*Review Article*

**Bridging Nutrition and Technology: A Comprehensive Review on Modern Food Processing System**

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**ABSTRACT**

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| Fruits and vegetables are vital for human health, environmental sustainability, and the resilience of food systems. While their benefits, such as high concentrations of vitamins, minerals, fiber, and bioactive compounds, are well-known, global consumption remains below recommended levels. Addressing this gap requires a comprehensive approach that considers food production systems, processing innovations, dietary habits, and environmental factors. Modern challenges like post-harvest losses, affordability, perishability, and inadequate infrastructure hinder the optimal use of fruits and vegetables. To overcome these challenges, innovative and sustainable food processing technologies are needed. High Hydrostatic Pressure and Pulsed Electric Fields are two such technologies that can preserve nutritional and sensory qualities while ensuring food safety and extending shelf life. Additionally, the valorization of food byproducts for applications in edible and biodegradable packaging promotes a circular economy and reduces environmental burden.  Alternative proteins from plant, marine, and microbial sources can also help meet growing nutritional demands while minimizing ecological impact. Integrated strategies, including consumer education, supportive policies, and the development of affordable and accessible nutrient-dense foods, are crucial. By advancing innovative food technologies and embracing holistic, sustainable practices, the global food system can be transformed to ensure nutrition security, reduce waste, and align with the United Nations Sustainable Development Goals. This requires a multidisciplinary perspective on rethinking the role of fruits and vegetables in building a health-oriented and environmentally responsible food future. |

*Keywords: Food processing, Edible packing, Alternative Protein, Pulsed Electric Fields, Health mitigation*

**1. INTRODUCTION**

Fruits and vegetables are essential components of a balanced diet, yet achieving sustainable and nutritious diets remains a global challenge. While current food production systems overproduce high-calorie, energy-dense foods, they fall short in providing adequate quantities of fruits and vegetables. Although there is sufficient global calorie availability, aligning this with balanced and sustainable dietary needs proves difficult. (Liu et al., 2022). The EAT-Lancet diet, often cited as a model for both health and environmental sustainability, tends to be more expensive than basic nutritional diets, making it unaffordable for many low-income populations. Promoting healthier eating patterns requires making nutritious foods both accessible and affordable. (Sharma et al., 2020).

Increasing the consumption of fruits and vegetables, along with a shift toward plant-based proteins, can help meet nutritional requirements, improve land-use efficiency, lower greenhouse gas emissions, and support biodiversity conservation. These dietary shifts play a critical role in advancing the United Nations Sustainable Development Goals (SDGs) ( <https://sdgs.un.org/goals> ).

The World Health Organization recommends consuming at least 400 grams of fruits and vegetables daily. The United Nations General Assembly declared 2021 as the International Year of Fruits and Vegetables to promote innovation and recognize the need for sustainable production and waste reduction. Despite rising consumer demand for nutritious, high-quality produce due to increased health awareness, most people still do not meet WHO’s dietary guidelines (Hoffmann et al., 2003). Several factors influence global fruit and vegetable consumption. These include agricultural conditions (climate, seasonality, greenhouse availability), economic factors shaped by local policies (affordability, food processing, transport, and storage infrastructure), and socio-cultural influences (dietary traditions, education, available food alternatives). Additionally, significant waste occurs during cultivation, storage, and processing, and its high moisture and organic content can lead to environmental pollution. Therefore, sustainable and precise processing techniques are crucial for improving the efficiency and environmental sustainability of the fruit and vegetable industry. Food processing has ancient roots, dating back millions of years. Fire played a pivotal role, with roasting meat emerging around 1.8 million years ago. Over time, methods expanded to include cooking, preservation, pickling, fermenting, freezing, and drying, eventually leading to advanced techniques like 3D printing (Caron et al., 2018).

Processing transforms raw materials into safe, nutritious, and edible products, while also supporting preservation and bioconversion. Growing consumer demand for fresh, sustainable foods has spurred research into cleaner, non-thermal technologies, including high hydrostatic pressure, cold atmospheric plasma, and pulsed electric fields (Olaniyi et al., 2024). Unlike traditional methods that can degrade nutrients, emerging thermal techniques like superheated steam, ohmic heating, and microwave-assisted processes help to better retain them. Advancements in non-thermal processing have enhanced food safety and quality, establishing it as a well-recognized and widely adopted practice.

To address the challenges of excessive petrochemical plastic use in food packaging, exploring alternatives like biowaste-based materials is crucial. While recycling is a solution, its effectiveness is limited by technical and economic factors; globally, a small percentage of plastic waste is actually recycled (Jain et al., 2024). The persistence of plastics in ecosystems and their harm to flora and fauna necessitate a shift to renewable, non-food-based options. Plastics' presence in various organisms highlights their widespread environmental threat.

Future food packaging should prioritize edible or biodegradable materials. Edible packaging, made from food-grade compounds, should possess bioactive properties like antimicrobial and antioxidant effects. These materials must also meet functional requirements, including acting as barriers against moisture, gases, and UV light, while maintaining mechanical strength and suitable opacity. Edible packaging might serve as primary packaging, complemented by non-edible secondary packaging for handling and hygiene (Fellows, 2022). For enhanced sustainability, bio-based and biodegradable plastics are preferable for secondary packaging. Large-scale commercialization of sustainable packaging faces challenges due to established systems for petrochemical-based plastics. Eliminating conventional packaging entirely is still in early stages, and further sustainability assessments are needed to ensure the safety and benefits of "greener" materials, avoiding unintended long-term consequences (Versino et al., 2023). It is important to consider that bioplastics may create unintended sustainability consequences such as environmental and social issues related to land use change during feedstock production, complicating waste management of other plastics. With the global population projected to reach 9.8 billion by 2050, the demand for both macro and micronutrients is expected to increase significantly (Oluwole et al., 2023). Ensuring an adequate protein supply is a major concern, especially since many technologically functional proteins come from animal sources. Proteins are crucial for food structure, functionality, and metabolic processes like growth and cellular repair. However, animal-based protein production is resource-intensive and has a considerable environmental impact.

Research increasingly links diet, health, and environmental sustainability, highlighting the urgent need to transform the global food system. To promote sustainable and nutritious diets, alternative protein sources must be explored. Current food science and technology research focuses on identifying novel protein sources, improving extraction techniques, and modifying functional properties like solubility and emulsification. Key areas of investigation also include enhancing organoleptic qualities (taste, texture, and appearance) and developing advanced processing and texturization methods (Rashwan et al., 2025). As the climate warms, land used for growing energy-intensive crops is becoming less productive, thus alternative proteins may be a solution to feed the earth's growing population in a sustainable way.

**2. CONTEMPORARY APPROACHES TO FOOD PROCESSING AND CULINARY TECHNIQUES**

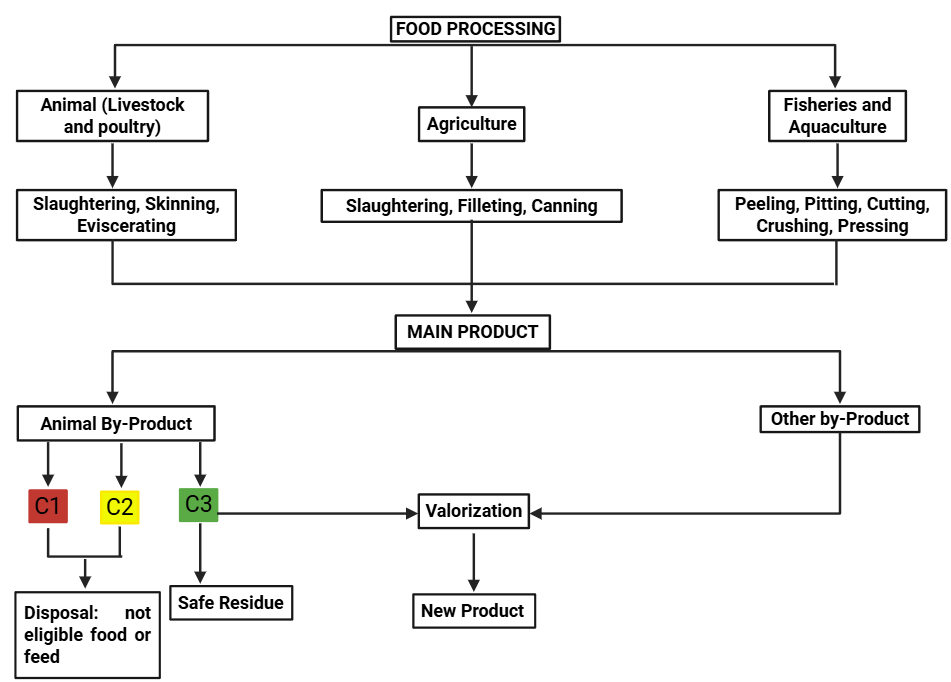
Food processing is essential for converting agricultural produce into consumable food products. At the industrial level, various unit operations transform raw materials into food ingredients and finished goods, enhancing their shelf-life stability for distribution within the food value chain. These operations involve deliberate alterations in food between its origin and consumption. Many traditional unit operations, like washing, chopping, heating, chilling, freezing, fermenting, baking, and cooking, have been used in industrial processing and home cooking for meal preparation. In both large-scale food manufacturing and home cooking, ingredients are added to improve flavor or aid processing (Oluwole et al., 2023). A wide range of conventional industrial food processing techniques exist, each using specific energy inputs to transform raw materials into consumable products. Newer technologies like high-pressure processing, microwave heating, and ultrasound are also being explored as innovative alternatives to traditional methods. The processes of converting raw ingredients into consumable meals are comparable whether in domestic kitchens or industrial food processing. Comparing how industries transform agricultural products into safe, edible food with methods used in homes and restaurants offers valuable insights. Many culinary techniques used in households and food service establishments are designed to improve taste and broaden the range of acceptable food options. These methods have been refined over generations in culinary environments.

In food processing, carefully regulating inputs like heat and mass transfer is essential for maintaining efficiency and uniformity. While home cooks can manage these elements, industrial processing enables superior precision and optimization, which leads to more consistent outcomes (Fellows, 2022).

Over time, renowned chefs have expanded the culinary landscape by integrating innovative methods and unique ingredients. This includes the use of specialized equipment such as controlled-temperature water baths, liquid ice, ohmic heating, and techniques like sous vide cooking or vacuum cooking with the Gastrovac® in an oxygen-free environment. Additionally, chefs are incorporating additives like hydrocolloids and enzymes such as transglutaminase to create distinctive textures ((Caron et al., 2018). These advancements in culinary techniques have been made possible by adopting industrial food processing methods that were once uncommon in traditional cooking. Such innovations enhance food safety, extend shelf life, and preserve sensory qualities with minimal alterations.

**2.1 Food byproduct:**

It's great to see the growing interest in utilizing food processing byproducts for active edible packaging. This approach aligns with the increasing focus on sustainability and circular economy principles within the food industry (Schieber, 2017) This review's focus on marine, agricultural, and animal sources is a good way to categorize these byproducts fig. 1. Many studies have explored the ability of biopolymer-based food packaging materials to carry and control-release active compounds. Also, the implementation of green active packaging can significantly reduce the risk of foodborne pathogen outbreaks, improve food safety and quality, and minimize product losses, while reducing waste and maintaining sustainability. (Aspevik et al., 2017).

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**Fig. 1. By-products formed during food processing (Hamed et al., 2023)**

**2.1.1 Marine processing byproducts**

*2.1.1.1 Residual materials from fish and shellfish:*

Seafood byproducts, created throughout the entire supply chain, differ in quantity depending on the species and processing methods involved (Ghosh, 2016). Shellfish, such as crustaceans and mollusks, can generate byproducts comprising up to 80% (Suresh et al., 2018) of their mass, primarily from heads and shells. Finfish byproducts typically range from 25% to 50% (Rustad et al., 2011). Tuna canning, for example, can lead to as much as 70% waste, including meat, belly flaps, heads, and skin. In Norway, the utilization of byproducts from aquaculture and wild-caught pelagic fish is impressively high, reaching 91% and 100%, respectively. However, the utilization rate for white fish byproducts is considerably lower, at only 44% (Hjellnes et al., 2020). To maximize the benefits derived from these byproducts, it is best to maintain food-grade quality for potential human consumption. Non-edible byproducts can be transformed into high-value products like protein powders, oils, and pharmaceuticals. Successfully implementing these strategies could significantly increase food production from aquaculture by as much as 61% and boost revenue from byproducts by up to 800%.

*2.1.1.2 Residual materials from algae:*

The worldwide seaweed industry, with an annual valuation of US$ 5.5–6 billion, is growing. Most of the market caters to human consumption, with the remainder supporting applications in supplements, fertilizers, and cosmetics (Tedesco and Stokes, 2017). Seaweed is a source of proteins, lipids, polysaccharides, minerals, and bioactive compounds like pigments and polyphenols. Polysaccharides like alginates, carrageenans, and agar are used extensively across various industries. However, seaweed waste often accumulates on beaches, causing environmental issues. Effective management of these byproducts presents both economic and environmental opportunities (Ganesan et al., 2018).

Cyanobacteria and microalgae are cultivated for bioproducts used in food, nutraceuticals, and aquaculture feed. A sustainable biorefinery model, which utilizes remaining biomass for high-value compounds, is crucial for economic viability. These organisms also hold promise for active packaging due to their storage of biopolymers like lipids and proteins. Microalgae-based edible films are being created by combining them with other biopolymers, using compounds like protein concentrates from *Spirulina* and *Chlorella* species (Lourenço-Lopes et al., 2020). Fruit and vegetable byproducts, constituting 20%–40% of processed materials, also show promise for edible packaging. Waste from grape, wine, and canned fruit processing contains valuable compounds such as antioxidants and dietary fibers, making them suitable for enhancing the properties of food packaging.

**2.1.2 Agricultural processing byproducts**

*2.1.2.1 Residual materials from vegetable and fruits*

Processing fruits and vegetables for beverages, ready-to-eat products, and other food items leads to considerable waste in the form of peels, seeds, pulps, and pomaces (Bas-Bellver et al., 2020). These byproducts, which account for 20%–40% of the processed materials, are abundant in bioactive compounds, including polysaccharides, proteins, and antioxidants. For example, grape and wine production generates approximately 59 million metric tons of solid waste each year, while fruit and vegetable canning and freezing contribute around 6 MMT (Sagar et al., 2018). Interestingly, discarded components like citrus peels and mango seeds often have higher concentrations of beneficial compounds compared to the pulp.

Repurposing these residues for edible films and coatings can lower costs and improve food packaging. Their natural fibers, polyphenols, and essential oils offer antimicrobial and antioxidant qualities, enhancing packaging performance and supporting sustainability.

**2.1.3 Animal processing byproducts**

*2.1.3.1 Residual materials from the meat industry*

The slaughtering process yields both edible (e.g., liver, heart, kidney, tripe) and non-edible (e.g., skin, bones, blood, feathers, hooves) byproducts. Utilizing these byproducts can significantly enhance the profitability of the meat industry, contributing 11.4% and 7.5% to beef and pork revenue, respectively (Toldrá et al., 2016).

Edible byproducts, which are rich in proteins, minerals, and vitamins, have the potential to help address malnutrition. Non-edible residues support industries such as leather and textiles. Gelatin, a substance derived from collagen found in animal skin, bones, and hooves, is widely used as a gelling and stabilizing agent in the food industry. While gelatin is primarily sourced from pigs and cattle, alternative sources like fish and poultry are also available. Gelatin is also used in edible packaging (Santana et al., 2020). Combining it with other biopolymers can improve its functionality and extend the shelf life of food products, follow table 1 for better understanding.

*2.1.3.2 Residual materials from the dairy industry*

The dairy industry transforms raw milk into a variety of products, including cheese, yogurt, butter, and ghee, resulting in byproducts like whey and buttermilk, both of which possess considerable nutritional value (Rafiq and Rafiq, 2019). Caseins and whey are the main protein waste products from dairy processing. Caseins constitute approximately 80% of the protein content in bovine milk (Ryder et al., 2017). Whey, a byproduct of milk curdling, is rich in proteins, vitamins, and lactose. The cheese industry is the largest producer of whey, generating about 8–9 liters per kilogram of cheese, which amounts to an annual total of 180–190 million tons (Mazorra-Manzano et al., 2020). Although nearly 50% of this whey is processed into whey powder, protein concentrates, and isolates for use in the food and pharmaceutical industries, substantial quantities remain untreated. Milk proteins are well-suited for biomaterials because of their excellent barrier and film-forming properties follow table 1 for better understanding.

**Table 1. Biobased materials derived from food industry byproducts that can be utilized in inactive edible packaging (Hamed et al., 2022)**

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| --- | --- | --- | --- | --- |
| **Food Byproduct** | **Origin** | **Discarded Parts** | **Bioactive Compounds** | **Biopolymers** |
| Agricultural | Cereals | Corn cobs, brans, brewers, spent grain, and husks | Polyphenols, vitamins, minerals, and phytosterols | Starch, cellulose, lignin, and hemicellulose |
| Agricultural | Vegetables and Fruits | Grape skins, stones/pits, seeds, peels, pulps, bagasses, and pomaces | Essential oils, dietary fibers, pigments, and polyphenols (such as anthocyanins) | Pectin, proteins, starch, and cellulose |
| Animal | Dairy | Liquid resulting from the curdling of milk | Lactose and water-soluble vitamins | Casein and whey |
| Animal | Meat | Feathers, heart, meat trimmings, bones, skin, fatty tissues, hoofs, tongue, liver, skull, kidney, lung, tripe, horns, feet, blood | Vitamins and polyunsaturated fatty acids (PUFA) | Gelatin and structural collagens |
| Marine | Algae | Leftover biomass post-compound extraction or naturally accumulated biomass along coastal areas | Proteins and peptides, omega-3 (primarily EPA and DHA), polyphenols, pigments (such as β-carotene, astaxanthin, and fucoxanthin), polysaccharides (including xylans, fucoidans, laminarin, floridean starch, and ulvans), along with essential vitamins and minerals | Alginate, agar, and carrageenans |
| Marine | Fish | Fish head, processing remnants (including skin, fins, bones, scales, and muscle), and internal organs such as liver, kidney, and roe | Peptides, protein hydrolysates, omega-3 fatty acids (mainly EPA and DHA), iodine, vitamin D, selenium, phosphorus, and calcium | Gelatin, collagen, and myofibrillar proteins |
| Marine | Crustaceans | Shells | Calcium carbonate and astaxanthin | Natural biopolymer chitin |

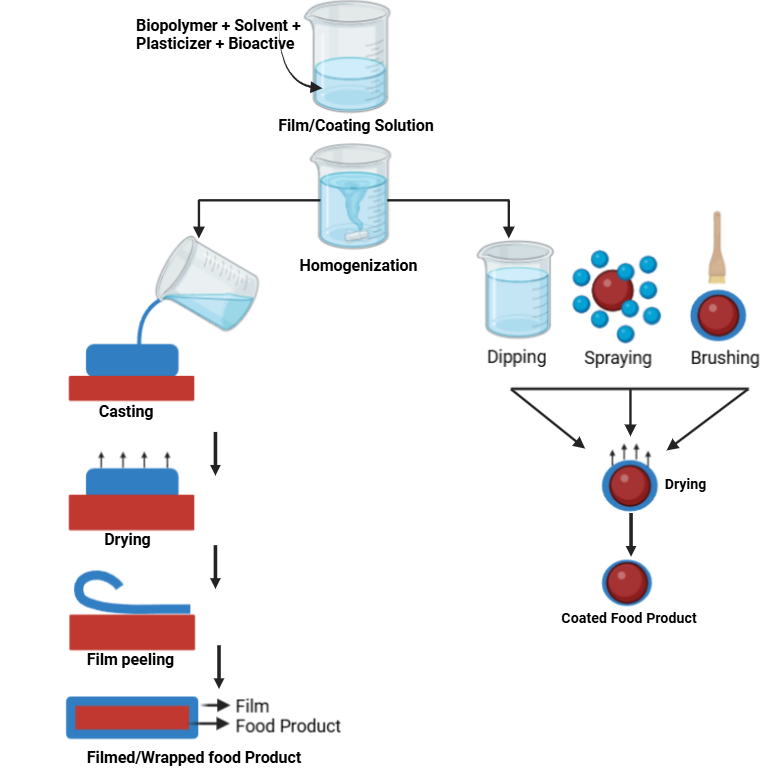
**Edible Packaging**

You're right about the differences between edible films and coatings and their applications. Your distinctions regarding their forms (preformed sheets versus liquid applications), thickness (50-250 μm for films), application methods (wrapping, layering, or pouches versus spraying, dipping, or brushing) as shown in fig. 2, and purposes (moisture and gas barriers, protection, and shelf-life extension) are all accurate. (Pinto et al., 2022) explains the difference in application techniques, noting coatings are applied directly while films are separate. (Avramescu et al., 2020) reiterates this distinction, highlighting films as prefabricated and coatings as liquid-based. You also correctly mention the use of bioactive compounds like vitamins and polyphenols for added benefits, and the environmentally friendly nature of edible packaging due to its renewable sourcing and potential for consumption with the product. (Dubey & Dubey 2020) discusses the use of edible films to encapsulate these bioactive compounds, while several sources such as (Dubey & Dubey 2020) mention their application to various food products like seafood, fruits, and vegetables to extend shelf life.

Finally, the point about biodegradability versus edibility and the need for FDA-approved components is crucial. (Chen et al., 2019) emphasizes the safety aspect of edible films made from food sources.

That's a great summary of the components and sources of edible packaging! You're right to point out the importance of a biopolymer matrix (polysaccharides, proteins, and lipids) and a solvent like water as the base (Choudhary et al., 2021). The use of additives to enhance properties is also crucial, and you've correctly identified plasticizers, antioxidants, and bioactive compounds as examples. The point about food processing byproducts is particularly relevant. Several sources highlight the potential of these byproducts. For instance, crustacean shells (chitin), seaweeds (alginates and carrageenan), whey protein, and corn zein are all valuable film-forming components. As mentioned in (Uranga et al., 2021), by-products from the lobster industry and fisheries are rich in biopolymers like collagen, gelatin, chitin, and chitosan. These can be extracted from fish skin, bones, scales, and tendons, or from crustacean and mollusk shells.

This approach aligns with sustainability efforts by valorizing waste streams (Dilucia et al., 2020). Edible packaging is built upon a biopolymer matrix, typically using water as a solvent, to provide structure. Polysaccharides, proteins, and lipids from natural sources form these biopolymers. Additives then boost mechanical strength, flexibility, shelf life, and sensory appeal. Plasticizers, for instance, enhance flexibility, while active compounds like antioxidants, antimicrobials, and prebiotics improve quality, preservation, and offer health benefits (Guimaraes et al., 2018). Food processing byproducts are excellent sources of film-forming materials. Chitin from crustacean shells, seaweed-derived polysaccharides like alginate, carrageenan, and agar, whey protein from cheese production, corn zein from ethanol processing, and collagen or gelatin from animal skins are all valuable. Additionally, functional ingredients like anthocyanin-rich grape skins from wine production, and various fruit and vegetable peels and pomaces, can be utilized. Using food by-products aligns with the concept of a circular economy and can reduce the environmental impact of food production.



**Fig. 2. Procedure for Formulating Active Edible Coatings and Films (Pinto et al., 2022)**

* 1. **Alternative Protein**

The definition of "alternative proteins" can shift depending on the region. While a broad definition might include insects and other non-animal sources, a more specific definition focuses on proteins from sources with low environmental impact or ethical animal husbandry practices. Your review's focus on land plants, algae, fungi, and insects is valid given their potential for a smaller ecological footprint (Tolnay et al., 2020). Here's a slightly revised version of your statement:

The interpretation of "alternative proteins" is region-specific. In areas like Sub-Saharan Africa, where plant-based proteins are common, the term carries a different meaning compared to Europe. A more precise definition excludes sources like insects, focusing instead on proteins derived from methods with a reduced environmental impact or ethical animal husbandry. This review examines sustainable protein sources, including land plants, algae, fungi, and insects, recognized for their potential to minimize environmental impact (de Souza Celente et al., 2023). Cultured meat is excluded due to its developmental stage and ongoing debates about its environmental benefits. However, future technological advancements may establish it as a viable alternative.

Here are some additional points that you may find helpful:

* **Mycoprotein**: Mycoprotein, a type of fungal protein, is an alternative protein source (Ahmad et al., 2022).
* **Solein**: Solein is a protein that can be used in a variety of foods.
* **Insects:** Insects are a promising alternative protein source.

**Protein Content Variation:** It is right to highlight the range in protein content among alternative sources. While legumes and insects are protein-rich, others like potatoes have lower concentrations. It's important to consider the overall yield based on raw material availability.

**Sidestream Valorization:** The utilization of sidestreams from starch or oil production (e.g., potatoes, soybeans) is a key aspect of sustainable protein production. This approach reduces waste and creates value-added products.

**Structural Differences:** The distinction between globular storage proteins in plants/algae and striated muscle tissue in insects is important for understanding their functional properties.

**Processing Considerations:** Processing steps like chitin removal are crucial for improving the usability of some alternative protein sources.

**Plant Protein Classification:** There is a mention of Osborne's classification based on solubility (albumins, globulins, prolamins, glutelins) is a standard way to categorize plant proteins.

Here are some additional points:

* **Duckweed**: Duckweed is a promising plant-based protein source, with rapid growth and high protein content.
* **Mycoprotein**: Mycoprotein is a fungal protein source with a fibrous texture.
* **Insects**: The need for novel and diverse sources of protein to feed the growing world population is urgent. Insect protein has been researched intensively in recent years and may fulfill these needs.

Plant-based proteins exhibit diverse solubility characteristics based on their source. For instance, wheat, maize, and rice are characterized by a high content of water-insoluble prolamins and glutelins. In contrast, oats, quinoa, and amaranth are richer in water-soluble albumins and globulins (Sim et al., 2021). Legumes and pulses primarily store proteins as globulins and albumins, with globulins often making up more than 50% of the total protein content. However, the specific composition varies depending on the species and growing conditions. Some legumes also contain 2S albumins, which contribute to their cysteine content. It's worth noting that certain albumins can act as antinutritional factors, such as enzyme inhibitors and lectins (Lam et al., 2018).

Oilseed proteins, such as those found in rapeseed and sunflower, are mainly composed of 11S globulins, followed by albumins. The protein composition of pumpkin seeds can vary depending on the species. For example, *Cucurbita maxima* is rich in albumins, while other species may have significant glutelin fractions. (Pham et al., 2017). Potatoes predominantly contain patatin, which is an 88-kDa glycoprotein dimer. They also contain various protease inhibitors that range in size from 5 to 25 kDa.

Insect proteins are classified into sarcoplasmic (water-soluble), myofibrillar (salt-soluble), and connective tissue proteins (soluble in acid or alkaline solutions, or insoluble). These protein types correspond to albumins, globulins, and glutelins, respectively, with myofibrillar and connective tissue proteins being the most abundant.

**2.2.1 Protein Extraction and Fractionation:**

Protein extraction from cells is a complex process involving multiple steps, from initial disruption of the cell structure to final purification and concentration of the target protein as show fig. 3. The specific methods employed at each stage must be tailored to the source material, whether it be plant, animal, microbial, or insect-based, to maximize yield while preserving protein functionality. (Tamayo et al., 2018)

*2.2.1.1 Tissue Disruption*

The initial step, tissue disruption, aims to break open cells and make intracellular proteins accessible. Mechanical methods like pressing, chopping, milling, blending, or high-pressure homogenization can be used. Chemical and enzymatic treatments, such as acid or alkaline hydrolysis, enzymatic digestion, and exposure to microwaves or pulsed electric fields, can also assist in cell breakdown. However, optimization is crucial as harsh conditions can denature proteins and compromise their functionality. Electroporation, as explored in studies on *E. coli*, offers another approach for protein extraction (Grossmann and Weiss 2021).

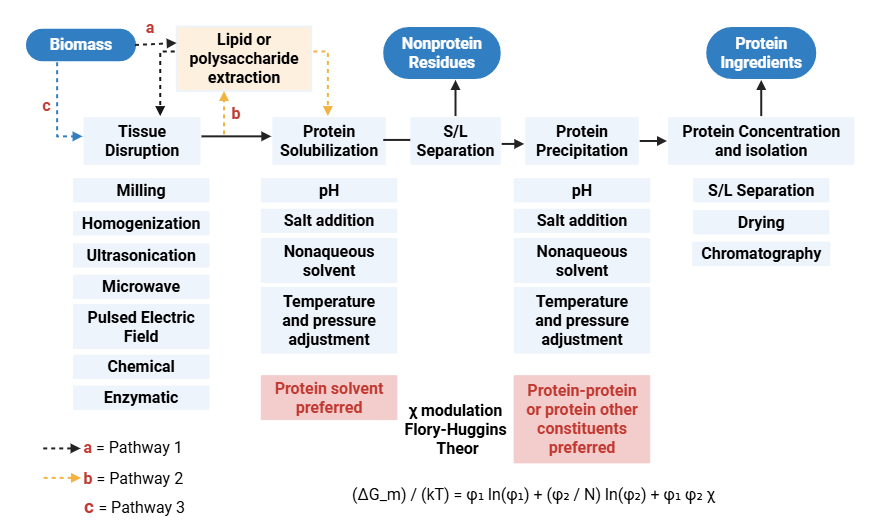
*2.2.1.2 Solubilization*

Following cell disruption, solubilization is crucial to dissolve proteins. Factors such as pH, ionic strength, temperature, and pressure are adjusted to optimize protein-solvent interactions. Techniques such as solvent, physical, enzymatic, and acid hydrolysis are employed, with the latter two potentially breaking down long-chain proteins into valuable short-chain peptides and amino acids (Emami et al., 2018).

*2.2.1.3 Precipitation and Concentration*

Protein precipitation separates proteins from other soluble components by altering the solubilization conditions to induce aggregation. Subsequent concentration and purification steps involve techniques like filtration, centrifugation, sedimentation, vacuum evaporation, spray drying, freeze drying, or vacuum drying. Chromatographic methods provide high purity but are typically reserved for specialty proteins due to cost. Aqueous two-phase extraction offers an efficient separation method, especially for nucleic acids from proteins.

Optimizing the extraction cascade for specific source materials is essential to balance protein yield and functionality. Innovative approaches like dry fractionation combined with electroseparation offer resource-efficient alternatives. Continued research into the relationships between processing methods, protein structure, and function will drive advancements in protein extraction and facilitate novel food applications (Cornet et al., 2022).



**Fig. 3. Protein Extraction Cascade Overview: Protein extraction typically involves tissue disruption, solid–liquid separation, protein solubilization (explained by Flory-Huggins theory), precipitation, and concentration. The solubilization step considers factors like Gibbs free energy of mixing (Gm), Boltzmann constant (k), temperature (T), volume fractions (φi), chain segment number (N), and interaction parameter (χ) (Tamayo et al., 2018).**

**2.2.2 Consumer Trends and Environmental Impact:**

The alternative protein market is indeed experiencing growth, as highlighted by successful IPOs and increasing sales (Swann and Kelly, 2023). The $2.2 billion in plant-based food sales in 2018, while significant, underscores the considerable difference compared to the global meat market's $1.7 trillion valuation. This gap is expected to narrow as interest in alternative proteins continues to rise.

It's interesting that consumer interest isn't solely driven by sustainability concerns (Tso et al., 2020). Studies show that only a minority of consumers in various countries recognize the environmental impact of meat consumption. (Sanchez-Sabate and Sabaté, 2019). This limited awareness contributes to reluctance in changing dietary habits. Highlighting the environmental consequences can increase willingness to shift towards alternative proteins. Additional motivators include concerns about animal welfare, health issues, and the link between high animal protein intake and noncommunicable diseases. (Khara, 2023). Familiarity and repeated exposure play a vital role in consumer acceptance as individuals adapt to the taste and texture of alternative proteins (Accelerating Consumer Adoption of Plant-Based Meat: An Evidence-Based Guide for Effective Practice, 2023). Supermarkets can influence this transition through product availability and marketing strategies. The trend towards meat reduction or flexitarian diets is also worth noting (Sanchez-Sabate and Sabaté, 2019)

Current review focuses on understanding consumer motivations for reducing meat consumption and embracing alternative proteins, especially with the emergence of products with improved sensory qualities (Amato et al., 2023). However, there's a need for more large-scale population studies, particularly in developing countries where meat consumption is projected to increase the most (Eckl et al., 2021).

* 1. **High Hydrostatic Pressure processing: a non-thermal food preservation technology**

High Hydrostatic Pressure processing is a non-thermal preservation technique that extends shelf life, ensures safety, and maintains the quality of food products. Unlike traditional thermal methods, HHP offers several advantages, making it a valuable tool in the food industry.

HHP involves subjecting packaged food to high pressures (100-1000 MPa) within a specialized vessel. This process inactivates harmful microorganisms and enzymes, while preserving key nutrients, flavor, texture, and appearance (Torres Bello et al., 2014). HHP's minimal impact on sensory and nutritional qualities aligns with growing consumer demand for fresh-like products (Ghafoor et al., 2020). The isostatic nature of pressure application ensures uniform treatment regardless of food size or geometry, a distinct advantage over other processing methods. Furthermore, the enclosed system prevents post-pasteurization contamination (Sukmanov et al., 2019).

HHP primarily affects non-covalent bonds, leaving covalent bonds and thus, the basic molecular structure, largely intact (Wang et al., 2022). This explains its ability to denature proteins and modify carbohydrates without significant nutrient loss (Liu et al., 2022). While causing some temperature increase (approximately 3°C per 100 MPa), the overall process temperature remains relatively low, especially when starting with chilled products. This characteristic makes HHP ideal for heat-sensitive foods (Lawrence and Jung, 2020). The pressure-induced changes can enhance the functionalities of certain food components, offering opportunities for product innovation.

HHP effectively eliminates bacteria (excluding spores), extends shelf life, and enhances market value (Sukmanov et al., 2019). Different pressure levels are applied depending on the target microorganism; for instance, bacteria, fungi, and yeasts may require up to 600 MPa for inactivation. HHP finds application in various food categories, including fresh produce, meat, seafood, juices, dairy, and ready-to-eat meals. The technology's use in creating value-added and texture-modified meat products is also gaining traction (Chen and Makhatadze 2017).

Despite its benefits, high installation costs remain a barrier to wider adoption. Consequently, HHP is primarily utilized for high-value products where premium quality and extended shelf life are paramount. Growing consumer interest in minimally processed, nutritious foods is further driving the expansion of HHP applications in the food industry. (Lawrence and Jung, 2020)

**2.3.1 High-Pressure Processing of Fruits and Vegetables: Implications for Nutrition and Health**

HHP technology effectively preserves the overall quality of fruits and vegetables, including color, texture, flavor, nutritional content, and shelf life. This aligns with increased consumer demand for minimally processed, fresh-like products (Huang et al., 2020). HHP's ability to maintain these qualities stems from its minimal impact on covalent bonds in small molecules associated with flavor and color (Oey et al., 2016).

While HHP offers significant advantages, post-treatment storage conditions can still influence quality due to residual enzyme activity or microbial growth, leading to oxidation and biochemical changes. However, compared to traditional thermal pasteurization, HHP demonstrates superior retention of total phenolic content and antioxidant activity (Salazar-Orbea et al., 2021). These compounds play a crucial role in combating oxidative stress and reducing the risk of associated health issues. Some research even suggests that high pressure can enhance the extraction of polyphenols and color pigments (Viacava et al., 2021) further boosting the nutritional value of treated produce.

*2.3.1.1 Fruits and Their Derivatives*

HHP's application extends to a wide variety of fruits and their derivatives. In red-fruit products like strawberry mousses and pomegranate juice, HHP effectively preserves polyphenols and anthocyanins, albeit with a slight reduction in anthocyanin content post-processing. In citrus juices, HHP reduces microbial counts while maintaining other quality parameters. Studies have shown increased carotenoid and vitamin A levels after HHP treatment without affecting antioxidant capacity. However, it's important to note that vitamin C degradation can occur during storage (Zhao et al., 2013)

HHP also benefits processed fruit products like mango pulp, improving consistency and preserving color and bioactives. Similar positive effects, such as increased antioxidant and phenolic content, have been observed in tomato puree and grape by-products. Berries, including blackberries and strawberries, exhibit higher anthocyanin retention and antioxidant activity when treated with HHP compared to thermal processing (Jung et al., 2013). Moreover, HHP has demonstrated improved retention of bioactive compounds, enzyme inactivation, and enhanced shelf life in various other fruits, including apples, peaches, cashews, pineapples, blueberries, papayas, and prickly pears. These findings highlight HHP's potential as a versatile preservation technique for maintaining the quality and nutritional value of a diverse range of fruit products (Kurek et al., 2022).

*2.3.1.2 Vegetables and Their Derivatives*

HHP technology has demonstrated promising results in preserving the quality and nutritional value of various vegetables. Studies have shown that carrot and cucumber juices retain high antioxidant content, vitamin C, and desirable textural properties after HHP treatment. Similarly, spinach and carrots exhibit improved retention of phenolics and enhanced enzyme inactivation compared to traditional heat treatments.

Beyond juices, HHP positively impacts the characteristics of whole vegetables. Cabbage, pumpkin, and zucchini show enhancements in pectin structure, color, and phytochemical content following HHP processing (Denoya et al., 2022). Furthermore, HHP has been shown to aid in pectin extraction from sugar beet pulp when combined with acid, while sweet potato protein hydrolysates demonstrate increased antioxidant activity after treatment.

The benefits of HHP also extend to processed vegetable products. Black garlic, for example, exhibits enhanced thermal stability and improved chemical composition after HHP treatment. Cauliflower processed with HHP maintains its nutritional value and experiences low microbial counts for extended periods. Finally, red pepper paste shows improved microbial inactivation and increased antioxidant content post-HHP processing (Daher et al., 2017). These diverse applications highlight the potential of HHP as a valuable tool for preserving and enhancing the quality and nutritional profile of a wide range of vegetable products.

*2.3.1.3 Dairy Products*

HHP technology offers several advantages in dairy processing, enhancing flavor, texture, and shelf life without compromising nutritional value (Diez-Sánchez et al., 2020). For example, milk treated with HHP retains higher levels of amino acids and experiences a significant reduction in microbial load compared to traditional thermal methods. This is because HHP disrupts weaker chemical bonds while leaving essential molecules like sugars and vitamins largely unaffected.

HHP finds diverse applications in dairy, including the production of yogurt, cheese, and probiotic dairy products (Pérez Alcalá et al., 2023). It also enhances whey protein recovery, improves enzyme activity for coagulation, and extends shelf life. Furthermore, HHP helps reduce the formation of biogenic amines and preserves the functionality of bioactive proteins.

*2.3.1.4 Meat and Meat Products*

HHP presents a highly efficient non-thermal alternative for meat preservation. It extends shelf life while enhancing key sensory attributes such as color, texture, and juiciness (Liu et al., 2021). Effective across a wide range of pressures and temperatures, HHP improves water-holding capacity, reduces microbial growth, and preserves essential nutrients in meat. Its commercial applications encompass a variety of meat products, including beef, pork, ham, sausages, and chicken, contributing to enhanced quality and safety.

*2.3.1.5 Fish and Seafood*

Due to their highly perishable nature, fish and seafood benefit significantly from HHP treatment. This technology effectively inhibits microbial growth, extending shelf life without compromising product quality. Compared to traditional methods like freezing, HHP better preserves the taste, nutritional value, and appearance of fish and seafood.

HHP also eliminates harmful pathogens and improves the safety of seafood (Patel and Patel, 2023). While it can alter texture and moisture content to some extent, optimizing HHP conditions ensures consistent product quality. Products such as shrimp, squid, salmon, oysters, and fish fillets have demonstrated quality retention and improved microbial safety through HHP processing (Romulo, 2021) meeting consumer demand for minimally processed, clean-label products.

**2.3.2 Next-Gen Applications of High-Pressure Processing in the Food Sector**

High Hydrostatic Pressure processing is rapidly emerging as a key technology in the food industry, offering a unique way to enhance food safety, quality, and shelf life without relying on heat or chemical preservatives. A major area of expansion for HHP is in the production of clean-label foods, which retain their natural sensory and nutritional qualities while eliminating artificial additives and excessive processing. As consumer demand for minimally processed, preservative-free foods continues to rise, HHP offers an innovative solution for natural preservation and improved product quality.

Ongoing advancements in HHP technology focus on improved energy efficiency, reduced processing costs, and expanded applicability to a wider range of food products, aligning with broader sustainability goals. As the technology becomes more cost-effective and scalable, it will become increasingly accessible to small and medium-sized food producers, further integrating HHP into mainstream food processing. Continued research into optimizing pressure parameters for specific food types will enhance the adaptability of HHP, enabling customized processing techniques tailored to the unique characteristics of different products.

* 1. **Pulsed Electric Fields:**

Pulsed Electric Field treatment is gaining traction as an environmentally conscious alternative to traditional thermal food processing, aligning with sustainability goals due to its reduced energy and water consumption. Inefficiencies in conventional food production, such as food losses and quality degradation, can be mitigated by adopting advanced technologies like PEF and optimizing existing methods. PEF contributes to sustainable food production by preserving product safety and quality while offering economic benefits to the food industry. (Arshad et al., 2021). Sustainability assessments, including Life Cycle Assessments, confirm PEF's positive influence on environmental and economic sustainability, food safety, and food security. Ensuring food safety through processing and preservation is crucial, and implementing strategies like HACCP systems is essential for safeguarding consumer health PEF technology has demonstrated the ability to minimize harmful microorganisms, thereby enhancing food safety and supporting sustainable industry practices.

**2.4.1 Preservation Techniques Using Pulsed Electric Fields**

Food preservation uses methods to minimize spoilage factors, aiming to extend shelf life while preserving nutritional value, sensory qualities, and taste. Pulsed Electric Field technology is emerging as a promising non-thermal method for preserving liquid and solid foods sustainably.

For liquid foods like juices and milk, which are susceptible to microbial contamination, PEF offers advantages over traditional thermal pasteurization. PEF can be integrated into continuous processing, ensuring microbial safety at lower temperatures and minimizing negative effects on nutrition and sensory attributes. PEF treatment has been shown to achieve significant reductions in *E. coli* counts in milk, especially when paired with mild preheating. Similarly, PEF effectively reduces microbial loads in juices, with wider pulse durations proving more effective for microbial inactivation (Ghoshal, (2023). In solid food applications, PEF enhances physical properties like texture and nutrient retention. It accelerates dehydration by disrupting cell membranes, reducing drying time and energy consumption—beneficial for preserving fruits and vegetables. PEF pretreatment results in structural benefits such as shape retention and improved drying efficiency. In freezing applications, PEF accelerates ice crystal formation through electroporation, leading to better textural integrity upon thawing and reduced freezing time in foods like potatoes and apples.  In the meat industry, PEF modifies muscle structure, potentially improving tenderness and digestion. Studies have indicated reductions in shear force and better in-vitro digestion outcomes. These positive impacts highlight PEF’s potential role in enhancing meat tenderness and nutritional value. Overall, PEF technology enhances microbial safety and shelf life and improves structural and nutritional properties across different food types. PEF could serve as a key component in sustainable food preservation (Punthi et al., 2022).

**2.4.2 Influence of Pulsed Electric Field (PEF) Technology on Food Contaminants**

Food contaminants, including naturally occurring toxins, agricultural chemical residues, and food processing by-products, can compromise food safety and nutritional quality. Pulsed Electric Field processing is a promising non-thermal technique for reducing these contaminants.

One significant contaminant, 5-Hydroxy Methyl Furfural, forms during thermal processing via Maillard reactions and indicates quality degradation in sugar- and protein-rich foods. PEF treatment can significantly reduce HMF formation; for instance, PEF reduced HMF levels in tomato, strawberry, and watermelon juices compared to conventional heat treatments. Similarly, PEF treatment of date juice led to a reduction in HMF levels, preserving product quality with minimal heat-induced damage (Zhang et al., 2023) PEF technology is also effective in reducing mycotoxins, toxic substances produced by molds during food storage and processing. While heat treatments can degrade mycotoxins, they often negatively impact food quality (Morales-De la Peña et al., 2021). PEF, especially combined with mild heat, can significantly reduce aflatoxin levels. Research on ricin detoxification showed that short bursts of high-voltage PEF could alter the toxin’s molecular structure, decreasing its toxicity.

Furthermore, PEF shows promise in reducing pesticide residues in food, addressing concerns about long-term pesticide exposure. Studies indicate that PEF can break down pesticide molecules through electric field application. For example, PEF treatment of apple juice reduced methamidophos and chlorpyrifos residues. Treating cherry juice with PEF achieved significant pesticide removal, suggesting PEF as an alternative to chemical or high-heat detoxification methods (Evrendilek et al., 2021). However, further research is needed to validate these results across more food products.

**3. NEXT-GEN FOOD TECHNOLOGIES FOR BETTER HEALTH OUTCOMES**

This review topic effectively highlights innovative strategies for enhancing modern dietary practices by minimizing nutrient loss during food processing and preservation, aligning with the growing demand for healthier food options. It emphasizes the integration of functional foods with bioactive compounds that possess anti-diabetic, anti-inflammatory, anti-carcinogenic, and other health-promoting properties, supporting a sustainable lifestyle. (Sorrenti et al., 2023). HHP is a non-thermal processing technology that aligns with these goals, as it reduces the microbial load of food while maintaining its organoleptic and nutritional qualities. As the consumer demand for minimally processed foods grows, HPP provides an innovative solution for natural preservation and improved product quality. Heightened awareness of diverse food processing techniques and an expanding food supply chain has led to an increased focus on robust food safety systems like HACCP. Effective food safety necessitates continuous monitoring and control throughout the entire production process. Research indicates the importance of integrating hazard assessments throughout food production for effective safety management. Furthermore, innovative approaches to utilize agro-waste and develop nutritious food products, such as cookies enriched with pomegranate seed oil and sunflower meal protein concentrate, demonstrate potential functional food applications. Additionally, millet and banana based weaning foods offer affordable, nutritious options for underprivileged communities. Summer savory (*Satureja hortensis*) offers medicinal benefits due to its bioactive compounds like rosmarinic acid. It has antioxidant, antibacterial, cytotoxic, and anti-inflammatory properties, potentially preventing conditions like cancer and cardiovascular diseases. Its versatility makes it valuable in pharmaceuticals, diets, and as a feed additive. Spray-dried yogurt powder can enhance cookie formulations (Fazilah et al., 2018). The study found that *S. thermophilus* is more heat-resilient than *L. delbrueckii* subsp. *bulgaricus* during spray drying. Cookies with up to 15% SDYP showed improved protein and mineral content, antioxidant activity, and sensory properties. Optimizing temperature settings during spray drying can further improve culture viability and create functional cookies with enhanced nutritional benefits.

**4. Conclusion**

Fruits and vegetables are essential for human nutrition and global food security, offering vitamins, minerals, dietary fiber, and bioactive compounds. Regular consumption supports physiological functions and helps prevent chronic diseases. They also promote digestive and skin health and enhance immunity.

Horticulture significantly contributes to the agricultural GDP of many nations, supporting employment, especially among small farmers, and empowering women and rural communities. Diversifying fruit and vegetable crops enhances soil fertility and supports climate-resilient farming systems.

However, post-harvest losses, inadequate infrastructure, and contamination hinder optimal utilization. Perishability, microbial contamination, and pesticide residues pose threats to food safety and public health. Market fluctuations and inadequate policy support further aggravate the problem. Approximately 45% of fruits and vegetables are wasted worldwide. To address these issues, integrated approaches are needed, including pre- and post-harvest management, modern preservation technologies like Pulsed Electric Field, cold chain logistics, and food irradiation. Strengthening farmer education, promoting organic farming, and ensuring strict regulatory mechanisms can improve safety and shelf life. Consumer awareness campaigns can also enhance public health outcomes.

In conclusion, fruits and vegetables are fundamental to health, nutrition, economic development, and environmental sustainability. Bridging the gap between production and consumption through innovation, infrastructure development, and policy intervention is key to realizing their full potential. A collaborative effort from government agencies, scientists, food technologists, farmers, and consumers is essential to build a resilient and health-oriented food system centered around fruits and vegetables.

**Consent (where ever applicable)**

All authors declare that ‘written informed consent was obtained from the patient (or other approved parties) for publication of this case report and accompanying images. A copy of the written consent is available for review by the Editorial office/Chief Editor/Editorial Board members of this journal.

**Ethical approval (where ever applicable)**

The authors and the responsible authorities at the institute/organization where this work has been carried out give their explicit consent to submit and publish the work in JSRR if found suitable

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