, powdered, or dry, which allows formulating new kinds of instant and convenient meals, further considering continual increase in energy prices, new food processing technology that enables short-time heating and low-temperature drying/low-temperature frying with efficiency energy consumption and high product quality are also advantageous.

8. Methodological Approaches for Assessing Technological Impact

Processing is widely understood to include a set of operations intended to enhance attributes such as preservation, safety, nutritional value, convenience, and sensory properties of the material used. Food technology and preservation techniques (food technology) can be classified based on whether they seek to preserve, transform or enhance edible products. Each of these broad activities represents an important dimension of innovation; always from the perspective of transforming primary materials into complex, ready-to-eat products that satisfy consumer demands a set of situations can be envisaged where technological, processing and preservation advances have enabled the conception, realisation and commercial introduction of novel ready-to-eat food product concepts (Ester Betoret Valls et al., 2011). Important advances in other sectors of food technology can profoundly impact food processing at a product-oriented level. Food processing is a key activity in the elaboration of most ready-to-eat food products. Classically, the food-processing technologies that are most widely practised correspond to a few broad classifications associated with the specific aim of food processing processing activities (thermal, non-thermal, extraction, fermentation, blending, coagulation, drying, hydrocolloids, milling, frying, pasteurisation, extrusion, ultra-heat treatment (UHT),

sterilisation, encapsulation, co-crystallisation, 3D printing, coating, etc.), together with food quality parameters.

9. Challenges and Opportunities in Future Product Development

Food product development is a complex and risk-oriented activity influenced by market dynamics and trends, consumer attitudes and behaviours, and an ever-expanding range of processing technologies. Such technologies deliver new functional, sensory, and sustainable properties that can support innovative product development but often represent high investment costs, long validation times, and uncertain payoffs (Ester Betoret Valls et al., 2011). The best estimates suggest that 30-40% of new products fail shortly after launch, with failure rates exceeding 80% across the industry (N. Aguilar et al., 2019). Remaining hurdles to successful development include meeting regulations while maintaining product integrity, establishing resonance with target consumers, and addressing major information gaps regarding state-of-the-art processing techniques and their interactions.

Addressing these challenges through development of a conceptual framework visualising the strong links between contemporary processing technologies, innovative product development, and the detailed processing–property–product interplay that underpins technical assessment, enables identification of relevant processing technologies, emerging product concepts, potential technical synergies, and currently unmet consumer needs. Four core classes of processing technology stand out as offering significant advantages capable of enabling either substantial product differentiation within existing segments or entry into completely new segments. Suitable processing techniques fit within heating/cooling, fermentation, fluid application, and non-thermal categories, opening valuable prospects for further industry investigation. Directing attention to applied food technology also attends to a critical research gap and positions additional openly accessible resources—covering reviews, case studies, and downloadable process maps—for creation of further disruptive concepts and rapid assessment of the processing and problem resolution options available for any specified product context.

10. Conclusion

An extensive review of food processing technologies demonstrates their strong potential to facilitate innovative product development across a range of markets. While processing methods are conventionally associated with monitoring shelf life and safety, they are often overlooked as enablers of innovation in product formulation or design. Nevertheless, processing techniques remain key enablers of product design, facilitating breakthroughs across a variety of value propositions.

Regulatory, safety, and quality design controls are fundamental to ensuring the successful commercial adoption of processing technologies. Processing technologies are intrinsically tied to approaches for improving food and health; product innovations that combine these technologies and health-related attributes significantly enhance the opportunity for commercial success.

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CHAPTER-V

Algae-Based Bioplastics: Recent Advances, Biopolymer Sources, Bioengineering Applications and Sustainability Challenges

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Abstract

The increasing accumulation of petroleum-derived plastic waste has intensified the search for renewable and biodegradable alternatives. Algae have emerged as a promising feedstock for bioplastic development because of their rapid growth, diverse biochemical composition, ability to utilize non-arable environments, and potential integration with wastewater treatment and carbon capture systems. Algal biomass contains polysaccharides, proteins, lipids and other metabolites that can be converted into films, composites and polymeric materials through direct processing, extraction or fermentation-based approaches. Recent research has particularly emphasized polyhydroxyalkanoates, alginate, carrageenan, agar and other algal polysaccharides, as well as whole-biomass composites. This review examines the major classes of algal biomass used for bioplastic production, mechanisms of biopolymer recovery, processing strategies, material properties, bioengineering applications and environmental implications. The potential of algae-based materials in food packaging, agriculture, biomedical engineering and other sectors is discussed. Particular attention is given to major limitations, including biomass harvesting, extraction cost, process energy demand, variability in polymer yield, mechanical performance, scalability, life-cycle impacts and end-of-life management. Recent developments involving metabolic engineering, two-stage cultivation, biofilm cultivation, biorefinery integration, artificial intelligence and process monitoring may improve production efficiency. Overall, algae-based bioplastics represent a promising component of sustainable material systems, although further techno-economic and life-cycle validation is necessary before widespread commercial adoption.

Keywords: Algae; Bioplastics; Biopolymers; Microalgae; Sustainable materials; Circular economy

INTRODUCTION

Plastic materials have become indispensable in food packaging, agriculture, healthcare, transportation and consumer products because of their low cost, durability, light weight and versatility. However, the persistence of conventional petroleum-derived plastics and the accumulation of plastic waste have generated substantial environmental concerns. Consequently, increasing attention has been directed towards bio-based and biodegradable materials obtained from renewable biological resources.

Bioplastics encompass a heterogeneous group of materials and should not automatically be considered synonymous with biodegradable plastics. A bio-based polymer may be chemically

similar to a conventional polymer, while biodegradability depends on polymer chemistry and environmental conditions. Thus, both the origin of the material and its end-of-life behaviour must be considered when assessing its sustainability.

Conventional bioplastic feedstocks include starch-rich crops such as corn, wheat and potato and sugar-containing crops. However, dependence on agricultural crops can generate competition for arable land and potentially raise food-security concerns. Algae provide an alternative biomass platform because they can contain substantial quantities of carbohydrates, proteins, lipids and structural polysaccharides. They may also be cultivated in environments unsuitable for conventional agriculture, although the sustainability of cultivation depends strongly on water, nutrient and energy inputs (Cheah et al., 2023; Sudhakar et al., 2024).

Both microalgae and macroalgae have been investigated for bioplastic applications. Microalgal systems have received particular attention for production of intracellular and extracellular biopolymers and as feedstocks for fermentation. Macroalgae, particularly seaweeds, are important sources of hydrocolloids such as alginate, carrageenan and agar, which can be processed into films and composite materials. Recent reviews indicate increasing research activity in algal-based bioplastics, including PHA production, whole-biomass composites, seaweed-derived polymers and industrial applications (Cheah et al., 2023; Mogany et al., 2024).

The objective of the present review is therefore to critically examine algae-based bioplastics with emphasis on algal feedstocks, major polymeric components, production pathways, applications, sustainability considerations, technological challenges and future research opportunities.

MATERIALS AND METHODS

The available evidence was critically synthesized across key thematic dimensions, including feedstock characteristics, polymer composition, processing routes, potential applications, environmental implications, and technological limitations. The review adopts a narrative approach and is intended to provide a critical overview of the current state of knowledge rather than a systematic review or meta-analysis.

RESULTS AND DISCUSSION

1. Algae as a feedstock for bioplastic production

Algae comprise a diverse group of photosynthetic organisms broadly represented by microalgae, cyanobacteria and macroalgae. Their biochemical composition varies considerably according to species, cultivation conditions, growth phase, nutrient availability, light intensity, carbon supply and environmental stress.

The principal components relevant to bioplastic production include carbohydrates, proteins, lipids and structurally important polysaccharides. Consequently, algae can serve as either a source of extracted polymeric components or as whole biomass for composite material development.

Microalgae such as *Chlorella*, *Scenedesmus* and *Chlamydomonas* have attracted attention because of their rapid growth and biochemical versatility. Cyanobacteria are also important because certain strains can accumulate polyhydroxyalkanoates (PHAs), while algal-derived carbohydrates can serve as substrates for microbial fermentation to produce polymer precursors.

Macroalgae provide another important resource. Brown, red and green seaweeds contain polysaccharides such as alginate, carrageenan, agar and ulvan. These compounds possess film-forming and gel-forming characteristics and therefore have considerable potential in biodegradable packaging and coating applications (Sudhakar et al., 2024; Lomartire et al., 2023).

2. Major biopolymer sources from algae

2.1 Polysaccharides

Polysaccharides are among the most important structural components used in algae-based bioplastic development. Alginate obtained mainly from brown seaweeds can form hydrogels and films after ionic cross-linking. Carrageenan and agar, predominantly associated with red seaweeds, also exhibit strong film-forming properties.

Polysaccharide-based materials are attractive because they can be processed under relatively mild conditions. However, their hydrophilic nature may result in high water sensitivity and inferior moisture-barrier properties compared with conventional petroleum-derived packaging materials. Consequently, blending with hydrophobic components, cross-linking and incorporation of reinforcing materials are frequently explored to improve performance.

2.2 Polyhydroxyalkanoates

Polyhydroxyalkanoates are biodegradable polyesters that can accumulate intracellularly in certain microorganisms, including selected photosynthetic microorganisms. PHAs and related polymers have attracted considerable attention because of their biodegradability and thermoplastic characteristics.

Algal and cyanobacterial systems can contribute to PHA production either directly through intracellular accumulation or indirectly by providing carbon substrates for microbial production. Recent literature identifies PHA and PHA copolymers as major areas of research within algal bioplastics (Mogany et al., 2024).

2.3 Protein-based materials

Microalgal biomass can contain considerable amounts of protein. Proteins contain functional groups capable of forming intermolecular interactions and networks, making them potentially useful for biodegradable film formation.

However, protein-based materials may exhibit limitations in water resistance and mechanical stability. Modification through blending, cross-linking or incorporation of nanomaterials may improve functional characteristics. Further research is required to determine how species-specific protein composition influences final material performance.

2.4 Lipid-associated components

Algal lipids are primarily studied for biofuel and oleochemical applications, but they can also contribute to polymer and composite development. Lipid-derived components may improve hydrophobicity when appropriately incorporated into polysaccharide- or protein-based matrices.

The direct conversion of algal lipids into bioplastics should, however, be distinguished from the production of biodegradable polymers through fermentation. A clear understanding of these pathways is necessary when describing algae-derived plastic materials.

3. Production pathways for algae-based bioplastics

The production pathway depends on the selected algal species, target polymer and desired material characteristics.

3.1 Cultivation

Algal cultivation represents the first major stage in the production chain. Light intensity, temperature, pH, carbon dioxide availability, nitrogen and phosphorus supply strongly affect biomass productivity and biochemical composition.

Nutrient limitation can alter the intracellular accumulation of carbohydrates, lipids or other metabolites. Two-stage cultivation strategies have therefore been investigated in which biomass is initially produced under favourable conditions followed by controlled stress to increase accumulation of the desired metabolite.

However, increased metabolite productivity does not necessarily translate into economic feasibility because stress conditions may decrease total biomass productivity. Therefore, optimization should consider both biomass yield and target-product concentration.

3.2 Harvesting and biomass concentration

Algal biomass is generally dilute in cultivation systems, making harvesting an important cost and energy component. Centrifugation, filtration, sedimentation and flocculation can be used depending on the organism and production system.

The harvesting method influences downstream processing because residual salts, culture medium components and extracellular material can affect polymer recovery and final product quality.

3.3 Drying and pretreatment

After harvesting, biomass may be dried or processed as wet biomass. Drying can improve storage stability but may increase energy demand. Pretreatment can facilitate cell disruption and improve access to intracellular components.

Mechanical, chemical, thermal and enzymatic pretreatment methods have all been investigated. The optimal strategy depends on whether the objective is recovery of a specific polymer, fermentation substrate or whole biomass.

3.4 Extraction and recovery of biopolymers

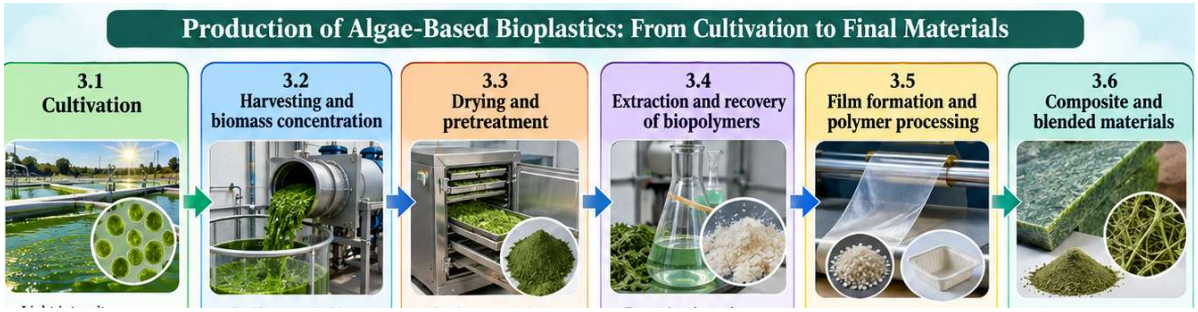
The extraction step depends on the target component. Seaweed polysaccharides such as alginate, agar and carrageenan can be recovered using established extraction processes, whereas intracellular components from microalgae may require cell disruption followed by solvent, aqueous or enzymatic extraction.

The challenge is to achieve high recovery while minimizing solvent consumption, energy demand, degradation of the polymer and generation of waste streams. Consequently, integrated biorefinery approaches are increasingly important.

3.5 Film formation and polymer processing

Recovered polymers can be converted into films, coatings, pellets or molded materials. Casting, extrusion, compression molding and related techniques can be used according to the material composition.

Plasticizers such as glycerol and sorbitol are commonly used in polysaccharide- and protein-based films to improve flexibility. However, increasing plasticizer concentration may reduce tensile strength and increase moisture sensitivity. Therefore, optimization of polymer–plasticizer ratios is necessary.



3.6 Composite and blended materials

One promising approach is the development of algal composite materials rather than relying exclusively on purified polymers. Whole algal biomass can be incorporated into polymer matrices as a filler or reinforcement.

This strategy may reduce purification requirements and improve resource efficiency. Recent literature emphasizes the potential economic advantages of direct use of algal biomass and integrated processing strategies (Sudhakar et al., 2024).

4. Material properties of algae-based bioplastics

The practical value of an algal bioplastic depends on its mechanical, thermal, barrier and biodegradation characteristics.

Important mechanical parameters include tensile strength, elongation at break and Young's modulus. Packaging materials require sufficient strength and flexibility to withstand handling, transportation and storage.

Water vapour permeability and oxygen permeability are particularly important for food packaging. Many polysaccharide-based materials are hydrophilic and therefore exhibit moisture sensitivity. Cross-linking, blending with hydrophobic polymers and incorporation of reinforcing materials may improve barrier properties.

Thermal stability is also important for processing. Materials intended for extrusion or molding must tolerate the temperatures used during manufacturing without significant degradation.

Bioplastics derived from renewable waste biomass can exhibit diverse functional properties depending on feedstock composition and processing conditions. Agricultural and food wastes containing starch, cellulose and other biopolymer-forming components have been investigated as potential raw materials for biodegradable plastic production (Biswas et al., 2024).

Biodegradation should be evaluated under defined environmental conditions. A material that biodegrades under industrial composting conditions may behave differently in soil, freshwater, marine environments or landfill conditions. Therefore, claims of biodegradability should always specify the environmental conditions and testing methodology.

5. Applications of algae-based bioplastics

5.1 Food packaging

Food packaging is one of the most frequently proposed applications. Algal polysaccharides can be used to prepare films and coatings with potential applications for short-shelf-life foods.

Active packaging systems may also incorporate antioxidant or antimicrobial compounds. However, regulatory approval, migration behaviour, sensory effects and food-contact safety must be evaluated before commercial application.

5.2 Agricultural applications

Algae-based films may be investigated for mulching, seed coatings and controlled-release systems. Their potential biodegradability can reduce the need for retrieval of conventional plastic agricultural films.

Nevertheless, agricultural applications require careful assessment of degradation rate, soil interactions and effects on plants and soil microorganisms.

5.3 Biomedical and bioengineering applications

Biocompatible algal polysaccharides have attracted attention for biomedical applications. Hydrogels and polymeric matrices derived from algal components can potentially serve as scaffolding materials, wound-care materials or controlled-release systems.

For biomedical use, however, biocompatibility alone is insufficient. Sterility, mechanical strength, degradation kinetics, immunological response, purity and reproducibility must be established before clinical translation.

5.4 Drug delivery

Algal polysaccharides can form hydrogels and other structured matrices that may facilitate controlled delivery of bioactive compounds. Their physicochemical characteristics can be modified through cross-linking and blending.

Further research should establish loading efficiency, release kinetics, stability and biological compatibility.

5.5 Three-dimensional printing

Emerging research is investigating algae-derived materials and algal composites for additive manufacturing. Their potential lies in the development of customized structures with reduced dependence on petroleum-derived materials.

However, printable materials require specific rheological behaviour, dimensional stability and post-processing characteristics. Therefore, formulation optimization remains an important research area.

5.6 Wastewater-integrated materials production

An important advantage of algae is their capacity to grow using nutrient-containing wastewater under suitable conditions. Integrating biomass production with wastewater treatment may improve resource efficiency.

Nevertheless, biomass grown on wastewater intended for material applications must be carefully characterized for heavy metals, pathogens, persistent contaminants and other undesirable substances before downstream utilization.

6. Environmental and sustainability considerations

Algae-based bioplastics are often described as sustainable because algae can fix carbon dioxide during photosynthesis and may be cultivated without direct competition with conventional food crops. Algae may also be cultivated using saline water or wastewater under suitable conditions.

However, sustainability cannot be inferred solely from the biological origin of the material. Cultivation, harvesting, drying, extraction, transportation, processing and disposal all contribute to the environmental footprint.

For example, energy-intensive harvesting and drying may offset some environmental advantages associated with algal cultivation. Similarly, chemical extraction may generate secondary waste streams.

Therefore, life-cycle assessment (LCA) should be used to compare algal materials with conventional plastics and other bioplastics under equivalent functional conditions. Recent reviews emphasize the importance of integrating cultivation, processing, energy use and end-of-life pathways when evaluating environmental performance (Mogany et al., 2024; Sudhakar et al., 2024).

6.1 Carbon management

Algal photosynthesis can capture carbon dioxide during biomass growth. However, carbon fixation should not automatically be interpreted as net carbon removal. The overall carbon balance depends on energy consumption, carbon sources, cultivation infrastructure, processing and product lifetime.

Consequently, future studies should report complete carbon balances rather than relying only on the carbon fixation capacity of algae.

6.2 Land and water use

Algae can potentially be cultivated on non-arable land and using saline or wastewater resources. This provides an opportunity to reduce competition with food crops.

Nevertheless, water consumption, nutrient requirements and the energy used to circulate and process cultivation media must be incorporated into sustainability assessments.

6.3 End-of-life management

Biodegradation is an important potential advantage of algae-derived materials, but degradation behaviour varies according to polymer composition and environmental conditions. Compostability, anaerobic digestion, recycling and controlled degradation should therefore be evaluated individually.

A biodegradable material is not automatically harmless in every environmental compartment. Standardized testing under relevant conditions is essential.

7. Major challenges

7.1 Biomass productivity

Low biomass concentration in some algal cultivation systems can increase harvesting costs. Improving biomass productivity while maintaining desirable biochemical composition is therefore essential.

7.2 Polymer yield and variability

The biochemical composition of algae varies with species, cultivation conditions and environmental stress. This variability can produce differences in polymer yield and final material characteristics.

Standardization of cultivation and downstream processing is therefore required for reproducible commercial products.

7.3 Extraction costs

Purification of individual biopolymers may require multiple processing steps. Chemical reagents, enzymes, solvents and energy contribute to production costs.

Whole-biomass processing and integrated biorefinery approaches may help reduce these costs by generating multiple value-added products from the same biomass stream.

7.4 Mechanical and barrier performance

Many algal polysaccharide materials exhibit limitations in moisture resistance and mechanical strength. Improving these properties without compromising biodegradability remains a major formulation challenge.

7.5 Scale-up

Most laboratory studies operate at relatively small scale. Conditions optimized in laboratory photobioreactors or flask cultures may not translate directly to industrial cultivation.

Scale-up introduces problems related to light penetration, temperature control, mixing, gas transfer, contamination and harvesting.

7.6 Economic feasibility

Commercial competitiveness depends on the complete value chain rather than biomass productivity alone. Cultivation, harvesting, extraction, processing, transportation and waste management must be considered.

Recent technology reviews indicate increasing commercial and patent activity in the algal-bioplastic sector, but economic and technical barriers remain important obstacles to widespread adoption (Mogany et al., 2024).

7.7 Regulatory and market considerations

Materials intended for food-contact or biomedical applications must satisfy appropriate safety and regulatory requirements. Consistent material quality and standardized testing are also necessary to establish consumer and industrial confidence.

8. Emerging technologies and future perspectives

8.1 Metabolic and genetic engineering

Metabolic engineering can potentially redirect cellular metabolism towards enhanced production of target polymers or their precursors. Advances in genome sequencing and genetic tools may enable strain improvement.

However, genetically modified algae also raise regulatory, ecological and containment considerations. Therefore, technological development must proceed alongside appropriate biosafety evaluation.

8.2 Two-stage cultivation

Two-stage cultivation offers a strategy for separating biomass production from metabolite accumulation. Algae may first be cultivated under conditions favouring rapid growth and subsequently subjected to controlled nutrient or environmental stress.

This approach may increase target metabolite concentrations, although optimization at industrial scale remains necessary.

8.3 Biofilm-based cultivation

Biofilm cultivation has attracted attention because it can facilitate biomass harvesting and potentially reduce energy requirements compared with conventional suspended cultures. Recent research has considered microalgal biofilms as a route towards more environmentally sustainable bioplastic production (Mogany et al., 2024).

8.4 Integrated algal biorefineries

A biorefinery approach may improve economic feasibility by generating several products from the same algal biomass. For example, proteins, pigments, lipids, carbohydrates and polymeric materials may be sequentially recovered.

This approach can reduce waste and distribute production costs among multiple products.

8.5 Artificial intelligence and process optimization

Artificial intelligence and machine-learning approaches are increasingly being explored for optimizing algal cultivation and bioplastic development. Sensors and Internet-of-Things systems can monitor parameters such as temperature, pH, light intensity, nutrient concentrations and biomass density.

Machine-learning models can potentially identify relationships between cultivation conditions and biomass composition, thereby assisting process control and formulation optimization (Bin Abu Sofian et al., 2024).

8.6 Circular economy integration

The greatest potential of algae-based bioplastics may lie in integration with other environmental and industrial processes. Algal cultivation could potentially be linked with wastewater treatment, carbon utilization, biofuel production and recovery of high-value compounds.

Such integrated systems could shift algae from a single-product feedstock towards a multiproduct resource platform.

CONCLUSION

Algae-based bioplastics represent an emerging class of bio-based materials with potential applications in packaging, agriculture, biomedical engineering and other sustainable-material sectors. The biochemical diversity of algae provides several routes for material development, including direct use of whole biomass, extraction of polysaccharides and proteins, production of PHAs and fermentation of algal-derived substrates.

The major advantages of algae include rapid biomass production, biochemical versatility and the possibility of cultivation in environments that are unsuitable for conventional agriculture. Nevertheless, the sustainability of algal bioplastics depends on the complete production and

end-of-life chain. Harvesting, drying, extraction, energy demand, polymer variability, mechanical performance, scale-up and economic feasibility remain important challenges.

Future research should therefore move beyond laboratory demonstrations towards integrated biorefinery systems, standardized material characterization, life-cycle assessment, techno-economic evaluation and application-specific safety testing. Integration of metabolic engineering, biofilm cultivation, process automation, artificial intelligence and circular-resource systems may further improve the feasibility of algal bioplastics.

Overall, algae should be regarded not simply as a replacement feedstock for petroleum-derived plastics but as a potentially multifunctional biological platform for sustainable material production. Successful commercialization will depend on balancing environmental performance, material functionality, economic viability and responsible end-of-life management.

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CHAPTER-VI

Comprehensive Review on Chrononutrition Besides Calories and Composition: Eating Against the Clock

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ABSTRACT:

The study of the relationship between meal time, the circadian rhythm, and metabolic health is known as chrononutrition. Although calorie intake and nutrient content have been the main emphasis of traditional nutritional methods, there is mounting evidence that the timing of meal consumption is crucial for metabolic control. The impact of mealtime, frequency, and breakdown on glucose metabolism, tolerance to insulin, lipid profile, and energy balance is highlighted in this review, which summarises recent studies concerning chrononutrition and its consequences for metabolic health. An increased risk of overweight, Type 2 diabetes, metabolic disorder, and cardiovascular diseases has been linked to circadian rhythm disruption caused by inconsistent dietary habits, late-night meals, shift employment, and extended eating windows. On the other hand, by coordinating the consumption of nutrients with endogenous biological clocks, time-aligned eating habits including early meal times and time-restricted feeding seem to promote metabolic efficiency. The fundamental mechanisms include energy expenditure, gut microbiome cycles, metabolism-related gene expression, and circadian regulation of hormone secretion. A new paradigm for nutritional strategies that go beyond macronutrient composition and calorie counting is provided by an understanding of chrononutrition. It may be possible to improve metabolic health and prevent lifestyle-related metabolic problems by including meal time methods into nutritional guidelines.

Keywords: Metabolic syndrome, Obesity, Insulin sensitivity, Circadian rhythm, Time- restricted eating, and Metabolic health

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INTRODUCTION:

Chrononutrition is an emerging field within nutritional science that examines how the timing, frequency, and regularity of food intake influence human health beyond calorie quantity and nutrient composition (Codoñer-Franch et al., 2023). Human physiological processes are regulated by an intrinsic circadian rhythm, an approximately 24-hour cycle that synchronizes behavior, metabolism, and hormone secretion with the light–dark cycle (Ahluwalia, 2022). The suprachiasmatic nucleus (SCN) of the hypothalamus acts as the central biological clock, coordinating peripheral clocks across tissues through neural and hormonal signaling to maintain rhythmic gene expression (Chaix et al., 2019). The timing of food intake relative to circadian rhythms plays a crucial role in maintaining cardiometabolic health (CMH) and may significantly contribute to the prevention of cardiovascular diseases (CVD) (Katsi et al., 2022). Based on circadian preference, individuals are categorized into morning (early) and evening (late) chronotypes, with evening chronotypes showing greater susceptibility to unhealthy eating behaviors, night-time eating, and metabolic disturbances (Ahluwalia, 2022). In contrast, morning chronotypes tend to demonstrate better metabolic profiles and mental health outcomes, highlighting the role of circadian alignment in disease prevention (Codoñer-Franch et al., 2023).

Recent evidence suggests that macronutrients, micronutrients, and bioactive food compounds can directly or indirectly modulate both central and peripheral circadian clocks, thereby influencing metabolic regulation (Chaix et al., 2019). During daytime hours, genes associated with glycogenesis and lipogenesis are predominantly active, whereas nighttime promotes growth, cellular repair, glycogenolysis, and lipolysis, indicating time-dependent metabolic efficiency (Tippairote et al., 2021).Disruption of meal timing relative to circadian rhythms has been implicated in the rising prevalence of obesity, type 2 diabetes, atherosclerosis, and non-alcoholic fatty liver disease, posing a significant global public health burden (Kamarul Zaman et al., 2023; Mishra et al., 2023; Lange et al., 2023).

Among chrononutrition-based interventions, time-restricted eating (TRE) has gained considerable attention as a strategy that confines food intake to a specific daily window while maintaining prolonged fasting periods (Kirkham et al., 2022). TRE, a subtype of intermittent fasting, typically involves eating windows ranging from 4 to 12 hours without intentional caloric restriction and has demonstrated potential benefits in metabolic health (Sun et al., 2023). Unlike traditional calorie restriction, TRE aligns food consumption with the active phase of the circadian cycle, thereby optimizing metabolic efficiency and improving cardiometabolic outcomes (Ahluwalia, 2022; Tippairote et al., 2021).

From a public health perspective, targeted health education and promotion strategies focusing on meal timing can guide individuals toward establishing consistent eating routines aligned with circadian rhythms, potentially delaying or mitigating metabolic risk factors associated with cardiometabolic and cardiovascular diseases (Katsi et al., 2022). Overall, growing epidemiological and clinical evidence

supports chrononutrition-based interventions such as TRE as promising, non-pharmacological strategies for the prevention and management of cardiometabolic disorders by restoring metabolic rhythmicity (Naous et al., 2023).

CIRCADIAN MISALIGNMENT: MECHANISTIC INSIGHTS:

The circadian system consists of a network of interconnected central and peripheral clocks, with the suprachiasmatic nucleus (SCN) of the hypothalamus acting as the master pacemaker that coordinates daily rhythms of sleep–wake cycles, feeding–fasting behaviors, energy metabolism, body temperature, and endocrine functions (Mohawk et al., 2012). Peripheral clocks located in metabolically active tissues such as the liver, pancreas, heart, and gut respond to both central clock signals and external cues, particularly nutrient availability and feeding timing (Gutierrez Lopez et al., 2021). Under physiological conditions, circadian rhythms regulate metabolic processes in a time-dependent manner, resulting in predictable daily fluctuations in glucose tolerance, hormone secretion, sleep depth, and body temperature (Asher & Sassone-Corsi, 2015). Specifically, glucose tolerance is higher during daylight hours, melatonin secretion increases during the evening and night, cortisol peaks in the early morning, and body temperature rises during the early hours of the night, reflecting tightly regulated circadian control (Asher & Sassone-Corsi, 2015).

At the molecular level, circadian rhythms are generated by a transcriptional–translational feedback loop involving core clock genes, including *CLOCK*, *BMAL1*, *PER1*, *PER2*, *CRY1*, and *CRY2*, whose protein products regulate rhythmic gene expression across tissues (Mohawk et al., 2012). These clock genes function through heterodimerization and nuclear translocation mechanisms that activate or repress downstream metabolic genes, thereby synchronizing cellular metabolism with environmental light– dark cycles (Piggins, 2002; Steele et al., 2021).

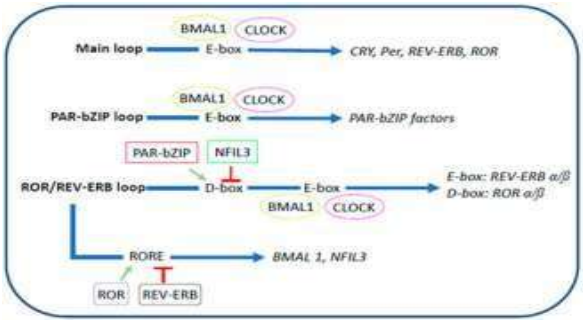


Figure 1. Molecular transcription cascade of clock genes. CLOCK: Circadian locomotor output cycles kaput, BMAL1: brain and muscle aryl hydrocarbon nuclear receptor translocator like 1, Per: period,

CRY: cryptochrome, ROR: retinoic acid related orphan receptor, PAR-bZIP: proline and acidic amino acid-rich basic leucine zipper protein, NILF3: nuclear factor interleukin 3 regulated, DBP: D-box

binding protein, TEF: thyrotroph embryonic factor, HLF: hepatic leukemia factor. Adapted from Schurhoff and Toborek, 2023 (Schurhof et al.,2023)

Circadian misalignment occurs when behavioral cycles such as meal timing, sleep, and physical activity are desynchronized from endogenous circadian rhythms, leading to impaired communication between central and peripheral clocks (Boivin et al., 2016). Chronic circadian disruption induces maladaptive shifts in hormonal signaling, glucose metabolism, lipid handling, and inflammatory pathways, which collectively increase susceptibility to metabolic and cardiometabolic disorders (Gutierrez Lopez et al., 2021).

Individual variability in circadian organization gives rise to distinct chronotypes, reflecting differences in preferred timing of daily activities and food intake across the 24-hour cycle (Nitta et al., 2023). Even though the circadian system exhibits a degree of flexibility to short-term environmental changes, persistent circadian misalignment can trigger long-lasting dysregulation of metabolic homeostasis through altered gene expression and neuroendocrine signalling (Boivin et al., 2016; Pácha & Sumová, 2013). Emerging evidence highlights that misaligned eating patterns, particularly late-night food consumption, interfere with circadian-controlled metabolic pathways, reinforcing the mechanistic link between circadian disruption and cardiometabolic disease risk (Asher & Sassone-Corsi, 2015; Mohawk et al., 2012).

CHRONONUTRITION IN SHIFT WORK AND SOCIAL JET LAG:

Shift work, characterized by irregular and nonstandard working hours, poses a substantial challenge to the maintenance of consistent eating patterns and circadian alignment, thereby increasing vulnerability to metabolic and cardiometabolic disorders (Geliebter et al., 2000; Bonham et al., 2016). In shift workers, eating behaviours are influenced not only by food composition but also by when, where, and why food is consumed, with workplace constraints, fatigue, and limited food availability shaping meal timing decisions (Gupta et al., 2019). Night and rotating shift schedules frequently lead to irregular meal timing, increased snacking during nighttime hours, and reduced regularity of main meals, even in the absence of increased total energy intake (Lowden et al., 2010; Souza et al., 2019). Evidence from observational and meta-analytic studies indicates that shift workers tend to follow a traditional three- meal pattern with reduced regularity, particularly during night shifts, reflecting a misalignment between biological rhythms and eating behaviour (Lowden et al., 2010). Breakfast skipping is especially prevalent among night and rotating shift workers, as individuals often prioritize sleep after completing overnight duties or consume meals outside conventional morning hours, disrupting circadian–metabolic coordination (Kim et al., 2013). Such irregular eating patterns contribute to social jet lag, a condition defined by the mismatch between biological circadian rhythms and socially imposed schedules, which

has been associated with adverse metabolic outcomes, including obesity, insulin resistance, and cardiovascular risk (Loef et al., 2019; Williams et al., 2021). Chronotype further modulates the metabolic impact of shift work, with evening chronotypes showing poorer dietary quality, delayed eating times, and increased cardiometabolic vulnerability compared with morning chronotypes (Muscogiuri et al., 2020). Beyond individual behaviour, occupational factors such as missed meal breaks, high workload demands, and caregiving responsibilities frequently prevent shift workers from utilizing designated eating periods, leading to meal skipping and prolonged fasting during biologically inappropriate times (Monaghan et al., 2018). Physiologically, hunger and appetite follow endogenous circadian rhythms that decline during the biological night, and eating during this phase occurs when metabolic efficiency is reduced and hormonal signalling Favors glucose intolerance and lipid dysregulation (Scheer et al., 2009; Akerstedt, 2003).

Collectively, these findings highlight shift work and social jet lag as critical real-world models of circadian disruption, underscoring the importance of chrononutrition-based strategies—such as structured meal timing and time-restricted eating—to mitigate cardiometabolic risk in occupational settings (Bonham et al., 2016; Gupta et al., 2019)

MEAL TIMING AND METABOLIC OUTCOMES:

Meal timing has emerged as a critical determinant of metabolic health, independent of total caloric intake and diet composition, by influencing circadian-regulated metabolic pathways (Chaix et al., 2019). Evidence from epidemiological and interventional studies indicates that early eating patterns, in which a greater proportion of daily energy intake occurs earlier in the day, are associated with improved glucose regulation, lipid metabolism, and body weight control compared with late eating patterns (Liu et al., 2023). Early time-restricted eating (eTRE), characterized by food consumption during the early active phase of the circadian cycle, has demonstrated beneficial effects on insulin sensitivity, blood pressure, lipid profiles, and weight regulation in human studies (Jamshed et al., 2022; Liu et al., 2023). A randomized controlled trial in young adult women showed that confining food intake to an early window (8:00 AM–2:00 PM) resulted in significant weight loss while preserving lean muscle mass, outperforming delayed eating schedules and conventional eating windows (Yu & Ueda, 2025). Similarly, among adults with obesity, eTRE combined with energy restriction was more effective than energy restriction alone in improving weight loss, diastolic blood pressure, and mood, highlighting the metabolic advantage of aligning eating time with circadian rhythms (Jamshed et al., 2022).

Breakfast consumption has been widely recognized as a pivotal component of healthy meal timing, with consistent breakfast intake being associated with improved nutrient profiles, lower added sugar consumption, and enhanced metabolic regulation throughout the day (Gibney et al., 2018; Kurtgil &

Pekcan, 2023). Conversely, breakfast skipping has been linked to increased risks of obesity, type 2 diabetes mellitus, cardiovascular disease, and all-cause mortality, suggesting that omission of the first daily meal disrupts circadian-metabolic coordination (Ofori-Asenso et al., 2019; Xia et al., 2024). Long- term cohort evidence indicates that habitual breakfast skipping is associated with a significantly higher risk of cardiovascular disease incidence and mortality, although heterogeneity in study definitions warrants further standardized investigation (Ofori-Asenso et al., 2019).

In contrast to early eating, late-night food consumption has been identified as a maladaptive behaviour that impairs glucose tolerance and lipid metabolism due to eating during the biological night, when melatonin levels are elevated and metabolic efficiency is reduced (Meléndez-Fernández et al., 2023). Late-night eating promotes desynchronization between central and peripheral clocks, leading to inappropriate activation of nutrient-sensing pathways such as AMPK and mTOR during periods optimized for fasting, cellular repair, and autophagy (Ni et al., 2019; Chaix et al., 2019).

This circadian misalignment induced by mistimed meals contributes to abnormal metabolic regulation and elevates cardiometabolic risk, including the development of obesity, insulin resistance, type 2 diabetes, and cardiovascular disease (Mason et al., 2020; Chellappa et al., 2019). Metabolic hormones that communicate meal timing signals to circadian clocks—such as insulin, cortisol, ghrelin, leptin, adiponectin, GLP-1, and IGF-1—exhibit circadian rhythmicity, with peak levels occurring at specific times of day to optimize nutrient metabolism (Charlot et al., 2021).

Notably, hormonal responses involved in appetite regulation and insulin sensitivity appear more efficient earlier in the day, reinforcing the metabolic benefits of early meal timing over late or irregular eating schedules (Charlot et al., 2021). Overall, these findings underscore that when food is consumed plays a decisive role in shaping metabolic outcomes, supporting chrono nutrition-based strategies such as early time-restricted eating and regular breakfast consumption for cardiometabolic disease prevention.

GUT MICROBIOTA AND CHRONONUTRITION INTERACTIONS:

The gut microbiota (GM) represents a complex and dynamic ecosystem of microorganisms residing in the human gastrointestinal tract and is increasingly recognized as an auxiliary metabolic organ that plays a pivotal role in host energy balance and metabolic regulation (Sonnenburg & Sonnenburg, 2019; Bishehsari & Keshavarzian, 2019). Through direct interactions with the host, the GM contributes to the maintenance of intestinal barrier integrity, digestion and absorption of nutrients, regulation of inflammatory responses, and modulation of metabolic and hormonal signalling pathways (Shen et al., 2013). Dietary patterns, including food quality, food processing, cooking methods, and the intake of prebiotics and probiotics, are major determinants of GM composition and function, thereby influencing immune and metabolic responses in the host (Vitacolonna et al., 2022; Nova et al., 2022). In particular,

high-fat diets have been shown to induce gut microbial dysbiosis, characterized by reduced microbial diversity and alterations in the Firmicutes-to-Bacteroidetes ratio, which are associated with systemic inflammation and obesity-related metabolic dysfunction (Verdam et al., 2013; Turnbaugh et al., 2009). Emerging evidence indicates that the GM itself exhibits diurnal oscillations, with rhythmic fluctuations in microbial composition and metabolic activity that are synchronized with host circadian rhythms (Zarrinpar et al., 2014; Thaiss et al., 2014). Disruption of host circadian rhythms through irregular sleep patterns, mistimed eating, or altered feeding–fasting cycles can significantly disturb the diurnal dynamics of the GM, leading to microbial dysbiosis and impaired host metabolic homeostasis (Bishehsari et al., 2020).

Conversely, the gut microbiota can actively influence host circadian regulation by modulating clock gene expression and metabolic pathways, highlighting a bidirectional relationship between circadian rhythms and microbial function (Thaiss et al., 2016; Gutierrez Lopez et al., 2021). Chrononutrition behaviors, including meal timing and time-restricted eating, have been shown to reshape GM rhythmicity, thereby synchronizing microbial metabolic outputs with host feeding–fasting cycles and improving metabolic efficiency (Zarrinpar et al., 2014; Chaix et al., 2019). Nutrients and food-derived bioactive compounds play a critical role in this interaction, as plant-based fibers and polyphenols can be metabolized by the GM into short-chain fatty acids (SCFAs), vitamins, and bioamines, which exert beneficial effects on circadian alignment and metabolic health (Parkar et al., 2019; Tuohy et al., 2012). These microbiota-derived metabolites may help resynchronize disrupted circadian rhythms by influencing peripheral clocks and metabolic signalling pathways, thereby mitigating metabolic alterations associated with modern lifestyle behaviors (Parkar et al., 2019; Erdmann et al., 2008).

Overall, the interaction between chrononutrition and the gut microbiota represents a key mechanistic link through which meal timing and dietary composition jointly regulate circadian and metabolic homeostasis, offering promising avenues for precision nutrition strategies aimed at preventing and managing metabolic disorders (Bishehsari et al., 2020; Gutierrez Lopez et al., 2021).

CONCLUSION:

Current evidence indicates that chrononutrition plays a crucial role in cardiometabolic health beyond calorie intake and dietary composition, emphasizing the importance of aligning meal timing with endogenous circadian rhythms. Disruption of this alignment through irregular eating patterns, late-night food consumption, shift work, and social jet lag contributes to circadian misalignment, leading to impaired glucose and lipid metabolism and increased cardiometabolic risk.Interventions such as early meal timing, regular eating patterns, and time-restricted eating have shown promising effects in improving metabolic outcomes by reinforcing circadian synchronization. Additionally, the interaction between chrononutrition and the gut microbiota highlights a key mechanistic pathway through which meal timing influences metabolic homeostasis.

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CHAPTER-VII

Early Onset of Bone Degeneration in Youth: The Interplay of Nutrition, Genetic Predisposition, and Lifestyle Factors

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Abstract

Bone degeneration has long been considered a health concern primarily associated with ageing; however, accumulating evidence indicates a disturbing rise in compromised bone health among adolescents and young adults. Early-onset bone degeneration is particularly significant because it interferes with the attainment of peak bone mass, a critical determinant of lifelong skeletal strength and fracture resistance. This review critically synthesizes current scientific literature to examine the multifactorial determinants of bone degeneration in youth, with a specific focus on nutritional inadequacies, genetic predisposition, hormonal regulation, and lifestyle-related factors. Inadequate intake of calcium, vitamin D, protein, and essential micronutrients during growth years has been consistently linked to reduced bone mineral density. Genetic susceptibility, mediated through variations in key bone-related genes, further modulates individual vulnerability, especially when combined with adverse environmental influences. Hormonal disturbances arising from delayed puberty, reproductive disorders, or endocrine dysfunctions significantly disrupt bone remodelling processes. Additionally, sedentary behaviour, poor dietary habits, substance use, chronic stress, and insufficient sleep have emerged as critical lifestyle contributors to early skeletal deterioration. The review highlights the complex interaction among these biological and behavioural factors and underscores the importance of early identification of at-risk individuals. Emphasis is placed on preventive strategies, including nutritional optimization, lifestyle modification, and targeted screening, to preserve bone health during the formative years of skeletal development. A comprehensive understanding of these interconnected determinants is essential for reducing the long-term burden of osteoporosis and fracture-related morbidity.

Keywords:

Early-onset bone degeneration; youth and young adults; bone mineral density; peak bone mass; nutrition and micronutrients; genetic predisposition; hormonal regulation; lifestyle factors; skeletal health; osteoporosis prevention

1. Introduction

Bone is considered to be living tissue that changes and rebuilds itself continuously throughout the lifetime. Bone density, size, and strength increase during the childhood and adolescent period; therefore, it can be stated that the modelling of bone is predominant in this phase. The peak bone mass is approximately 90% achieved by the end of the adolescent period, and it continues to grow

in the early adulthood period (Hereford et al., 2024). Achieving optimal peak bone mass is essential, as it helps prevent degenerative diseases such as osteoporosis and fragile fractures throughout life. Earlier, bone decay and osteoporosis were associated with natural aging; however, nowadays, bone-related issues such as low bone mineral density and low bone quality are seen in children, adolescents, and young adults. Bone degeneration in youth is concerning, as a deficiency in the early stage is often irreversible and has the potential to increase the risk of future fracture.

Several factors, including poor dietary choices, genetic predisposition, and unhealthy lifestyle habits, contribute to bone decay in young individuals (Singh et al., 2023). A lack of physical exercise and low-nutrientdence food harms bone health in the young population. Additionally, genetic differences that affect bone metabolism may make some people more likely to have decreased bone mass, especially when the environment is not good for bone health. This review intends to examine the role of the lack of proper nutrition, genetic predisposition, and lifestyle in early bone degeneration in youth. This review critically examines the peer review journal and articles in order to highlight all the factors associated with early bone decay, identify vulnerable groups, and to evaluate the opportunity for the early prevention of the disease.

2. Bone Development and Physiology in Youth

2.1 Bone Modeling and Remodeling

The two processes that are closely related in the formation of the bones during the time period of late teenage and early adulthood. are the modelling and remodelling of bone. When bone grows, it is referred to as bone modelling (formation of new bone and remodelling of existing bone), and when both osteoclasts and osteoblasts work in a coordinated manner, this is called remodelling (Wawrzyniak & Balawender, 2022). In children and adolescents, modelling is the leading form that allows bone size and mass to increase without reabsorption through hormonal regulation, these processes are important. Osteoblast proliferation and bone formation are triggered by growth hormone and (IGF-1) insulin-like growth factor-1 (Okawa et al., 2024). Sex hormones especially oestrogen and testosterone, are necessary in pubertal accrual of bone and epiphyseal closure. Impairment of skeletal development may occur when disruption of these hormonal pathways occurs as a result of nutritional deficiency, chronic disease, or lifestyle stressors of lifestyle.

2.2 Peak Bone Mass

Peak bone mass is the ultimate or the maximum bone tissue that has been developed by the conclusion of skeletal growth (Chevalley& Rizzoli, 2022). It depends on genetic components, nutrition, physical exercise, hormonal condition, and general health. The individuals that are incapable of reaching the optimum peak bone mass are at a very high probability of having osteoporosis despite the absence of accelerated bone loss in later life.It has been found that the development of osteoporosis can be postponed by over ten years given a 10% increase in peak bone mass. On the other hand, lifelong effects of early deficit in bone accrual may manifest, thus the need to address risk factors, which can be transformed at the youth (Kralick & Zemel, 2020).

3. Nutritional Factors Influencing Early Bone Decay in Youth

3.1 Calcium and Phosphorus

Bone is mainly composed of calcium, which is required in skeletal mineralization. In times of high growth, the need of calcium is especially high. The loss of bone mineralization due to lack of dietary calcium and the subsequent increases in bone reabsorption in response to low serum calcium may take place (Proia et al., 2021). Both calcium and phosphorus plays a crucial role in strengthening bone and also liable for health and rigid skeletal health. Phosphorus is considered as the building block of hydroxyapatite that mineral that is liable to provide strength to the bones (Serna, &Bergwitz, 2020). Phosphorus deficiency is not very common; however, the ratios of calcium to phosphorus are usually imbalanced in high amounts of processed food and soft drinks, which can have negative impacts on bone health.

3.2 Vitamin D

Vitamin D is a key nutrient relative to absorption of calcium and metabolism of bones. Childhood and adolescent deficiency reduces the efficiency of using calcium, which causes inefficient mineralization of the bone. Lack of outdoor activities and decrease in dietary intake has caused wide spread vitamin D deficiency among the young population in the world (Lipset al., 2021). Lack of vitamin D has been linked to reduced bone mineral density (BMD), high risk of fractures and skeletal retardation. There is also emerging evidence that vitamin D can have an effect on muscle strength and balance indirectly which affects the risk of fractures.

3.3 Protein Intake

The bone matrix is predominantly proteinous and is a key to the functioning of the osteoblast. Proper protein consumption helps build bones and enhances the impact of calcium and vitamin D (Proia et al., 2021). Nonetheless, consuming protein at excessively high levels without a sufficient amount of calcium can lead to urinary calcium leakage, which can have adverse implications for bone development (Bargagli et al., 2021). Protein intake in most adolescents, particularly those on restrictive diets, may not be adequate to enable them to develop their skeletal systems optimally.

3.4 Micronutrient

Some of the micronutrients that promote bone health include magnesium, zinc, vitamin K and vitamin C. Magnesium aids in the formation of bone crystals, whereas zinc aids in osteoblast functions. Vitamin K is needed in carboxylating osteocalcin, which is a bone mineralizing protein (Tesfamariam, 2019). The insufficiency of these micronutrients, which is often related to the lack of diversity in the diet, can slightly harm the quality of bones and predispose them to aging deterioration.

3.5 Malnutrition and Eating Disorders

Malnutrition and eating disorders negatively impact overall immunity and this directly affects bone health and makes the bone vulnerable. Malnutrition at any stage of life can lead to osteoporosis and in some studies, states that early life exposure to inadequate nutrition eventually increases the risk for osteoporosis and fracture in adulthood and this include all socioeconomic statuses and demographics (Xu et al., 2025). .Bone health has significant effects of malnutrition in

the youth. Other disorders like anorexia nervosa are correlated with extreme loss of BMD, hormonal imbalances, and risk of fracture (Søeby et al., 2023). The result of energy deficiency is the inhibition of the release of gonadotropin, causing a decrease in oestrogen or testosterone which are vital in bone accrual. The bone deficits may be persisting even after the restoration of weight indicating the long-term skeletal effects of nutritional deprivation at the critical growth stages.

4. Genetic Predisposition to Bone Degeneration

4.1 Heritability of Bone Mineral Density

Bone mineral density is most closely associated with heredity where genetic factors have been known to explain an individual difference of 50-80 percent. Twin and family studies have always shown that genetic factors have a good impact on bone mass, bone geometry, and bone turnover (Gregson, & Duncan, 2020). It can be stated that hereditary not only impact peak bone mass but also influences bone remodelling rate hormonal influences and nutrient metabolism to a large extent. In adults low inherited bone mineral density is capable to increase the risk of developing osteoarthritis additionally, it can also increases the risk of fractures in adolescence and children.

4.2 Key Genes Involved in bone

decay And Gene–Environment Interactions.

There are a number of genes that are associated with bone metabolism. Differences in genes of vitamin D receptors affect the absorption of calcium and BMD. Type I collagen gene mutations influence the quality of bone matrix and cause inherited bone fragility diseases (Robinson & Rauch, 2019). Polymorphs in oestrogen receptor genes also affect skeletal response to hormonal changes at puberty. There is no genetic predisposition that acts alone. Genetic risk can be alleviated or aggravated by environmental factors including nutrition and physical activity. As an example, persons with genetic differences that are linked to low bone mass can gain almost normal bone mass when they are exposed to the best form of nutrition and mechanical loading in their growing form.

5. Lifestyle Factors Contributing to Early Bone Degeneration

5.1 level of Physical Activity and Sedentary

Behaviour

Weight-bearing physical exercise is a strong bone formation stimulus through mechanical loading. Running, jumping, and resistance training are also some of the activities that increase bone strength by promoting the activity of osteoblasts. Conversely, sedentary lifestyles, which grow progressively with the use of screens, decrease mechanical stimuli required in building bone accrual (Bruyère et al., 2025). There is a persistent low physical activity that results in low BMD in youths compared to their active counterparts

5.2 Consumption of alcohol and Smoking

The use of alcohol, especially in excess, interrupts the process of remodelling the bones and disrupts the metabolism of nutrients. Smoking has adverse effects on bone by disrupting the osteoblasts functions, calcium uptake as well as the hormonal balance (Tarantino, et al., 2021). The onset of such behaviours at an early age increases skeletal risk in the long term.

5.3 Sleep Patterns and Stress

Sleep is crucial for human life has this not only have maintaining healthy brain function but also has maintain a overall healthy body and capable of mitigating the risk of inflammation obesity diabetes and bone issues as well. In some studies it has been shown that sleep is extremely important for maintaining balance of core body tissue such as bone fat muscle mass. Lack of sleep is capable of decreasing bone mass known as osteopenia which further progresses to osteoporosis state is known for low bone mineral density and escalate the rate of bone reabsorption. Sleep is vital in hormonal regulation such as the secretion of growth hormone and IGF-1 that helps in bone formation (Stich et al., 2022). Cortisol levels are increased by chronic sleep deprivation and psychological stress which stimulate bone reabsorption and suppress bone formation.

5.4 Use of Medications

Some of the drugs often prescribed to the young age group like glucocorticoids and anticonvulsants have a negative impact on bone metabolism (Miziak et al.,2019). Persistent use in growth may greatly decrease the BMD and skeletal maturation. Antiepileptic drugs, especially the older enzyme-inducing ones have shown to decrease bone mineral density in younger adult by disrupting the vitamin D metabolism and that eventually impact calcium absorption that facilitates secondary hyperparathyroidism that takes out Calcium from the bone and often directly impact the bone cells which makes the bone more susceptible to fracture risk.

6. Interplay between Nutrition, Genetics, and Lifestyle

The bone health of the youth is a product of the dynamic interplay between biological and environmental factors. Genetic vulnerability may be overcome by optimum nutritional level whereas unhealthy living can increase genetic risk. As an example, a genetically predisposed person can suffer severe bone deficits when he or she is subjected to the absence of vitamin D and physical inactivity. This complexity of nature highlights the relevance of the holistic approaches to bone health that rely on cumulative exposures throughout the life span as opposed to the single risk factors. It is evident that now a day the cases of osteoporosis and other bone related diseases are increasing and it can be seen in younger adults to a large extent. Some of the studies have shown that from the age group of 30 -39 and 40- 49, the prevalence for osteoporosis in female especially at a lumber spine was 3% and 3.4% respectively. On the other hand, in case of male it was 0% and 4% respectively.

Skeletal site	Age, y						P-value
	30–39	40–49	50–59	60–69	≥70	Total[a]	
Females (n = 216)							
Lumbar spine							
Osteoporosis	3.0	3.4	14.3	18.6	36.4	11.1	<0.001*
Osteopenia	21.2	22.4	36.5	48.8	27.3	31.9	
Left femur neck							
Osteoporosis	0	0	7.9	11.6	27.3	6.0	0.001*
Osteopenia	30.3	37.9	36.5	58.1	36.4	39.8	
Right femur neck							
Osteoporosis	0.0	1.7	3.2	9.3	18.2	4.2	0.05*
Osteopenia	39.4	32.8	41.3	53.5	36.4	40.3	
Left total femur							
Osteoporosis	0	0	3.2	7.0	18.2	3.2	0.017*
Osteopenia	18.2	19.0	25.4	39.5	27.3	25.9	
Right total femur							
Osteoporosis	0	0	1.6	9.3	27.3	4.2	0.002*
Osteopenia	27.3	22.4	31.7	32.6	18.2	27.3	
Males (n = 308)							
Lumbar spine							
Osteoporosis	0	4.0	6.5	4.3	5.6	3.9	0.527
Osteopenia	15.5	28.0	24.7	27.7	27.8	24.7	
Left femur neck							

Image1: Age-wise distribution of prevalence of osteoporosis (%) and osteopenia (%) at different sites of the skeleton in both genders.

Source: (Kaushalet al., 2018)

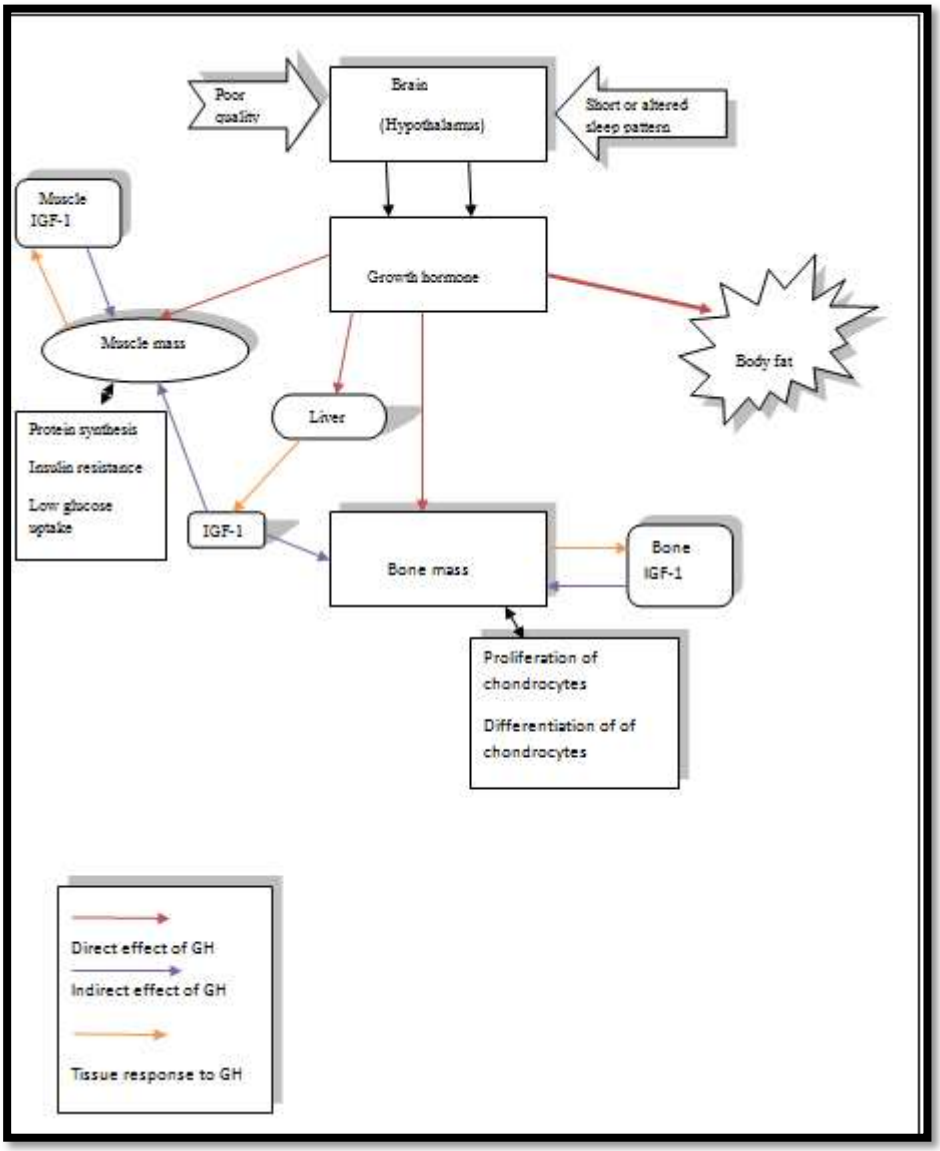


Image 2: Interplay between Nutrition, Genetics, and Lifestyle

Source: (Stichet al., 2022).

7. Clinical and Public Health Implications

It is important to identify high risk individuals for bone degeneration at an early age. The strategies of screening can consist of evaluation of the nutritional intake, physical activities, family history, and, in a few rare instances, bone density. Nutrition education, physical activity promotion, and minimization of sedentary lifestyles among the youth should be the centre of focus in order to mitigate the chances of bone-related diseases and promote better health among the youth. Community programs and schools are very important in creating the environment in which the skeleton can develop rigid and strong and teens and young adults gain the knowledge related to bone health.

8. Future Research Direction

Long-term longitudinal outcomes of early bone deficit and the occurrence of crucial intervention timeframes remain unclear and need further longitudinal research. Genomics could facilitate the development of a customized approach to prevention depending on the genetic profile of individuals. Also, the effects of the combined effects of diet, exercise, and psychosocial factors will also be studied, thus improving knowledge on the bone health trajectories.

9. Conclusion

Bone degeneration among young people is a serious and mostly avoidable social health issue. Nutrition, genetic predisposition, and lifestyle interact in intricate ways to determine skeletal development and long-term bone health. Optimization of the peak bone mass requires proper nutrient intake, physical activities, and interventions on harmful behaviours in the critical growth stages. The global burden will be greatly alleviated by an extensive, life-course perspective of bone health that can achieve immense benefits in terms of osteoporosis and fractures.

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CHAPTER-VIII

A Review on Seasonal Food Insecurity and Its Impact on Child Feeding Practice in Rural Communities in India

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Abstract

Food quality refers to the nutrient density, variation in diet which provides all essential nutrients that support the growth and development of children. Although traditional household feeding practices have focused mainly on increasing food quantity to meet energy requirements, which are lacking in essential nutrients. Poverty, illiteracy, cultural beliefs, seasonal variation and food accessibility often depend on a single or very few food groups that restrict sufficient consumption of macro and micronutrients. This review summarizes the relative roles of food quantity and food quality in child nutrition with emphasizing the effect of micronutrient deficiencies on cognitive development. The review also highlights the importance of age-appropriate complementary feeding. Several studies explored the improvement in the weight of children by increasing both quantity and quality of their diet. The government has taken various initiatives to deliver proper nutrients; however, the nutritional status of Indian children has not achieved the peak value due to some limitations in program implementation. Therefore, it suggests that not only the amount, but the variation in diet also ensures the consumption of multiple food groups and essential nutrients, and provides a consistent nutrient supply throughout the growing period. Community awareness, behavioral changes, inclusion of elder family members and local bodies in preparing foods and delivering crops are crucial to ensure optimal child nutrition and sustainable improvements in their health.

Keywords: Cognitive development, Food quantity, Growth, Nutrients, Quality.

Introduction

Food insecurity is defined as a lack of consistent access to sufficient, safe, and nutritious food. In agricultural communities, food insecurity is mainly seasonal, resulting in compromised nutritional status, psychological distress, and increased risk of infectious diseases, particularly among young children (McQuade et al., 2019). Food insecurity is commonly seen during pre-harvest period, typically occurs in March. The diminished availability of food supplies affects the household's food resources (Belayneh et al., 2020). Therefore, it remains a persistent issue in rural India despite economic growth and public nutrition programs such as Integrated Child Development Services (ICDS) and the National Food Security Act (Rai et al., 2014). Seasonal food insecurity—periods of food scarcity linked to agricultural cycles and climatic variations—can intensify vulnerabilities in rural households, particularly among children during critical growth periods (McQuade et al., 2019). Seasonal variations not only affect the quantity of food

available in rural settings but also impact the quality and diversity of diets provided to children, influencing feeding practices that are critical for early development (Rai et al., 2014). There is lack of integrative research evidence regarding seasonal dimensions of food insecurity and child feeding practices, particularly in rural Indian agricultural communities. Most studies treat food insecurity and child feeding practices as static conditions, which overlap one of the major causes of child malnutrition in India. This review highlights how seasonal variations influence the nutritional quality of diets among infants and young children in rural settings, including breastfeeding, complementary feeding and meal frequency.

Causes of seasonal food insecurity:

In the fast-changing globe, the availability of safe and secure foods is a challenging job. Despite various government initiatives to enhance rural livelihoods, seasonal food insecurity remains a constant problem, indicating poverty, lack of basic healthcare and education services, fluctuations in market prices, political conflicts, infrastructure and transportation issues to avail secured foods. However, climate change in rural areas greatly affects food production and availability (Dodd et al., 2020).

Impact of Food insecurity on maternal nutrition and breastfeeding practice

Maternal malnutrition often results in the birth of undernourished children. Severe malnutrition, especially within the first two years of life, can lead to irreversible cognitive impairment (Maitra et al., 2019). This strong association highlights the direct and immediate link between food security and human development. Various studies showed that food insecurity can reduce the frequency of exclusive breastfeeding (Frazier et al., 2021; Buccini et al., 2024). The importance of exclusive breastfeeding, particularly during the first 1000 days of life, highlights the nutritional deprivation and compromises optimal growth and development in young children (Buccini et al., 2024).

Child Feeding Practices in India

Infant and young child feeding practices include exclusive breastfeeding, timely introduction of complementary foods, and sufficient meal frequency and diversity. Studies showed that inadequate complementary feeding practices are common in low-income and rural settings and are associated with increased risk of malnutrition (Gunnal et al., 2024). Maternal workload intensifies during certain agricultural seasons. It often leads to early cessation of exclusive breastfeeding or reliance on inappropriate, easily accessible foods that do not meet the nutritional needs of young children (Bettoni et al., 2013). Consequently, it hinders the healthy growth and development of infants and young children. Poor feeding practices affect the nutritional status and may lead to child morbidity (Chikhungu et al., 2014) during such a period of food insecurity.

Food insecurity and Nutritional Outcomes in India

Food insecurity in India contributes directly to poor child nutrition outcomes. For young children (6–23 months), dietary variation remains low. Rural children often rely on limited food groups, resulting in dietary deficiencies and undernutrition (Borkotoky et al., 2025). Although

much India-based research documents poverty, maternal education, and socio-economic determinants of child feeding, seasonal food insecurity as a specific risk factor is less frequently studied. However, research from Bangladesh demonstrated that dietary patterns change across seasons due to variations in food availability, which affects the nutritional status of children (Hasan et al., 2023). Chandrasekhar et al. demonstrated that children from food-insecure households have higher odds of being severely stunted or underweight (Chandrasekhar et al., 2017). Gupta et al. found 38% food insecurity in urban slums in India, affecting the children 5.92 times more likely to be underweight (Gupta et al., 2014).

Low variation in diet and inadequate complementary feeding during seasonal food shortages contribute to higher rates of undernutrition, stunting, and wasting among rural children (Nambiar et al., 2025). Additionally, the prevalence of wasting among children in India shows seasonal patterns, increasing during monsoon seasons due to food scarcity and disease burden (Dwivedi et al., 2023). Apart from undernutrition, the cognitive performance of children is also adversely affected by food insecurity (Pavia et al., 2025). Food scarcity thrives in increased consumption of energy-dense foods rich in fats and sugars, as these items are relatively inexpensive, readily available, and provide immediate satiety. Prolonged reliance on fat- and sugar-rich foods can therefore exacerbate various forms of malnutrition, particularly micronutrient deficiencies (Gurri et al., 2021).

Seasonal Effects on Food Availability

Climate variation affects crop production and household food availability (Sharma and Singh, 2017). Agriculture-dependent rural households face variable food supply due to crop cycles, monsoon failures, and market access constraints (Jones et al., 2022). During seasonal shortage, household food stock gets depleted and market price increases which restricts easy access to nutritious foods (Bettoni et al., 2013). These fluctuations affect household food security status, with lean seasons correlating to reduced food accessibility (Jones et al., 2022).

Conclusion

Seasonal food insecurity significantly impacts child feeding practices in rural India, resulting in insufficient dietary diversity and suboptimal complementary feeding during periods of food scarcity. This can result in reduced dietary diversity and inadequate intake of essential micronutrients among young children. Seasonal constraints can also influence complementary feeding practices. Addressing these seasonal effects requires integrated agricultural and nutrition policies that enhance food access and caregiver support across all seasons. Promoting diversified household food production, including pulses, vegetables, fruits, and small-scale livestock or poultry, can improve access to nutrient-rich foods throughout the year.

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CHAPTER-IX

Utilizing fruits and vegetables for plant-based innovation – A Review

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Abstract

Fresh fruits and vegetables are in high demand due to their health benefits. Fruits and vegetable processing generates large amounts of waste, including seeds, pulp, and skin. Surprisingly, these discarded parts contain valuable compounds like Carotenoids, fibre, and antioxidants that can improve our health. The food industry is now exploring new ways to extract and preserve these compounds. Some innovative techniques like supercritical fluid extraction, ultrasonic-assisted extraction, and microwave-assisted extraction to retrieve these valuable compounds. Microencapsulation methods protect sensitive compounds and outline potential food products that can be developed from agricultural waste. Using waste to develop valuable products is a crucial step towards sustainable development. Fruit and vegetable waste can be successfully incorporated into various food products, such as baked goods, jams, and meat products that promote health and well-being, ultimately contributing to global food security.

Keywords - Fruit and vegetable waste, Carotenoids, Fiber, Antioxidants, Supercritical fluid extraction, Ultrasonic-assisted extraction, Microwave-assisted extraction, Microencapsulation Agricultural waste utilization.

Introduction

Fruits and vegetables are packed with nutrients and are a big part of our diet. But what happens to the leftover parts like peels, seeds, and leaves? These by-products are actually rich in healthy compounds like antioxidants, vitamins, and phenolic compounds. In fact, they often have more of these beneficial compounds than the edible part. (Vilarino et.al; 2017, Majumder, p et.al; 2021)

Fruits and vegetables are essential to our diet, providing vital nutrients and phytochemicals that help prevent chronic diseases. However, processing these foods generates massive amounts of waste. This waste, including seeds, peels, and leaves, contains valuable bioactive compounds that can be extracted and used in various industries. (Choudhary,m et.al., 2019;Esparza, I et. al;2020)

In 2021, the United Nations General Assembly designated it as the International Year of Fruits and Vegetables. This initiative aims to highlight the importance of producing fruits and vegetables in a healthy and sustainable manner, leveraging innovation and technology. A key objective is to reduce food losses and waste, promoting a more efficient and environmentally friendly food system.(Liu, x et. al;2022)

As people become more health-conscious, there's a growing interest in using these by-products as functional foods or nutraceuticals. Fruits and vegetables play a vital role in our diet and lifestyle, and with the global population growing, the demand for these foods is increasing. (Vilarino et. al;2017; Majumder, p et. al;2021)

Researchers have made efforts to utilize these compounds, extracting them through different techniques. The extracted compounds can be used to fortify food products, develop pharmaceuticals, or create cosmetics. However, these compounds are prone to degradation, so they need to be protected through encapsulation. (Dorta, E et. al;2017;Banerjee, j et. al;2017)

Encapsulation involves coating the compounds with a material to shield them from environmental factors. The choice of coating material depends on the type of compound being encapsulated. The encapsulated compounds can then be used to develop functional food products with potential health benefits.(Shishir, M, R, I et. al;2018;Trigo, j. P et. al;2020)

This review paper explores the sources of bioactive compounds in fruit and vegetable waste, their functional properties, and recent advances in extraction techniques. It also discusses the effects of operating conditions on microencapsulation and the development of functional food products using these encapsulated compounds. (Pattnaik, M et. al;2021)

VALUABLE COMPOUNDS IN WASTE -

Food waste, particularly from fruits and vegetables, is a rich source of bioactive compounds. These compounds have nutritional and therapeutic benefits, making them ideal for producing functional foods.(Banerjee, j et. al;2017;Espinosa-Alonso, et. al;2020)

Fruits and vegetables contain various bioactive molecules, including lipids, amino acids, fatty acids, polyphenols, and flavonoids. Antioxidants, such as carotenoids and phenolic compounds, can help prevent chronic diseases like cancer, cardiovascular disease, and diabetes. (Bar-ya'akov, I et. al, 2019, Jan, N.V et. al, 2017)

Carotenoids, found in plant tissues, have antioxidant properties and are used in the food industry as natural colorants. Phenolic compounds, characterized by an aromatic ring, have antioxidant and anti-inflammatory properties. (Sharma, G. N et. al;2018, Ben-othman, s et. al;2020)

The peels, pomace, and seeds of fruits and vegetables are rich in phenolic compounds, including flavonoids, phenolic acids, and tannins. These compounds have been linked to several health benefits, including reducing the risk of chronic diseases. (Padam, B. S et. al;2014;Szymanska-chargot, M et. al;2017)

Essential oils, found in the peels and seeds of citrus fruits, have antimicrobial and anti-inflammatory properties. Other plant by-products, such as sapodilla plum, contain saponins and triterpenoids with antimicrobial and anti-inflammatory activities.(Baskar, M et. al;2020;Rakholiya, k et. al;2014)

Fruits and vegetables are rich in bioactive compounds like phenolics and dietary fiber, which offer health benefits due to their antioxidant properties. These compounds can also regulate inflammation and are found in high amounts in fruit and vegetable by-products. (Shahidi et. al;2015;Ferrentino et. al;2018)

Polyphenols, a type of micronutrient, are abundant in these by-products. They have various health benefits and are classified into different groups, including flavonoids, phenolic acids, and lignan. (Majumder, P et. al;2021)

1. **Terpenes,** are a class of compounds found in plant essential oils and resins. They have antioxidant properties and are divided into several categories, including:
2. **Carotenoids**: Found in orange, yellow, and green fruits and vegetables, they help prevent aging and reduce oxidative stress.(Tan et. al;2019;Bohn et. al;2017)
3. **Limonoids**: Found in citrus fruit peels, they have antitumor, antioxidant, and anti-inflammatory properties.(Shi et. al;2020)
4. **Saponins**: Found in beans, quinoa seeds, and legumes, they have cytotoxic, immunomodulatory, and antidiabetic properties.(Majumder, P et. al;2021)

Carotenoids, limonoids, and saponins in fruits and vegetables have antioxidant and anti-inflammatory properties, reducing the risk of cancer, heart disease, and other conditions.

- **Dietary fiber,** in fruit and vegetable by-products promotes gut health, reduces cholesterol and blood sugar levels, and supports healthy bowel function.(Banerjee et. al;2017;Verspreet et. al;2016)
- **Polysaccharides**, found in plant cell walls, have antioxidant, anti-tumor, and antimicrobial properties, with potential applications in food, pharmaceuticals, and cosmetics.(Jung et. al;2017)
- **Phytosterols**, similar to cholesterol, can lower cholesterol absorption in the intestine, reducing the risk of coronary heart disease. Phytosterols have biological functions, including lowering cholesterol and anti-inflammatory effects.(Bot, A et. al;2019;Majumder, P et. al;2021)
- **Organosulfur compounds**, found in cruciferous vegetables, have antioxidant, anti-inflammatory, and anti-cancer properties. (Goncharov N. et. al;2016;Gupta, P et. al;2015)
- **Organic acids**, such as oxalic and ellagic acid, have antioxidant, anti-inflammatory, and detoxifying effects.(Majumder, P et. al;2021)
- **Plant amines**, including chlorophyll, have antioxidant, anti-inflammatory, and detoxifying properties.(Majumder, P et. al;2021)

These compounds have potential health benefits, including reducing the risk of chronic diseases and promoting overall well-being.

Innovative Extraction Techniques -

Extracting bioactive compounds from fruit and vegetable waste requires various techniques, depending on the source and properties of the compounds. However, extraction methods can be harsh, using temperature, pH, frequency, or electromagnetic waves, which may damage the extracted compounds. (Pattnaik, m et. al;2021)

Table - 1

Extraction techniques	Bioactive compound	Source	Solvent/Enzymes	Yield	Reference
Pulsed electric field extraction	Anthocyanin Phenolics and anthocyanin content polyphenols phenolic content carotenoids	Grape by-product blueberry press cake grape seeds red grape pomace citrus sinensis peels	Water and ethanol 50% ethanol and 0.5 Hcl ethanol water acetone in water (20%-80%) Ethylacetate	14.05mg cy-3-glu eq. /g dry matter increased yield by 63% and 78% compared to conventional method 9g/100g GAE 52,645 ppm GAE in dry extract 12.09mg GAE/g DW 262.3+-3.5mg/ 100g DW	Bobinaite et. al;2015;Majumder, P et. al;2021
Enzyme-assisted extraction	Carotenoids Anthocyanins	Pumpkin crocus sativus capsicum annuum	Pectinex, ultrasp pectinex, viscozymel, cellulose and Pectinase	2mg/100g 6.7mg/g 41.72-279.83 mg/100g	Ghosh et. al;2015;Nath et. al;2016
Super critical fluid extraction	Phenolics polyphenol content	Orange pomace (dry) grape seed fraction skin (grape pomace)	Pure ethanol ethanol/water (9:1)	21.2 GAE/g of extract 20.7 GAE/g of extract 7.7 mg GAE/g 11.9 mg GAE/g	Espinosa-pardo, et al 2017;Manna et. al;2015

Ultrasound-assisted extraction	Carotenoids (All-trans-lycopene beta-carotene) total phenolic Naringin (flavonoid) phenols, antioxidant, Anthocyanins natural color	Tomato pomace red grape pomace grape fruit solid waste grape seeds pomegranate rinds.	Hexane and ethanol water	7.49-14.08mg/100g dry weight 50,959 ppm GAE in dry extract 24-36 mg/g dw 5.41mg GAE/100ml 2.29mg/ml 20%	Drosou et al, 2015;Garcia-castello et., 2015

(Pattnaik, m et. al;2021)

Preservation and microencapsulation:

Bioactive compounds, especially polyphenols, are sensitive to heat, light, oxygen, and pH due to their molecular structure. To protect these compounds and maintain their effectiveness, encapsulation is a useful strategy.

Encapsulation involves enclosing bioactive compounds in a solid matrix, which offers several benefits:

- Protects sensitive compounds from environmental factors

- Enhances bioavailability

- Masks unpleasant flavors

- Controls release in the gastrointestinal tract

Various encapsulation methods are available, and the choice of technique depends on the target compound and its properties. (Echeverria, F et. al;2020;Pachuau, L et. al;2021)

Table - 2

Preservation process	Bioactive compounds	Source	Solvent/ enzymes	Yield	Process condition
Spray chilling	Proanthocyanidin, ginger Oleoresin, Cyanocobalamin	Cinnamon extracts, ginger	Vegetable fats oleic acid or plam fat solid lipid microparticles	>87%, >96%, up to 100%	Melting point 48°C, 25°C

Spray Drying	Various	Various Sources	Water	Variable	High-temperature air flow rate, feed flow rate
Freeze Drying	Various	Acerolapulp and residue	Gum Arabiet Maltodextrin 1:1	Higher microencapsulation efficiency than spray-dried powders	-40°C, 24-48h
Fluidized Bed Coating	Various	Various	Various	Variable	Temperature control, air flow rate, coating material selection
Microwave-assisted freeze-Drying (MFD)	Not Specific	Not Specific	Not Specific	Variable	Pressure: 8 µbar to 30 µbar, Microwave power: 23 W to 110 W, Temperature probe: Glass fiber temperature

(Pattnaik, M et. al;2021;Majumder, M et. al;2021;Gitter,J.H et. al;2019)

Potential food products

Table - 3

Vegetables	**By-product**	**Major bioactive principles**	**Food Industry**	**Pharmaceutical industry**	**Biotechnology**
Cauliflower	Leaves, stem, and seeds	Sinigrin, dietary fiber, phenolic compounds, vitamin c	Ready-to-eat foods, nutraceuticals	Hypertension, hyperglycemia	Production of enzymes, Glucoamylase
Tomato	Peels, seeds,	Carotenoids, vitamin C, vitamin E,	Functional food	Antioxidant, Carcinogen-	

	pomace	phenolic compounds		protectives	
Carrot	Carrot peels, carrot pomace	Anthocyanidin, carotenoid, dietary fiber	Biodegradable and edible plastics	Anticancer, antioxidant, preventive action for cardio and digestive disease	Edible vaccine

(Majumder, P et. al;2021)

Fruit	**By-product**	**Major Bioactives principles**	**Food industry**	**Pharmaceutical industry**	**Biotechnology**
Mango	Mango peels, mango seeds	Dietary fiber, phenolics, alkylresorcinols, flavonoids, carotenoids, sugar	Functional food, food packaging material, food additives	Coating and pharmaceutical packaging materials	Industrial problem of alpha- amylase enzymes
Apple	Defeatted apple seeds, aapple pomac	Phloridzin, pectins cellulose, hemicellulose, lignins	Chewing gum, stabilizers for oil water emulsion	Antidiabetic, antioxidant	Substrate for microbial fermentation
Grape	Grape pomace, grape seeds	Hemicelluloses, cellulose, pectin, polyphenols, phenolic acid, flavonoids, stilbenes, anthocyanins	Nutraceuticals, functional foods, muffins, brownies	Antioxidant, protective anti aging agents, antimicrobial, antiinflammatory, cardioprotective, anticancer	Fermentation substrate for microbial growth
Avocado	Avocado peels and seed	Phenolics, carotenoids, vitamins	Cream soup, food packaging, colorants in food products	Anticancer, antidiabetic, antihypertensive	Biodiesel production
Banana	Banana peels and plantain flower, rhizomes, fruit stalk	Phenolics, flavonoids, phytosterols, carotenoids, alpha-cryptoxanthin	Sweet candy, nutrient and food additives	Bioethanol, antimicrobial, antihyperglycemi, antioxidant, antiinflammatory,	Substrate in biotechnological conversion process for solid state

	pseudo-stems	anthocyanins, amines		anti aging	fermentation.
Citrus	Citrus peels, citrus peels oils	Hesperidin, Naringin, rutin narirutin, quercetin, diosmin, tangeretin	Probiotics, food additives, flavor additives	Antidiabetic, antioxidant, antitumor, anti-inflammatory	Solid state fermentation process as substrate

(Majumder, P et. al;2021)

BENEFITS AND CHALLENGES:-

Fruit and vegetable by-products are a valuable resource that can benefit society, the economy, and the environment. These by-products are rich in nutrients, fiber, and bioactive compounds that can be used to create healthy food products, pharmaceuticals, and cosmetics.

Currently, many of these by-products are wasted, but they can be transformed into valuable products, reducing waste and improving sustainability. This can also create new job opportunities and boost the economy.

The food industry can use these by-products as natural antioxidants, antimicrobials, flavorings, colorants, and sources of dietary fiber and proteins.

By utilizing fruit and vegetable by-products, companies can reduce waste, improve their environmental profile, and increase profitability.

Overall, these by-products have the potential to become a valuable resource, rather than being discarded as waste.(Majumder, P et. al;2021)

Market opportunities and trends:

Food waste contains valuable bioactive compounds that can be extracted and used to create functional food products. This reduces waste and adds value to the products.

Future Trends

1.**Green Technology:** There's a growing demand for eco-friendly extraction methods using minimal or no solvents.

2. **Advanced Extraction Methods:** Developing solvent-free extraction techniques is a future goal.

3.**Non-Thermal Technologies**: Focus on emerging technologies like Pulsed Electric Field (PEF) to improve extraction yields and reduce energy consumption.

4.**Value-Added Food Products:** Incorporating fruit and vegetable by-products into food products can enhance nutritional value.

5. **Further Research:** More studies are needed to understand the health benefits of bioactive compounds and how they're absorbed by the human body. (Pattnaik, M et. al;2021)

Recommendations and implementation:

Effective waste management is crucial for a sustainable society. It's not just about disposing of waste, but also about how we generate, collect, and manage waste as a whole.

Traditional approaches to waste management are outdated and unsustainable. They focus on short-term solutions and lack flexibility.

A sustainable waste management system:

- Looks at the bigger picture and how different parts are connected

- Is adaptable and open to change

- Focuses on processes and finding ways to improve them

- Diverts waste from disposal and finds new uses for it

To make the transition to a sustainable waste management system, we need to identify areas where we can make a significant impact and create change.(Season, J. K et. al;2010)

Discussion/future directions:

The global population is expected to increase to 11.2 billion by 2100, posing a significant challenge to food security and environmental sustainability. To address this, reducing waste and reusing food resources are crucial strategies. Fruit and vegetable by-products can be transformed into valuable food products, reducing waste and creating economic opportunities. Innovative technologies can help produce high-quality, dehydrated nutraceutical products. The key to economic viability lies in the yield and quality of extracts, market value, and universal process design for development and marketing. Furthermore, waste management is a critical aspect of sustainability, requiring a systems approach that incorporates feedback loops, adaptability, and diversion from disposal. Traditional reductionist approaches are unsustainable, lacking flexibility and long-term thinking. A sustainable waste management system must be focused on processes, embody adaptability, and divert wastes from disposal. Transitioning to such a system requires identification and application of leverage points that effect change. By adopting innovative technologies, sustainable waste management practices, and a systems approach, we can reduce waste, promote food security, and create a more sustainable future.

Conclusion:

In conclusion, the increasing global population and associated food security concerns necessitate the adoption of sustainable strategies to reduce waste and promote efficient use of resources. Fruit and vegetable by-products, rich in bioactive compounds, offer immense potential for transformation into valuable food products, nutraceuticals, and pharmaceuticals. The development of innovative extraction technologies, drying methods, and sustainable waste management practices is crucial to unlock the economic and environmental benefits of these by-products. By embracing a systems approach to waste management, incorporating feedback loops, adaptability, and diversion from disposal, we can minimize waste, promote food security, and contribute to a more sustainable future. Ultimately, the successful valorization of fruit and vegetable by-products requires a multifaceted approach that integrates technological innovation, sustainable waste management, and a commitment to reducing environmental footprint, thereby ensuring a food-secure and sustainable future for generations to come.

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CHAPTER-X

Sesame Seeds (*Sesamum indicum L.)* as a Functional Food: Nutritional Profile and Therapeutic Applications

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Abstract

Sesame (Sesamum indicum L.) also known as Queen of oil seeds, has been cultivated for thousands of years and enjoyed for its culinary versatility. Sesame is among the key annual oil crops widely grown in almost all regions of tropical and subtropical Asia and Africa for its very nutritious and delicious seeds. In addition to their rich nutritional profile and drought resistant features, sesame seeds have recently received attention due to their potential health benefits. This review provides a comprehensive overview of the various nutrient components and ways they contribute to good health. Total dried sesame seeds are rich in unsaturated lipids, particularly oleic acid and linoleic acid. A good source of protein in plant kingdom, rich in sulfur amino acids such as methionine and cysteine, but low in lysine. High fiber content and mostly present in the hull of the seed. The article further goes on to discuss the benefits of sesame seeds in terms of minimizing the risk of chronic disease based on its high polyunsaturated fatty acids composition. Sesame can reduce the lipid peroxides and influence the enzymes that regulate the balance of the oxidative state in the body.. The importance of bioactive polypeptides from sesame seeds is also reviewed, discussing their use as nutritional supplements, nutraceuticals, and functional ingredients. Though Sesame seeds carry potent health benefits and can be a very good snacking option or used in food formulation to reduce inflammation in patients but still the safe quantity recommendation as per geographical distributions remains unexplored.

Keywords: Sesame (*Sesamum indicum* L.), nutrition profile, oxidative stress, cellular inflammation, bioactive compounds, health benefits.

Introduction

Sesame (Sesamum indiculam L.) seeds are one of the tropical crops of premium category of oil seeds with diversified health benefits and are processed under various techniques world-wide.(Elluch,Bedigian and Zitoun,2011) .It is known as the most oldest oilseed in the world (Yen and Shyu 1989).Sesame seeds production ranks 6th among the oilseeds (Lee et al 2010.The different application of sesame seeds in food products such as crackers,biscuits,salads,sweets,cookies has made this seed popular among the people (Elleuch et.al 2011).Sesame oil,which makes up about processed products such as cooking oil,salad dressing, medicated soaps,insectisides and in pharmaceutical products.(Elleuch e al 2011,Namiki 2007).In addition to the high quality oil sesame seeds contain substantial quantitiesn of protein,minerals,phytosterols with high potential for improving overall metabolic health from cellular level.

Due to the nutritional and health possibilities of sesame seeds research on processing and application of these seeds has increased greatly in recent years and is continuing.(Ji,Liu,Shi Wang and Wang,2019).

Prior to consumption and oil sextraction sesame seeds are subjected to several pretreatments processing methods such as dehulling,moistening,roasting,steaming and heating. To enhance the oil recovery and quality.(Sahidi,Amarowicz,Abar-Gharbia et al 2019).

Among these pre treatment techniques roasting is by far the most frequently used method and can cause microconstructural,physical and chemical changes of the seeds thereby significantly affecting the oil recovery and other quality factors of sesame seeds.(Ji,Liu,Shi Wang and Wang 2019)

Chemically, foods are composed mainly of water, lipids, proteins, and carbohydrates with small proportions of minerals and organic compounds. Minerals are salts, and organic substances are vitamins, emulsifiers, acids, antioxidants, pigments, polyphenols, flavours.

Carbohydrates

Sesame seed hull is the major by-product of sesame seed oil extraction. It is mainly composed of 70–80% carbohydrate polymers (including hemicelluloses, cellulose, and pectic polysaccharides) (Liu, H. M., He, M. K., Yao, Y. G., Qin, Z., Cai, X. S., & Wang, X. D. (2021). Seven carbohydrates have been found in the seeds: D-glucose, D-galactose, D-fructose, raffinose, stachyose, planteose, and sesamose (Hegde, D. M. (2012).

Protein:

The protein in sesame is a complete protein, of which the ratio of essential amino acid content is very similar to that of the human body (Morris, J. B., Wang, M. L., & Tonnis, B. D. 2021). Sesame protein is rich in variety, mainly including globulin, clear protein, alcoholic protein, and glutenin, of which globulin has the highest content and alcoholic protein has the least (Cui, C., Liu, Y., Liu, Y., Cui, X., Sun, Z., Du, Z., ... & Zheng, Y. 2021). Sesame meal, a by-product of sesame processing, also contains about 50% protein. The high value of the in vitro protein digestibility showed that sesame protein isolate could be used to enrich and act as a supplement in some food systems, especially in developing countries where protein deficiency is a major health challenge for children. Relevant studies have shown that peptides are not only utilized by nutrients that promote growth and development but also are important for the regulation and health of the organism. In Asian countries, the health benefits of black sesame seeds are considered to be greater than those of white sesame seeds because of the different shades of the seed coat (Salunkhe, D. K. (1992).

A genome-wide association study of sesame seed coat color by Cui et al., found that the protein content of sesame seeds increased as the color of the seed coat deepened Vangaveti, V. N., Jansen, H., Kennedy, R. L., & Malabu, U. H. 2016).

One of the more intuitive aspects is that the protein content of black sesame seeds is higher than that of white sesame seeds. The four proteins that have been reported in sesame are albumin, globulin (α and β), prolamin, and glutelin fractions (Hegde, D. M. 2012). Nineteen essential amino acids have been isolated and identified from roots, seeds, flowers, stems, and leaves. They are as follows: alanine, arginine, aspartic acid, cysteine, glutamic acid, glycine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, serine, threonine, tyrosine, valine, tryptophane, proline, and γ-aminobutyric acid (Wang, R., Lu, X., Sun, Q., Gao, J., Ma, L., & Huang, J. 2020).

Fat

The lipids in sesame are mainly found in the seeds and are an important component of sesame. Sesame has the highest oil content among the major oil crops, up to 45~57%, which is why it has been known as the “Queen of Oil” since ancient times (Hu Y M et al 2017).

Sesame oil is reported to contain 80% unsaturated fatty acids and a small amount of saturated fatty acids (Ozedemir IS et al 2018).

Linoleic acid and linolenic acid are unsaturated fatty acids, which are essential fatty acids, but cannot be synthesized in the body and therefore must be obtained through diet. Linoleic acid can participate in cholesterol metabolism, increase the toughness of vascular epithelial cells, and contribute to growth and development.

Linolenic acid can promote lymphatic B-cell differentiation and proliferation, and improve the acquired exogenous immunity (Dar, A. A., & Arumugam 2013). Sesame oil, as an important product form of sesame, contains major unsaturated fatty acids, oleic (18:1) and linoleic (18:2) acids in the range of 26.60% to 54.85%, while minor unsaturated fatty acids are in the range of 0.13% to 0.89%. The content of saturated fatty acids varies from 0 to 10.58%, which is certainly a good supplement for essential fatty acids (Salunkhe DK et al 1992).

Twelve unsaturated fatty acids have been found in sesame seeds. They are as follows: oleic acid, linoleic acid, palmitic acid, stearic acid, arachidic acid, linolenic acid, palmitoleic acid, lignoceric acid, caproic acid, behenic acid, myristic acid, and margaric acid (Dar, A. A., Kancharla, P. K., Chandra et al 2019). However, it is well known that some side effects may occur with excessive consumption of any food, and the same is true for sesame seeds. For example, sesame seeds are high in unsaturated fatty acids and excessive consumption of sesame seeds can cause the body to gain weight, which is not friendly to dieters. Excessive intake of sesame seeds can lead to gastrointestinal discomfort and cause endocrine disruption in the body, which may lead to an increased risk of cardiovascular disease (Dalibalta, S., Majdalawieh, A. F., & Manjikian, H 2020).

Omega-3 fatty acids can inhibit platelet aggregation, increasing the risk of bleeding (Phang, M., Garg, M. L., & Sinclair, A. J. 2009), and sesame seeds are rich in this ingredient. Omega-3 fatty acids are known to lower blood pressure, and excessive consumption of sesame seeds is also associated with a risk of severe hypotension (Nyantika, A. N., Tuomainen, T. P., Kauhanen, J., Voutilainen, S., & Virtanen, J. K. 2016). In addition, sesame seeds contain some antinutrients, such as oxalic acid and phytic acid, which, in

excess, can have certain effects on the body, such as affecting the digestion and absorption of mineral elements and proteins in the gut and increasing the risk of kidney stones.

Vitamins

Vitamins also occupy a certain proportion in the nutrient composition of sesame, of which vitamin E is the richest in sesame (Mili, A., Das, S., Nandakumar, K., & Lobo, R. 2021). In particular, vitamin E can be present in black sesame seeds at levels up to 50.4 mg/100 g. Studies have shown that γ-tocopherol is the major form of vitamin E in sesame seeds, while there is relatively less α-tocopherol. In vitro experiments have shown that γ-tocopherol has a stronger antioxidant capacity than α-tocopherol, but the overall vitamin E has a stronger functional activity (Hegde, D. M. 2012).

Vitamin A, thiamine, riboflavin, niacin, pantothenic acid, folic acid, ascorbic acid, α-tocopherol, β-tocopherol, γ-tocopherol, δ-tocopherol, and tocotrienol, all the twelve vitamins have been reported to be isolated from sesame seeds (Fasuan, T. O., Gbadamosi, S. O., & Omobuwajo, T. O. 2018).

Mineral Content

Sesame seeds have been reported to be a source of several minerals, such as K (525.9 mg/100 g), P (516 mg/100 g), Mg (349.9 mg/100 g), Na (15.28 mg/100 g), Fe (11.39 mg/100 g), Zn (8.87 mg/100 g), and Mn (3.46 mg/100 g) (M Elleuch et al).

Flavonoid properties

In addition to being rich in nutrients, sesame also contains many important functional components such as sesamin, sesamolin, sesamol, sesaminol, sesamolin phenol, and other lignan-like active ingredients (Pathak N et al 2014). The content of each component in sesame varies depending on the extraction method and external growing conditions, e.g., hot-pressed sesame oil has a higher content of sesamol, sesamin, and total lignans than cold-pressed and refined sesame oil (Khuimphukhieo, I.; Khaengkhan et al ,2018). The lignan content in sesame can be affected by factors such as strain, genotype, growing location (soil and weather), and growing conditions (irrigation, fertilization, and harvest time) (Xu, F.; Zhou, R.; Dossou, S.S.K.; Song, S.; Wang, L ,2021).

A variety of phytochemical compounds have been identified and isolated from sesame seeds, seed oils, and various plant organs, including lignans, polyphenols, phytosterols,

phenols, aldehydes, anthraquinones, naphthoquinones, triterpenoids, and other organic compounds.



Figure 1: Sesame Seeds

Lignans

Sesame lignans are the main active ingredients in sesame seeds and have strong antioxidant activity (Dar, A.A.; Verma, N.K.; Arumugam,2015). Epidemiological studies have shown that sesame lignans have beneficial effects in regulating blood lipids and improving liver function. These properties are also responsible for the oxidative stability of sesame oil (Andargie, M.; Vinas, M.; Rathgeb, A.; Möller, E.; Karlovsky,2021).

Sesamin represents about 50% of the sesame lignans, with sesamolin, sesamol, and sesaminol accounting for a small proportion of the weight. The mean levels are 2.48 mg/g (range 1.11–9.41 mg/g) and 1.72 mg/g (range 0.20–3.35 mg/g) for sesamin and sesamolin (Andargie, M.; Vinas, M.; Rathgeb, A.; Möller, E.; Karlovsky,2021). During the pressing process, sesame seeds undergo denaturing transformations represented by sesamin and sesamolin, into unsaturated low polymeric structural substances such as sesamol, sesaminol, and sesamolin phenol (Wu, L.; Yu, L.; Ding, X.; Li, P.; Dai, X.; Chen, X.; Zhou, H.; Bai, Y.; Ding,,2017).

It has been shown that the lignan content of sesame seeds is strongly related to seed coat color, with black sesame seeds having the highest sesamin, sesamol, and total lignans content, while white sesame seeds have a relatively low sesamin content. The range of total lignin content in yellow, black, brown, and white sesame seeds was 2.52-5.94, 3.56-12.76, 2.66-6.68, and 2.83-5.66 mg/g, respectively (Shi, L.-K.; Liu, R.-J.; Jin, Q.-Z.; Wang, X.-G.,2017).

A total of twenty-six lignans have been identified and reported from the aerial organs and seeds, namely sesamin, sesamolin, sesamol, (+)-episesaminone, (+)-episesaminol 6-catecho, pinoresinol, (−)-pinoresinol 4-*O*-glucoside, (+)-pinoresinol di-*O*-*β*-D-glucopyranoside, glucopyranosyl-(1→6)]-*β*-D-glucopyranoside], sesaminol, (+)-sesaminol 2-*O*-*β*-D-glucoside, (+)-sesaminol diglucoside, (+)-sesaminol 2-*O*-*β*-D-glucosyl(1→2)-*O*-[*β*-D-glucosyl(1→6)]-*β*-D-glucoside, sesamolinol, (+)-sesamolinol 4′-*O*-*β*-D-glucoside, sesamolinol 4′-*O*-*β*-D-glucosyl (1→6)-*O*-*β*-D-glucoside, matairesinol, samin, sesangolin, and disaminyl ether (Fasuan, T.O.; Gbadamosi, S.O.; Omobuwajo, T.O,2018).

Sesamin

Sesamin is one of the most abundant lignans in the composition of sesame seeds and has good physiological activity. Studies have found that sesamin has good antioxidant properties, cholesterol lowering, lipid metabolism regulation, blood pressure stabilization, and anti-tumour effects (Majdalawieh, A.F.; Massri, M.; Nasrallah, G.K,2017). Sesamin is metabolized in the body mainly by the action of cytochrome P-450. The metabolites of sesamin exist in body fluids and tissues mainly as glucosinolates and sulfate-conjugated forms, the excretion of sesamin is via bile, urine and feces, and the elimination of sesamin is mainly achieved by metabolism (Tomimori, N.; Rogi, T.; Shibata, H,2017).

The variation in the content of sesamin, an oil-soluble lignan, may be related to the variation in the variety of sesame, local climate, and soil type, ranging from 60.14 to 69.10 mg/100 g (Ghotbzadeh Kermani, S.; Saeidi, G.; Sabzalian, M.R.; Gianinetti,,2019). When the unroasted and pressed sesame oil was decolorized with acidic white clay, some of the sesamin was formed by isomerization to the stereoisomer episesamin of sesamin with a content of about 0.28% (Kancharla, P.K.; Arumugam, N,2020).

Sesamolin

Sesamolin is the second most abundant lignan in sesame. Since sesamolin does not contain phenolic hydroxyl groups, its antioxidant effect in the body is much weaker than that of sesamol. However, under certain heating conditions, sesamolin can gradually convert to sesamol. Taking advantage of this conversion feature, the addition of sesamolin enhances the antioxidant properties of oils and fats under heating conditions (Mili, A.; Das, S.; Nandakumar, K.; Lobo, R,2021).

Sesamol

Sesamol is present in low levels in sesame lignin, but it is the main flavor component and quality stabilizer of sesame oil, with good antibacterial and antioxidant properties. Studies have shown that sesamol is stable under sunlight conditions and can be used simultaneously with food additives containing Zn^{2+} and Mg^{2+}, but not with strong oxidants (Jayaraj, P.; Narasimhulu, C.A.; Rajagopalan, S.; Parthasarathy, S.; Desikan, R,2020).

Sesaminol

Sesaminol is an important fat-soluble lignan. It is found at low level in sesame seeds but demonstrates good antioxidant properties and thermal stability. Under acidic conditions, sesamolin can be readily converted to sesaminol (Katayama, S.; Sugiyama, H.; Kushimoto, S.; Uchiyama, Y.; Hirano, M.; Nakamura, S,2016).

Extraction techniques for various bioactive compounds:

Traditionally, solid-liquid extractions are the most commonly utilized method to extract lignans from SC by heating or stirring and using water and polar organic solvents (methanol, ethanol or acetone) or their aqueous mixtures (Lee et al., 2005, Mohdaly et al., 2011, Sarkis et al., 2014). However, these methods have several drawbacks, including long extraction times, large solvent consumption and high energy consumption.

Emerging technologies such as microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), supercritical fluid extraction (SFE) and accelerated-solvent extraction (ASE) are gaining more attention among scientists and manufacturers, because they are considered ‘green’ processing approaches. The UAE is based on the principle of cavitation (production, growth and collapse of bubbles in the extraction solvent and sample material, allowing better contact and diffusion of solvent with the plant matrix), while MAE take advantage of changes in the tissue and cell structures caused by electromagnetic waves. ASE uses high pressure to keep solvents in liquid state above their boiling point, which facilitates the extractability of the targeted analytes (improvement of diffusion and mass transfer phenomena), whereas SFE employs supercritical fluids as solvents for the extraction of bioactive compounds (Ameer et al., 2017). All these processes involve short extraction times and relatively low solvent volume, thus reducing substantially energy consumption (Kaderides et al., 2019, Nayak et al., 2015). Among the techniques employed for extracting of lignans from SC, UAE (Eom et al., 2021, Long et al., 2020, Mekky et al., 2019, Moazzami et al., 2006b), SFE (Aregay et al., 2021, Bodoira et al., 2017) and the pulsed electric fields (Sarkis et al., 2015) have been explored.

Besides the importance of extraction parameters such as time, temperature, pressure, the composition of the solvent medium, the solid-to-solvent ratio (SS) and the extraction technique itself exerts a significant impact on the extraction efficiency (Kumar et al., 2021).

Therapeutic application as functional food

In practical applications, the incorporation of antioxidant ingredients into oils is necessary to prevent their oxidation. Refined sesame oil contains antioxidants that improve the storage life of the oil in the food industry. This is because high-temperature roasting is required during the refining process of sesame oil. The Maillard reaction between the reducing sugars and the free amino acids during high-temperature roasting not only contributes to the flavor of the sesame oil, but it also improves the antioxidant activity of the oil. The sesamin and sesaminol content of sesame oil is also affected during the roasting process. This is because of the high-temperature decomposition of sesamolin; also, sesamolin can act as a precursor to sesamol. Sesame oil, unroasted, had a low content of sesamol; however, after roasting, the sesamol content was significantly high. Sesamol has been reported to possess antioxidant activity; hence, the roasted sesame oil is not easily rancid [66]. The use of the antioxidant content of sesame seeds is necessary to add antioxidant activity to oils. For instance, the addition of the outer skin of sesame seed extracts to sunflower oil may improve the oxidation inhibition of the oil.

Sesame (Sesamum indicum) seeds have long been used as a traditional health food in East Asia and its oil has been an important component of natural Indian remedies and Chinese medicine to increase energy and prevent aging (Mahendra Kumar and Singh, 2015). Sesame is rich in a variety of lignans, such as sesamin, episesamin, sesamol, sesamolin, and c-tocopherol, which are a group. of bioactive phenolic compounds also found in flax, barley, buckwheat, millet, oats, rye, nuts, and legumes (Jeng and Hou, 2005). However, they are most abundant in sesame seed, with sesamin as the major isomer (1520 ± 6.8 lmol/100 g) (Liu et al., 2006; Liang et al., 2015). Raw sesame oil contains 0.5–1.1% sesamin and 0.2–0.6% sesamolin that contribute to the medicinal properties of the oil, since these lignans are said to possess antioxidant activities (Kumar and Singh, 2015). A variety of biochemical actions have been attributed to sesamin, such as the specific inhibition of D5-desaturation of (n-6) fatty acids that aids in blocking the formation of pro-inflammatory prostaglandins, protection against ethanol and carbon tetrachloride-induced liver damage, enhancing the bioavailability of c-tocopherol, and suppressive effects against induced carcinogenesis in animals (Peñalvo et al., 2005). Although the exact mechanism of some of these effects is unknown, it is proposed that the role of sesamin is proactive and that its metabolites are

responsible for the physiological effects (Peñalvo et al., 2005). A study by Nakai and colleagues illustrates that sesamin undergoes oxidative demethylenation of methylene dioxyphenyls to catechol or methoxycatechol in rat liver, which are important moieties that contribute to antioxidant activities (Nakai et al., 2003).

Products developed from Sesame seed

In recent years, with the improvement of people's living standards and health consciousness, the consumption of sesame and its products is on the rise. In the international market, the demand for sesame seeds has surged, with major consumer countries such as Japan, Korea, Turkey, Egypt, the United States, and Israel. In China, sesame oil is irreplaceable in the catering and cooking industry, with about 45% of sesame production used for sesame oil processing, 22% for sesame paste processing, 22% for peeled sesame processing, 5% for baked goods, and 6% for other uses (Qu, Y.; Ren, C.; Jiang,,2021).

Common Food Products

- Baking Additives: Adding sesame protein isolate improved the nutritional value of muffins. Muffins with 15% sesame protein isolate are best accepted by professionals regarding their taste.(Dossa K., Diouf D., Wang L., Wei X., Zhang Y., Niang M., Fonceka D., Yu J., Mmadi M.A., Yehouessi L.W., et al.2017)
- Used with vegetable oils: Using sesame oil together with vegetable oils makes it capable of imparting nutritional, protective, and physicochemical properties (Rodriguez G., Villanueva E., Cortez D., Sanchez E., Aguirre E., Hidalgo.2020)
- Ghee for Baking: Chemical transesterification of sesame oil. It can be employed to enhance physical characteristics, such as SFC and melting points. SMP, as well as SFC, reduced following interesterification. Blend of sesame oil and palm stearin. It may result in trans-fat-free ghee (Rudsari M.T., Najafian L., Shahidi S.A. 2019)
- Healthy food: Sesame seed oil's components, properties, and possible health values of phenolic substances make sesame an ideal food in healthcare (Tai T.-S., Tien N., Shen H.-Y., Chu F.-Y., Wang C.C.N., Lu C.-H., Yu H.-, Kung F.-P., Chuang H.-H., Lee Y.-R., et al..2019)
- Antioxidants: The extract from the sesame skin in the sunflower oil may improve the stability of the sunflower oil against oxidation (Tai T.-S., Tien N., Shen H.-Y., Chu F.-Y., Wang C.C.N., Lu C.-H., Yu H.-, Kung F.-P., Chuang H.-H., Lee Y.-R., et al.2019)

Conclusion

Sesame seed is a good source of potent biologically active phytochemicals like sesamin, sesamolin, tocopherols, PUFA, phytosterols, and other phenolic compounds. The pretreatment technology ultrasonic/microwave-assisted extraction is commonly applied for sesame seed extraction. In order to raise comprehensive utilization rates of by-products based on improved processing technologies, product quality, nutritional components, and other factors are improved during production processes. New techniques on sesame are relatively undeveloped and need more exploration research. In the processing procedures involving extraction and refining, nutritional values on sesame oil are decreased generally; some impurities and hazard factors are also generated. Hence, on more research studies based on above processing principles such as a process characterized by high efficiency, environmentally safe and pollution-free processing, energy-saving designs and processing method constructs, standardized production technological procedures, as well as stringent processing quality controls. In above processing procedures considering comprehensive benefits on pure natural products like food materials—such as on original tastes and nutrients on sesame oil—by-products can better apply overall processes on sesame.

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CHAPTER-XI

Nutraceuticals: the link between Nutrition and Medicine: An Overview

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Abstract

Nutraceuticals represent a rapidly expanding field at the intersection of nutrition and medicine, emphasising the role of food-derived products in the prevention and management of disease. The term "nutraceutical" encompasses a broad range of substances, including functional foods, dietary supplements, herbal products, and bioactive compounds that provide health benefits beyond basic nutritional value. Growing scientific evidence suggests that nutraceuticals can modulate physiological functions, enhance immune response, reduce inflammation, and lower the risk of chronic diseases such as cardiovascular disorders, diabetes, cancer, and neurodegenerative conditions. This overview highlights the concept, classification, sources, and mechanisms of action of nutraceuticals, as well as their therapeutic potential in promoting health and preventing disease. In addition, regulatory considerations, safety concerns, and challenges related to standardisation and clinical validation are discussed. By bridging the gap between traditional nutrition and modern medicine, nutraceuticals offer a promising approach to preventive healthcare and personalised nutrition, supporting a shift from disease treatment to health promotion.

Keywords

Functional foods, Dietary supplements, Bioactive compounds, Preventive healthcare, Nutrition and medicine; Chronic disease management

1. Introduction

The relationship between food and health has long been recognized, but advances in nutritional biochemistry, molecular biology, pharmacology, and food technology have increasingly demonstrated that certain food components may exert biological effects beyond their basic nutritional functions. This scientific interface between nutrition and medicine has contributed to the emergence of **nutraceuticals**, a broad term used for food-derived substances or products associated with potential health-promoting or disease-preventive effects (Brower, 1998; Chakraborty et al., 2012).

The term *nutraceutical* was coined by Stephen DeFelice in 1989 by combining the words **"nutrition"** and **"pharmaceutical."** It was originally used to describe a food or component of food that could provide health benefits, including potential roles in disease prevention or treatment (DeFelice, 1995; Chakraborty et al., 2012).

The growing interest in nutraceuticals is closely associated with the increasing burden of chronic diseases such as cardiovascular disease, diabetes, obesity, certain cancers, and metabolic

disorders. Diet is now recognized as an important determinant of health across the life course, and healthy dietary patterns can contribute substantially to the prevention of noncommunicable diseases (World Health Organization [WHO], 2026).

Nutraceuticals therefore occupy an interesting position between conventional foods and pharmaceutical products. They represent an attempt to understand and utilize biologically active components of foods while recognizing that their effects may involve complex physiological, biochemical, and molecular mechanisms.

2. Concept and Definition of Nutraceuticals

Although the term nutraceutical is widely used in scientific, commercial, and clinical contexts, there is **no universally accepted international definition**. Different organizations and researchers have used the term to describe food-derived compounds, dietary supplements, functional foods, herbal preparations, and isolated bioactive substances (Aronson, 2017).

Nutraceuticals may broadly include substances such as vitamins, minerals, dietary fibres, probiotics, prebiotics, polyphenols, carotenoids, phytosterols, omega-3 fatty acids, peptides, and other bioactive food components. Depending on their source and formulation, they may be consumed as foods, concentrated extracts, capsules, powders, beverages, or other preparations (Chakraborty et al., 2012).

The lack of a standardized definition creates challenges in distinguishing nutraceuticals from **functional foods, dietary supplements, fortified foods, herbal products, and pharmaceuticals**. Aronson (2017) emphasized that these categories frequently overlap and that the term nutraceutical itself may be scientifically imprecise.

Consequently, academic discussions should preferably identify the **specific bioactive component, source, dose, formulation, biological effect, and intended use**, rather than assuming that every product marketed as a nutraceutical has established therapeutic efficacy.

3. Nutrition as a Determinant of Health

Nutrition provides the substrates and regulatory molecules required for energy metabolism, tissue synthesis, immune function, reproduction, neurological activity, and maintenance of physiological homeostasis. Both nutrient deficiencies and excessive or imbalanced nutrient intake can contribute to disease development.

The WHO identifies adequacy, balance, moderation, and diversity as fundamental principles of a healthy diet. Diets containing adequate amounts of vegetables, fruits, legumes, whole grains, nuts, and other nutrient-rich foods are associated with better health outcomes, whereas diets high in excess sodium, free sugars, unhealthy fats, and highly processed foods may contribute to chronic disease risk (WHO, 2026).

The preventive potential of nutrition is particularly important in chronic disease because dietary exposures occur repeatedly over long periods. Cardiovascular disease, type 2 diabetes, obesity, hypertension, and several other disorders are influenced by dietary patterns in conjunction with genetic, environmental, behavioural, and socioeconomic factors (Willett, 2013).

Nutraceutical research extends this concept by investigating whether specific food-derived compounds can influence biological pathways associated with disease development. However, nutraceuticals should be viewed as **components of a broader dietary and lifestyle strategy rather than automatic substitutes for a balanced diet or evidence-based medical treatment**.

4. Nutrition and Medicine: The Emerging Interface

The boundary between nutrition and medicine has become increasingly interconnected. Traditional nutritional science primarily focused on meeting physiological nutrient requirements and preventing deficiency diseases, whereas contemporary nutrition investigates how foods and bioactive compounds influence cellular signalling, inflammation, oxidative stress, metabolism, immunity, and gene expression.

Nutraceutical research contributes to this transition by examining food-derived compounds through approaches traditionally associated with pharmacology and medicine. These include studies of dose-response relationships, mechanisms of action, bioavailability, pharmacokinetics, safety, clinical efficacy, and interactions with medications (Gurib-Fakim, 2006).

For example, omega-3 fatty acids have been investigated for their effects on lipid metabolism and inflammatory pathways; soluble dietary fibres have been studied in relation to gastrointestinal function and cholesterol metabolism; and certain polyphenols have been examined for antioxidant and signalling effects (Chakraborty et al., 2012).

This intersection has contributed to the development of the concept of **food as a biological intervention**, although the strength of evidence varies considerably among different compounds and health outcomes.

5. Major Categories of Nutraceuticals

Nutraceuticals can be classified according to their chemical nature, food source, biological activity, or intended health application.

5.1 Dietary Fibre

Dietary fibre includes carbohydrate polymers that are not completely digested and absorbed in the small intestine. Soluble and fermentable fibres can influence intestinal microbiota, short-chain fatty acid production, bowel function, glucose metabolism, and lipid metabolism (Slavin, 2013).

Sources include oats, barley, legumes, fruits, vegetables, whole grains, and certain seeds. Adequate dietary fibre is an important component of healthy dietary patterns and should preferably be obtained from diverse whole-food sources.

5.2 Probiotics

Probiotics are live microorganisms that, when administered in adequate amounts, confer a health benefit on the host (Hill et al., 2014). Commonly studied organisms include selected species of *Lactobacillus*, *Bifidobacterium*, and other microorganisms.

Probiotic research has investigated gastrointestinal health, antibiotic-associated diarrhoea, selected functional gastrointestinal disorders, and other conditions. However, health effects are

often **strain-specific**, and evidence for one probiotic preparation cannot automatically be generalized to another (Hill et al., 2014).

5.3 Prebiotics

Prebiotics are substrates selectively utilized by host microorganisms that confer a health benefit. Examples include certain fructans and galacto-oligosaccharides. They can modify the composition or activity of the intestinal microbiota and may contribute to gastrointestinal and metabolic health (Gibson et al., 2017).

5.4 Omega-3 Polyunsaturated Fatty Acids

Omega-3 fatty acids, particularly EPA and DHA, have been extensively investigated for their roles in cardiovascular physiology, lipid metabolism, inflammation, and neurological function. Marine fish and fish oils are important dietary sources, while certain plant foods provide alpha-linolenic acid.

Their biological actions involve membrane structure, lipid mediators, cellular signalling, and inflammatory pathways (Calder, 2017).

5.5 Polyphenols

Polyphenols are a large group of plant-derived compounds present in fruits, vegetables, tea, coffee, cocoa, spices, legumes, and other plant foods. Major groups include flavonoids, phenolic acids, stilbenes, and lignans.

Research has investigated their antioxidant, anti-inflammatory, vascular, metabolic, and cellular signalling effects. Importantly, their biological activity cannot always be explained simply by direct antioxidant activity; metabolism, microbial transformation, and cell-signalling mechanisms also contribute (Scalbert et al., 2005).

5.6 Carotenoids

Carotenoids include β-carotene, lycopene, lutein, and zeaxanthin. They are found predominantly in fruits and vegetables and have roles in pigmentation, antioxidant biology, and, for certain carotenoids such as β-carotene, vitamin A metabolism.

Lutein and zeaxanthin have attracted particular research interest because of their accumulation in ocular tissues and potential relevance to visual health.

5.7 Phytosterols

Phytosterols are plant sterols structurally related to cholesterol. They are found in vegetable oils, nuts, seeds, cereals, and fortified foods. Their principal investigated effect is reduction of intestinal cholesterol absorption, which can contribute to lowering circulating LDL cholesterol (Plat et al., 2000).

5.8 Bioactive Peptides

Bioactive peptides can be generated during food processing, fermentation, digestion, or enzymatic hydrolysis of proteins. Certain peptides have been investigated for potential antihypertensive, antioxidant, antimicrobial, immunomodulatory, and metabolic effects (Korhonen & Pihlanto, 2006).

6. Mechanisms of Action of Nutraceuticals

The biological effects of nutraceuticals may involve multiple interacting pathways rather than a single pharmacological target. Their mechanisms may include modulation of oxidative stress, inflammation, lipid metabolism, glucose metabolism, intestinal microbiota, cellular signalling, endothelial function, and gene expression.

6.1 Antioxidant Activity

Oxidative stress occurs when reactive oxygen species production exceeds antioxidant defence mechanisms. Excess oxidative stress can contribute to cellular damage and has been implicated in several chronic diseases.

Certain food-derived compounds, including polyphenols, carotenoids, vitamin C, and vitamin E, can participate in antioxidant systems or influence endogenous antioxidant pathways (Scalbert et al., 2005).

However, the biological activity of antioxidant-rich foods cannot be reduced simply to their capacity to neutralize free radicals in laboratory experiments. **Bioavailability and metabolism are crucial determinants of their effects in humans.**

6.2 Anti-inflammatory Effects

Chronic low-grade inflammation is involved in the pathophysiology of several metabolic and cardiovascular disorders. Certain nutraceutical components have been investigated for their ability to modulate inflammatory mediators and signalling pathways (Calder, 2017).

Omega-3 fatty acids, polyphenols, and selected phytochemicals have therefore received considerable research attention.

6.3 Modulation of Lipid Metabolism

Several nutraceutical components influence lipid metabolism. Soluble fibres may reduce intestinal cholesterol absorption and influence bile acid metabolism, while phytosterols compete with cholesterol for incorporation into intestinal micelles (Plat et al., 2000).

Omega-3 fatty acids have also been extensively investigated for their effects on circulating triglycerides and lipid metabolism.

6.4 Modulation of Glucose Metabolism

Dietary fibre, polyphenols, and certain other bioactive compounds may influence glucose absorption, insulin sensitivity, hepatic metabolism, and cellular glucose utilization.

However, evidence for metabolic benefits differs substantially according to the compound, dose, formulation, duration, and characteristics of the study population.

6.5 Gut Microbiota

The intestinal microbiome has become an important link between nutrition and systemic health. Dietary fibres and prebiotic compounds can be metabolized by intestinal microorganisms, producing metabolites such as short-chain fatty acids.

These metabolites may influence intestinal barrier function, immune responses, energy metabolism, and signalling pathways (Gibson et al., 2017).

Thus, the **food–microbiota–host interaction** represents an important mechanistic pathway through which nutrition may influence health.

7. Nutraceuticals and Cardiovascular Health

Cardiovascular disease is strongly influenced by dietary patterns and lifestyle factors. Nutraceutical research has therefore focused on compounds that may influence blood pressure, lipid profiles, endothelial function, inflammation, and oxidative stress.

Phytosterols can reduce intestinal cholesterol absorption, while soluble fibre can contribute to improvements in lipid metabolism. Omega-3 fatty acids have also been studied extensively in cardiovascular nutrition (Plat et al., 2000; Calder, 2017).

Nevertheless, the presence of a biological mechanism does not necessarily establish clinical effectiveness. The distinction between **biological plausibility, surrogate-marker improvement, and reduction in clinical events** is particularly important in evaluating nutraceutical interventions.

8. Nutraceuticals and Diabetes

The increasing prevalence of type 2 diabetes has stimulated research into dietary components capable of improving glucose regulation and metabolic health.

Dietary fibre may slow carbohydrate digestion and absorption and influence satiety and gut microbiota. Certain polyphenols have also demonstrated effects on cellular signalling and glucose metabolism in experimental studies (Slavin, 2013).

However, nutraceuticals should not be considered replacements for established diabetes management. Medical treatment, dietary modification, physical activity, weight management where appropriate, and monitoring of glycaemic status remain central components of diabetes care.

9. Nutraceuticals and Gastrointestinal Health

The gastrointestinal tract represents one of the most important targets of nutraceutical research because food components directly interact with the intestinal mucosa and microbiota.

Fibre, resistant starch, prebiotics, probiotics, and fermented foods can influence gastrointestinal physiology and microbial ecology. Certain probiotics have demonstrated benefits for specific gastrointestinal conditions, but their effects are dependent on strain, dose, formulation, and clinical context (Hill et al., 2014).

The development of microbiome science has further expanded the concept of nutraceuticals from individual compounds toward **diet–microbiome interactions**. This may eventually contribute to more individualized nutritional strategies.

10. Nutraceuticals and Immune Function

Nutrition is closely connected with immune competence. Adequate intake of proteins, vitamins, minerals, essential fatty acids, and other nutrients is necessary for normal immune function.

Certain nutraceutical compounds have been investigated for immunomodulatory properties. Vitamin D, zinc, omega-3 fatty acids, probiotics, and selected phytochemicals have all been studied in relation to immune responses.

However, supplementation is most clearly justified when dietary intake is inadequate or deficiency exists. The assumption that increasing intake above physiological requirements will necessarily produce additional health benefits is not supported for all nutrients or populations.

11. Nutraceuticals and Cancer Prevention

A substantial body of research has examined associations between dietary patterns, food components, and cancer risk. Fruits, vegetables, whole grains, legumes, and other plant foods provide numerous compounds that may influence oxidative stress, inflammation, cell proliferation, apoptosis, and detoxification pathways (World Cancer Research Fund/American Institute for Cancer Research, 2018).

Compounds such as carotenoids, flavonoids, glucosinolates, and other phytochemicals have therefore received extensive experimental investigation.

However, findings from cell culture and animal experiments cannot automatically be extrapolated to human cancer prevention. Furthermore, isolated high-dose supplements may not reproduce the effects associated with whole-food dietary patterns.

12. Nutraceuticals and Women's Health

Nutraceutical research has also expanded into women's health, including reproductive health, pregnancy, menopause, bone health, and metabolic disorders.

Folate is an important example of the connection between nutrition and medicine because folic acid supplementation before and during early pregnancy has an established role in reducing the risk of neural tube defects. This illustrates an important principle: certain food-derived or nutrient-based interventions can have clearly established medical applications when supported by robust clinical evidence.

Other compounds, including phytoestrogens, omega-3 fatty acids, probiotics, calcium, vitamin D, and selected botanical compounds, have been investigated in different aspects of women's health. However, the strength of evidence varies among individual interventions and clinical outcomes.

13. Nutraceuticals and Personalized Nutrition

Advances in genomics, metabolomics, microbiome science, and nutritional epidemiology are moving nutrition toward a more individualized model.

People can differ in their responses to the same food or bioactive compound because of genetic variation, age, sex, microbiome composition, metabolic phenotype, medication use, lifestyle, and underlying disease.

This has led to increasing interest in **personalized nutrition**, in which dietary recommendations may eventually be tailored according to individual biological characteristics. Nutraceuticals could

potentially become part of such individualized approaches, although clinical validation and standardized biomarkers are still required.

14. Nutraceuticals Versus Pharmaceuticals

Nutraceuticals and pharmaceuticals may share some biological targets but differ considerably in their development, regulation, formulation, evidence base, and intended use.

Pharmaceutical drugs are generally developed around defined active substances, standardized doses, pharmacological targets, and clinical indications. Nutraceutical products may contain complex mixtures of food-derived compounds, and their composition and bioavailability can vary.

This distinction is important because **"natural" does not automatically mean safe or effective**. Dietary supplements can interact with medicines or pose risks in individuals with certain medical conditions, and products purchased commercially may differ from preparations used in research studies (National Center for Complementary and Integrative Health [NCCIH], 2025).

15. Evidence-Based Evaluation of Nutraceuticals

The rapidly expanding nutraceutical market creates an important need for rigorous scientific evaluation. Evidence should ideally progress from mechanistic studies to well-designed clinical trials and systematic reviews.

Important considerations include:

- biological plausibility;
- standardized composition;
- dose and duration;
- bioavailability;
- appropriate control groups;
- clinically meaningful outcomes;
- adverse effects;
- medication interactions;
- population characteristics;
- reproducibility of findings.

The scientific literature contains examples in which promising laboratory findings have not translated into meaningful clinical benefits. Consequently, commercial claims should not be interpreted as equivalent to clinical evidence (Aronson, 2017).

16. Safety and Toxicological Considerations

One of the major challenges in nutraceutical research is the assumption that food-derived products are inherently safe. Although many nutraceutical ingredients have long histories of dietary consumption, concentrated extracts may produce physiological exposures that differ substantially from normal food intake.

Potential concerns include excessive dosing, contamination, adulteration, variability in active compounds, hepatotoxicity, nephrotoxicity, allergic reactions, and interactions with prescription medications.

The NIH Office of Dietary Supplements provides evidence-based information on vitamins, minerals, botanicals, probiotics, and other dietary supplement ingredients, illustrating the importance of evaluating individual ingredients rather than assuming that all supplements have equivalent safety profiles (National Institutes of Health Office of Dietary Supplements [NIH ODS], 2026).

Safety assessment should therefore include both **short-term adverse effects and long-term exposure**, particularly when nutraceuticals are consumed chronically.

17. Bioavailability: A Major Challenge

The physiological effectiveness of a nutraceutical depends not only on its chemical composition but also on its absorption, metabolism, distribution, and elimination.

Many phytochemicals have relatively low bioavailability in their original forms. Food processing, cooking, fermentation, digestion, interactions with other dietary components, and intestinal microbial metabolism can substantially modify their biological availability.

Therefore, the concentration of a compound in a food cannot be used alone to predict its clinical effect. Research must consider **bioaccessibility, absorption, metabolism, tissue distribution, and biological activity**.

This is particularly important for polyphenols and other plant-derived compounds whose metabolites may be more biologically relevant than the original dietary molecules.

18. Role of Food Technology in Nutraceutical Development

Food technology has played an important role in transforming conventional foods into products with enhanced nutritional or functional characteristics.

Technological approaches include fermentation, encapsulation, microencapsulation, controlled release, fortification, extraction, enzymatic processing, and formulation with appropriate food matrices.

Such technologies can improve stability, palatability, shelf life, bioavailability, and targeted delivery of bioactive compounds.

However, processing can also alter the chemical structure and biological activity of food components. Consequently, nutraceutical product development requires collaboration between

food scientists, nutritionists, pharmacologists, toxicologists, clinicians, and regulatory scientists.

19. Nutraceuticals and Functional Foods: Distinction

Although the terms are frequently used interchangeably, functional foods and nutraceuticals are conceptually different.

A functional food is generally consumed as part of the normal diet and may provide physiological benefits beyond basic nutrition. Nutraceuticals are often discussed as concentrated or isolated food-derived substances presented in forms more closely resembling supplements or medicinal preparations (Aronson, 2017).

For example, oats consumed as part of the diet may be considered a functional food because of their fibre content, whereas a concentrated preparation containing a specific food-derived bioactive component may be marketed as a nutraceutical.

The distinction is not always consistent internationally, reinforcing the need for precise terminology.

20. Role of Nutraceuticals in Preventive Nutrition

Preventive nutrition aims to reduce disease risk through appropriate food choices, dietary patterns, physical activity, and other lifestyle behaviours.

Nutraceuticals may complement this approach when there is evidence that a specific component produces a meaningful health benefit. Nevertheless, the foundation of preventive nutrition remains a **diverse, balanced dietary pattern** rather than reliance on individual supplements.

The WHO emphasizes dietary diversity, adequate nutrient intake, moderation of unhealthy fats, sugars and sodium, and adequate consumption of fruits, vegetables, whole grains, and legumes as core components of healthy eating (WHO, 2026).

Thus, nutraceuticals should ideally be integrated into a broader nutrition strategy rather than viewed as a shortcut to health.

21. Limitations and Challenges

Despite considerable scientific interest, nutraceutical research has several limitations. First, the term itself lacks universal standardization. Second, commercially available products may differ in composition and dose from products evaluated in research studies.

Third, clinical trials frequently differ in participant characteristics, intervention dose, duration, and outcome measures, making direct comparison difficult. Fourth, evidence from in-vitro and animal studies is sometimes presented as though it demonstrates clinical effectiveness in humans.

Another concern is the potential for **commercial bias and exaggerated health claims**. Reviews of the field have highlighted the gap between mechanistic evidence, marketing claims, and clinically demonstrated benefits (Aronson, 2017; Wootton-Beard & Ryan, 2011).

Consequently, evidence-based nutraceutical science requires transparent reporting, standardized products, adequately powered clinical trials, long-term safety assessment, and clinically meaningful endpoints.

22. Future Perspectives

The future of nutraceutical science is likely to involve greater integration of nutrition, medicine, food technology, molecular biology, microbiome science, and personalized nutrition.

Emerging technologies such as metabolomics, proteomics, nutrigenomics, microbiome sequencing, artificial intelligence, and systems biology may improve understanding of how individual food components interact with biological systems.

Future nutraceutical research may therefore move away from the simplistic concept of a single compound producing a single effect and toward the investigation of **complex food matrices, dietary patterns, microbiome interactions, metabolic phenotypes, and personalized responses**.

At the same time, stronger regulatory frameworks and standardized terminology will be necessary to distinguish scientifically validated products from those supported primarily by preliminary or commercial evidence.

23. Conclusion

Nutraceuticals represent an important conceptual and scientific link between **nutrition and medicine**. They encompass a broad range of food-derived bioactive substances, including dietary fibres, probiotics, prebiotics, omega-3 fatty acids, polyphenols, carotenoids, phytosterols, peptides, vitamins, and minerals.

Their potential importance arises from their ability to interact with physiological processes involved in metabolism, oxidative stress, inflammation, lipid regulation, glucose homeostasis, gastrointestinal function, immunity, and cellular signalling. Nevertheless, the presence of a plausible biological mechanism does not by itself establish clinical efficacy.

The contemporary understanding of nutraceuticals therefore requires an **evidence-based approach**. Nutraceuticals should complement—not automatically replace—balanced diets, healthy lifestyles, and appropriate medical treatment. The strongest future direction lies in integrating rigorous clinical research with nutritional science, food technology, pharmacology, microbiome research, and personalized nutrition.

Ultimately, the link between nutrition and medicine is not simply the use of foods as medicines; it is the scientific understanding that **dietary components can influence biological processes and disease risk**, while recognizing that health outcomes depend on the whole dietary pattern, individual characteristics, dose, duration, safety, and quality of evidence.

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