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Review Paper

Nutraceutical Potential of Fruit and Vegetable Waste

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ABSTRACT

The rapid expansion of global fruit and vegetable production has led to the generation of substantial quantities of agro-industrial residues throughout harvesting, processing, distribution, and post-consumption stages. Materials such as peels, seeds, pomace, and pods are commonly discarded as waste, frequently disposed of in landfills where they contribute to environmental degradation and represent a significant loss of potentially valuable resources. However, growing scientific evidence indicates that these by-products are far from inert waste. Instead, they are rich repositories of bioactive compounds, including polyphenols, flavonoids, carotenoids, dietary fiber, and a wide range of other phytochemicals. Numerous studies have demonstrated that these constituents exhibit important biological activities, such as antioxidant, anti-inflammatory, antidiabetic, cardioprotective, and anticancer effects, underscoring their relevance in disease prevention and health promotion. This review critically explores the nutraceutical potential of major fruit and vegetable processing by-products, particularly those obtained from banana, citrus, apple, mango, onion, tomato, pea, and potato. It further discusses both conventional and advanced extraction strategies that enable the effective recovery of these bioactive compounds. In addition, key considerations related to safety assessment, quality assurance, and regulatory compliance for the incorporation of waste-derived ingredients into food products and nutraceutical formulations are addressed. Overall, the sustainable valorization of fruit and vegetable processing residues represents a promising strategy for mitigating environmental impact, enhancing economic value, and fostering innovation in functional food development. By aligning with circular economy principles, these agro-industrial by-products can be transformed into high-value nutraceutical ingredients, contributing to improved public health and long-term environmental sustainability.

INTRODUCTION

Nutraceuticals are products derived from foods or food components that are formulated to enhance health and address specific nutritional

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requirements. The term “nutraceutical” was first coined in 1989 by Dr. Stephen De Felice, integrating the concepts of “nutrition” and “pharmaceutical.”[1] These products encompass whole foods, fortified foods, dietary supplements, and isolated bioactive compounds that provide benefits extending beyond basic nutritional functions. In addition to supporting general well-being, nutraceuticals have been widely investigated for their potential role in the prevention and management of various chronic diseases. Their increasing acceptance among consumers is largely attributed to the perception that they offer therapeutic advantages while maintaining a favorable safety profile compared to synthetic drugs.[2]

Fruits and vegetables constitute fundamental components of a balanced and health-promoting diet due to their rich supply of essential vitamins, minerals, dietary fiber, and diverse phytochemicals. In response to global population growth, urbanization, and evolving dietary patterns that emphasize plant-based nutrition, the production of fruits and vegetables has expanded considerably. By 2017, global output had reached approximately 0.9 billion tons of fruits and more than 1 billion tons of vegetables.[3] Despite their nutritional importance and widespread consumption, substantial quantities are lost or wasted during harvesting, post-harvest handling, industrial processing, distribution, and household consumption. Both edible and inedible fractions are frequently discarded, leading to significant environmental burdens and economic losses. It is estimated that the fruit processing sector alone generates over 0.5 billion tons of waste annually.[3,4]

Although vegetable waste is biodegradable in nature, it is often disposed of in open dumping sites and landfills without appropriate treatment. During decomposition, organic waste emits unpleasant odors, attracts disease vectors such as

rodents and insects, and produces methane—a potent greenhouse gas that contributes to climate change. Furthermore, leachates generated from decomposing biomass may contaminate soil and groundwater resources, posing risks to ecosystems and public health. These environmental consequences underscore the urgent need for improved waste management strategies [5].

Accordingly, the sustainable management and valorization of fruit and vegetable by-products have emerged as critical areas of research and industrial innovation. Processing residues such as peels, seeds, skins, and pomace are increasingly recognized as valuable sources of bioactive compounds, including polyphenols, flavonoids, carotenoids, and dietary fibers. The recovery and utilization of these compounds offer an opportunity to transform waste streams into functional ingredients with potential health benefits. This review synthesizes current research on the sustainable valorization of fruit and vegetable by-products, with particular emphasis on extraction techniques, nutraceutical applications, and the integration of circular economy principles. By linking waste management strategies with health-oriented product development, it highlights a pathway toward environmental sustainability and improved public health outcomes.[4]

BIOACTIVE COMPOUNDS IN FRUIT AND VEGETABLE WASTE

Banana fruit waste

Banana (*Musa* spp.) is among the most widely cultivated and consumed fruits worldwide, valued for its high nutritional content and broad consumer acceptance. It is predominantly grown in tropical and subtropical regions, where it serves as both a staple food and a commercially important horticultural crop. Although bananas are primarily consumed fresh, they are also extensively



processed into a variety of products, including dried slices, chips, ice cream, smoothies, bakery products, flour, wine, and ingredients incorporated into functional food formulations.[6]

Over the past two decades, global banana production has expanded considerably, reflecting rising demand and improvements in agricultural practices. Average annual production increased from approximately 69 million tons during 2000–2002 to about 116 million tons in 2017–2019, with India emerging as the leading producer at nearly 32 million metric tons annually. This substantial production volume inevitably results in the generation of significant quantities of by-products. The banana peel, which constitutes up to 35% of the total fruit weight, represents the principal waste fraction. Consequently, an estimated 36 million tons of banana peel are produced each year worldwide. Despite its potential value, the majority of this biomass is discarded in landfills or disposed of alongside municipal solid waste.[7]

In recent years, growing scientific interest has focused on the nutritional and phytochemical composition of banana peels. These by-products are rich in micronutrients and possess considerable antioxidant capacity, largely attributed to the presence of phenolic compounds such as catechin and galocatechin, as well as dopamine. Additionally, banana peels contain diverse classes of bioactive constituents, including terpenoids, alkaloids, flavonoids, tannins, and phlobatannins. Experimental studies have demonstrated that these compounds exhibit a range of biological activities, including antilithic, antiulcerogenic, antidiarrheal, hypoglycemic, and hypolipidemic effects.[8]

Taken together, the compositional richness and biofunctional properties of banana peel highlight its potential as a sustainable raw material for nutraceutical and functional food applications, thereby transforming an underutilized agricultural residue into a value-added health-promoting ingredient.

Citrus fruit waste

Citrus fruits represent one of the most economically and nutritionally significant horticultural crops cultivated globally. Belonging to the family Rutaceae and classified under the genus *Citrus* L., these fruits are predominantly grown in tropical and subtropical regions, with annual global production exceeding 100 million tons. Citrus fruits are widely appreciated for their characteristic flavor, aroma, and vibrant coloration, and they constitute an integral component of daily diets across many cultures. In addition to their sensory appeal, they are recognized for their rich nutritional profile and associated health-promoting properties. Commonly cultivated varieties include oranges, lemons, grapefruits, mandarins, and limes.[9]

With the steady increase in consumer demand for fresh fruit and processed citrus-based products, global production has continued to expand. A substantial proportion of harvested citrus fruits is industrially processed into juices, concentrates, and flavored beverages. However, this processing generates considerable quantities of by-products, including peels, seeds, pulp residues, and pomace. Notably, citrus peels alone account for nearly 50% of the total fresh weight of the fruit, making them the principal component of citrus processing waste.[10]

Scientific investigations have demonstrated that citrus peels contain significantly higher concentrations of bioactive compounds than the edible pulp. These include phenolic compounds, flavonoids, vitamin C, essential oils, and other antioxidant constituents. The abundance of polyphenols and related phytochemicals in citrus waste contributes to a wide spectrum of biological activities, such as antioxidant, anti-inflammatory, anti-aging, antidiabetic, anticancer, anti-allergic, neuroprotective, and cardioprotective effects.[11]



Given their rich phytochemical composition and documented biofunctional properties, citrus processing by-products represent a highly promising and sustainable source of nutraceutical ingredients. Their valorization not only mitigates environmental concerns associated with agro-industrial waste but also supports the development of functional foods and health-oriented formulations with added economic value.

Apple waste

Apple (*Malus domestica*) is one of the most widely cultivated and consumed fruits across the globe, appreciated for its appealing taste, texture, and notable nutritional value. It is consumed both as fresh fruit and in processed forms such as juices, cider, purées, and dried or frozen products. The well-documented health benefits associated with apples are largely linked to their diverse range of naturally occurring bioactive compounds, including phenolic constituents, sugar alcohols, vitamins, organic acids, and amino acids.[12]

Apples are particularly rich in antioxidant phytochemicals. These include flavonoids such as quercetin and naringenin derivatives, catechin, epicatechin, and phloridzin, as well as phenolic acids like ferulic, *p*-coumaric, caffeic, chlorogenic, and gallic acids. Collectively, these compounds contribute to the fruit's strong antioxidant capacity, helping to counteract oxidative stress and potentially reducing the risk of various chronic disorders. Although a significant portion of global apple production is marketed for fresh consumption, a considerable share is utilized in industrial processing.[12,13]

The processing of apples results in the generation of substantial quantities of by-products, most notably apple pomace—the solid residue remaining after juice extraction. This by-product can account for up to 30% of the original fruit mass and consists mainly of peel and pulp residues (approximately 95%), along with smaller amounts

of seeds (2–4%) and stems (around 1%). Despite often being regarded as waste, apple pomace possesses considerable nutritional and functional value. It is especially rich in dietary fiber, which comprises roughly 35–60% of its dry weight. This fiber fraction includes pectin (5–10%), cellulose (7–40%), hemicellulose (4–25%), and lignin (15–25%).[14]

Beyond its fiber content, apple pomace contains appreciable levels of tannins, natural sugars, essential minerals, and a wide array of phenolic compounds. Due to this complex biochemical composition, apple processing residues exhibit notable antioxidant, anti-inflammatory, antidiabetic, cardioprotective, and anticancer properties. Nevertheless, despite its substantial health-promoting potential, apple pomace remains underexploited in many parts of the world. Strategic utilization and valorization of this by-product offer significant opportunities for the development of nutraceutical formulations and functional food ingredients, while also contributing to more sustainable agro-industrial waste management practices.[12]

Mango waste

Mango (*Mangifera indica* L.), a member of the family Anacardiaceae, is recognized as one of the most economically and nutritionally significant tropical fruits worldwide. It accounts for more than half of the total global production of major tropical fruits, underscoring its agricultural and commercial importance. Although mango is predominantly consumed fresh as a dessert fruit, it is also extensively processed into a diverse range of products, including chutneys, juices, jams, ice cream, dried mango powder, and canned slices preserved in syrup.[15]

Industrial processing of mangoes generates substantial quantities of by-products, primarily consisting of peels, seeds, and kernels. These residues, often regarded as waste, are increasingly



being recognized for their rich nutritional and phytochemical composition. Mango kernels are notable sources of essential macronutrients and micronutrients, including lipids, proteins, and minerals. Meanwhile, mango peels contain significant concentrations of bioactive compounds such as protocatechuic acid, mangiferin, and β -carotene, among other phenolic constituents and carotenoids.[16]

These phytochemicals exhibit a wide range of biological activities, including antioxidant, anti-inflammatory, antidiabetic, and anticancer effects, which contribute to their potential role in disease prevention and health promotion. Consequently, mango processing by-products represent a promising and sustainable source of functional ingredients for nutraceutical and food applications. Their effective valorization not only enhances economic returns from mango production but also supports environmental sustainability through the reduction of agro-industrial waste.[4]

Onion waste

Onion (*Allium cepa* L.) is one of the most extensively cultivated and widely consumed vegetables worldwide, valued for its culinary versatility as well as its nutritional and medicinal properties. Increasing recognition of its health-promoting effects has contributed to sustained growth in global production. However, onion processing—particularly peeling and trimming operations—generates a substantial volume of waste, accounting for approximately 37% of the total fresh weight of the bulb. This waste predominantly consists of dry outer skins and peels, which are commonly discarded and disposed of in landfills, thereby contributing to environmental concerns.[17] Despite being classified as agro-industrial waste, onion skins are a rich reservoir of bioactive compounds. They contain high concentrations of phenolic constituents and flavonoids, notably quercetin and

quercetin-4'-O-glucoside, along with various related compounds formed through natural degradation and oxidation processes. Importantly, these phytochemicals are often present in significantly higher amounts in the outer skins than in the edible inner bulb layers.[18]

The biological activities associated with these compounds have been extensively documented and include antioxidant, anti-inflammatory, anticancer, antidiabetic, antimicrobial, cardioprotective, and neuroprotective effects. Such properties highlight the considerable functional potential of onion processing by-products. Nevertheless, despite their demonstrated health benefits, onion skins remain largely underutilized, leading to the loss of a valuable natural resource.[19]

The strategic recovery and application of bioactive constituents from onion waste could contribute to sustainable agricultural practices and more efficient resource utilization. Furthermore, their incorporation into functional foods and nutraceutical formulations offers a promising approach to value addition, while simultaneously addressing environmental challenges associated with agro-industrial waste management.[3]

Tomato waste

Tomato (*Solanum lycopersicum* L.) is one of the most extensively cultivated vegetable crops worldwide and represents a major component of global horticultural production. In 2021, worldwide tomato output exceeded 189 million tons, with the European Union contributing more than 18 million tons, and Italy emerging as one of the leading producers within the region. Tomatoes play a central role in the Mediterranean dietary pattern and are consumed both fresh and in a wide array of processed forms, including paste, sauces, purees, ketchup, and canned products.[20]

Approximately half of the total tomato harvest undergoes industrial processing, resulting in the



generation of substantial quantities of by-products. These residues primarily consist of pomace—a mixture of peels and seeds—as well as separated seeds, vascular tissues, and peel fractions. Although traditionally regarded as waste, these by-products retain considerable amounts of nutrients and bioactive compounds, highlighting their potential for value-added applications. The incorporation of tomato processing residues into food systems aligns with circular economy principles by reducing waste streams while enhancing resource efficiency.[20]

Tomato peels are particularly noteworthy for their high concentration of carotenoids, especially lycopene and β -carotene, which may occur at levels up to five times greater than those found in the pulp, particularly in fully ripened fruits. During the ripening process, carotenoids and flavonoids—including naringenin chalcone, rutin, and kaempferol-3-rutinoside—accumulate predominantly in the peel. These phytochemicals not only contribute to the fruit's pigmentation and defense against environmental stress but also exhibit significant antioxidant activity with potential health-promoting effects.[21]

A growing body of research has investigated the application of tomato peels and pomace in the development of functional and nutritionally enhanced food products. Their incorporation into formulations has been shown to increase carotenoid content, dietary fiber levels, mineral composition, and overall antioxidant capacity. Consequently, tomato processing by-products represent a promising and sustainable source of functional ingredients for the nutraceutical and food industries, contributing both to improved nutritional quality and to environmentally responsible waste management practices.[20]

Pea waste

Pea (*Pisum sativum* L.) is the second most extensively cultivated leguminous crop globally

and represents an important source of plant-based protein and dietary nutrients. Peas are consumed in both fresh (green) and dried forms and play a significant role in human nutrition and agricultural economies. For instance, in 2020, India produced more than 5.7 million tonnes of peas, underscoring their agronomic and dietary importance. During industrial processing—particularly for frozen, canned, or dried products—the outer pods are typically removed and discarded. These pods constitute approximately 35–40% of the total fresh weight of the pea, thereby generating a considerable volume of agricultural residue. If not appropriately managed, such organic waste may create environmental concerns, including microbial proliferation, unpleasant odors, and potential health risks.[22]

Despite being commonly treated as waste, pea pods possess substantial nutritional and functional value. They are rich in dietary fiber, carbohydrates, and crude protein, while containing relatively low levels of fat and a modest caloric value (approximately 210 kcal per 100 g). In addition, pea pods serve as notable sources of essential minerals, including potassium, magnesium, iron, and zinc. Beyond their macronutrient composition, pea pods are abundant in diverse bioactive compounds. These include phenolic acids such as benzoic and cinnamic acids, as well as a wide spectrum of flavonoids. Identified flavonoid subclasses comprise flavanones (e.g., naringenin and hesperidin), flavanols (catechin and epicatechin), flavonols (quercetin, quercetin-3-galactoside, and rutin), flavones (luteolin, apigenin, and kaempferol-3-glucoside), and isoflavones (genistein and myricetin). Such phytochemicals are associated with antioxidant and anti-inflammatory activities, among other biological effects.[22]

Due to their substantial nutritional composition and diverse phytochemical content, pea pods hold considerable potential as a sustainable source of



bioactive ingredients for nutraceutical and functional food applications. Although often treated as processing waste, these by-products can be strategically utilized to develop value-added products with demonstrated health benefits. Their systematic valorization not only enhances the economic value of agro-industrial residues but also supports sustainable resource utilization and aligns with the principles of a circular economy by minimizing waste and promoting environmental stewardship.[3]

Potato waste

Potato (*Solanum tuberosum*) is one of the most extensively cultivated and economically significant food crops worldwide, serving as a staple dietary component for approximately 1.3 billion people. In 2021, global potato production surpassed 376 million tons, reflecting its major contribution to global food security. Following cereals, potatoes are regarded as one of the most important food crops due to their widespread consumption, affordability, and substantial nutritional value.[4]

A considerable proportion of harvested potatoes is subjected to industrial processing for the production of value-added products such as chips, puree, dehydrated flakes, and French fries. During these operations, the outer peel is removed, resulting in the generation of substantial quantities

of by-products. Potato peels account for approximately 15–40% of the fresh weight of the tuber, thereby contributing to significant volumes of agro-industrial waste annually. Consequently, peel residues represent one of the principal by-products of the potato processing sector. Although traditionally considered waste, potato peels possess a rich phytochemical profile and have attracted increasing scientific interest as a potential source of functional ingredients. They are particularly valued for their high concentration of polyphenolic compounds. Among these, chlorogenic acid (trans-5-O-caffeoylquinic acid) is the predominant phenolic constituent. Additional important bioactive compounds include hydroxycinnamic acids such as ferulic acid and caffeic acid, as well as related derivatives like neochlorogenic acid.[23]

These phenolic constituents are associated with significant antioxidant and anti-inflammatory properties, contributing to a range of potential health benefits. Owing to their biofunctional attributes, potato peels have been widely investigated for applications in nutraceutical development and as natural antioxidants in food systems. The effective valorization of potato processing by-products not only enhances economic returns but also aligns with sustainable waste management practices by transforming agro-industrial residues into valuable health-promoting ingredients.[5]

Source	Waste part	Active constituents	Nutraceutical potential
Banana	Peel	Gallocatechin, Dopamine	Antioxidant, Anti-inflammatory, Antidiabetic
Citrus fruits	Peel	Vitamin C	Strong antioxidant, Anti-aging
Apple	Pomace	Quercetin, catechin, and phloridzin	Antidiabetic, Anticancer, Cardioprotective, Neuroprotective
Mango	Peel, kernel	Protocatechuic acids, mangiferin, and β -carotene	Anti-inflammatory, Anticancer, Antioxidant, Antiviral
Onion	Onion skin	Quercetin	Anti-inflammatory, Antioxidant
Tomato	Seed and peel	lycopene and β -carotene	Antioxidant, Cardioprotective, Photoprotective
Pea	Outermost pod	Dietary fibre	Antidiabetic, Anti-obesity



Potato	Peel	Chlorogenic acid	Antioxidant, Cardioprotective, Anti-inflammatory
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EXTRACTION METHODS

1. Maceration:

Maceration is a conventional extraction technique widely employed for the isolation of bioactive constituents from plant materials. In this method, coarsely powdered plant material is immersed in an appropriate solvent within a closed container, ensuring complete coverage of the sample. The system is then maintained at room temperature for a minimum period of approximately three days. During this time, intermittent stirring or gentle agitation is carried out to enhance solvent penetration and facilitate the diffusion of phytochemicals into the extraction medium. Following the extraction period, the liquid phase is separated from the residual plant matrix through filtration or decantation. The solvent present in the filtrate is subsequently removed, typically by evaporation using a water bath or drying oven, to obtain a concentrated extract. Maceration is recognised for its operational simplicity, low cost, and minimal requirement for specialised equipment. Importantly, because it is generally performed at ambient temperatures, this technique is particularly suitable for the extraction of thermolabile compounds that may degrade under elevated thermal conditions.[24]

2. Soxhlet Extraction:

Soxhlet extraction is a conventional technique referred to as continuous hot extraction and is widely applied for the efficient recovery of bioactive compounds from plant matrices. The method is performed using a Soxhlet apparatus, typically composed of a round-bottom flask, an extraction chamber fitted with a siphon tube, and a

condenser positioned at the top. In this procedure, dried and finely powdered plant material is placed inside a porous thimble, usually made of filter paper or cloth, which is then inserted into the extraction chamber. A suitable solvent is added to the round-bottom flask and heated to its boiling point. Upon heating, the solvent vaporises and rises into the condenser, where it cools and condenses back into liquid form. The condensed solvent subsequently drips into the extraction chamber, thoroughly contacting the plant material and dissolving the target phytochemicals. As the solvent accumulates in the chamber and reaches the level of the siphon tube, it automatically siphons back into the boiling flask, carrying the extracted compounds with it. This cyclic process of evaporation, condensation, and siphoning is repeated multiple times, ensuring exhaustive extraction of soluble constituents. The extraction is generally considered complete when the solvent in the chamber appears colourless and leaves no residual solute upon evaporation. Soxhlet extraction is particularly suitable for plant materials that contain compounds readily soluble in the selected solvent along with insoluble impurities. However, due to the prolonged exposure to elevated temperatures, this technique is not recommended for thermolabile or heat-sensitive bioactive compounds.[25]

3. Microwave-Assisted Extraction (MAE):

Microwave-assisted extraction (MAE) is an advanced extraction technique that utilizes microwave energy to enhance the recovery of bioactive compounds from plant materials. In this method, dried and finely powdered plant samples are mixed with a suitable solvent and exposed to microwave radiation for a short duration. The



microwave energy induces rapid internal heating by interacting with polar molecules within the plant matrix and solvent. This localized heating leads to cell wall disruption, thereby facilitating the efficient release of intracellular phytochemicals into the surrounding solvent. MAE offers several advantages over conventional extraction methods. It requires comparatively smaller equipment, significantly reduces extraction time, and improves overall extraction efficiency. The rapid and uniform heating mechanism enhances mass transfer, resulting in improved recovery of target compounds. Furthermore, MAE is widely recognized as an environmentally sustainable (“green”) extraction technique. It generally involves lower solvent consumption and reduced energy input, contributing to minimized environmental impact. Owing to its speed, efficiency, and eco-friendly attributes, MAE has gained considerable attention for the extraction of functional bioactive compounds in nutraceutical and food research applications.[26]

4. Supercritical Fluid Extraction (SFE):

Supercritical fluid extraction (SFE) is an advanced and environmentally sustainable extraction technique that predominantly employs carbon dioxide (CO₂) as the solvent. In this approach, dried and finely powdered plant material is loaded into a high-pressure extraction vessel. Carbon dioxide is then subjected to conditions above its critical temperature and critical pressure, at which point it enters a supercritical state—exhibiting properties intermediate between those of a liquid and a gas. In this state, CO₂ possesses enhanced diffusivity and solvent strength, enabling it to efficiently penetrate the plant matrix and solubilize target bioactive compounds. The supercritical CO₂ containing dissolved phytochemicals is subsequently directed into a separation chamber, where a controlled reduction in pressure causes the

extracted compounds to precipitate and be collected. The CO₂ can then be recompressed and recycled within the system, contributing to process efficiency and sustainability. SFE offers several notable advantages, including minimal reliance on organic solvents, high selectivity toward specific classes of compounds, and relatively short extraction times. Moreover, because the process is conducted in a closed system with limited exposure to oxygen and light, it reduces the risk of contamination, oxidation, and thermal degradation of sensitive bioactive constituents. These attributes make SFE particularly suitable for the extraction of high-value phytochemicals intended for nutraceutical, pharmaceutical, and functional food applications.[26]

5. Enzyme-Assisted Extraction (EAE):

Enzyme-assisted extraction (EAE) is a biotechnological approach that enhances the recovery of bioactive constituents from plant matrices through the application of specific hydrolytic enzymes. In this method, fresh or dried plant material is treated with selected enzymes under carefully controlled conditions of pH and temperature to ensure optimal enzymatic activity. Commonly employed enzymes include cellulase, pectinase, and hemicellulase, which target key structural polysaccharides of the plant cell wall. These enzymes catalyse the degradation of cellulose, hemicellulose, and pectin, thereby disrupting the integrity of the cell wall structure. As a result, intracellular bioactive compounds are more readily released into the extraction medium, enhancing mass transfer and overall extraction yield. EAE is regarded as a mild and efficient technique, particularly suitable for the recovery of sensitive phytochemicals. By facilitating extraction under relatively gentle conditions, this method not only improves efficiency but also helps preserve the structural integrity and functional properties of valuable bioactive



compounds, making it highly relevant for nutraceutical and functional food applications.[27]

REGULATORY AND SAFETY CONSIDERATIONS

Despite the significant potential of fruit and vegetable by-products as functional ingredients in health-promoting foods, their incorporation into nutraceutical and food systems must comply with stringent safety and regulatory requirements. These materials may be exposed to various contaminants, including pesticide residues, heavy metals, and pathogenic or spoilage microorganisms. Therefore, comprehensive control measures—such as appropriate washing, hygienic processing, validated decontamination procedures, and safe storage and handling practices—are essential to ensure product safety and quality.[16]

International regulatory authorities, including the European Food Safety Authority (EFSA) and the U.S. Food and Drug Administration (FDA), establish permissible limits for chemical and microbiological contaminants in food and food-derived products. Compliance with these guidelines is mandatory to safeguard public health and facilitate market authorization.

Furthermore, successful commercialization of upcycled agro-industrial by-products requires robust traceability systems, standardized processing protocols, and rigorous quality control throughout the production chain. Ensuring consistency, safety, and transparency not only supports regulatory compliance but also strengthens consumer trust and acceptance of sustainably developed nutraceutical and functional food products.[28]

CONCLUSION

The escalating generation of fruit and vegetable waste poses significant environmental challenges,

including resource inefficiency and increased ecological burden. However, these by-products simultaneously present promising opportunities for innovation in the field of nutraceutical development. Materials such as peels, seeds, and pomace, traditionally regarded as low-value waste, are now increasingly recognized as abundant sources of bioactive compounds with substantial therapeutic potential.

These phytoconstituents exhibit a broad spectrum of biological activities, including antioxidant, anti-inflammatory, cardioprotective, and anticancer effects, thereby highlighting their relevance in the formulation of health-promoting products. The strategic valorization of such agro-industrial residues contributes not only to improved waste management practices but also to enhanced environmental sustainability.

Moreover, the integration of circular economy principles within the food processing sector enables the transformation of by-products into value-added nutraceutical ingredients. This approach reduces environmental impact, optimizes resource utilization, and supports the advancement of functional foods and preventive healthcare solutions. Ultimately, the sustainable conversion of fruit and vegetable waste into nutraceutical products represents a synergistic strategy that aligns ecological responsibility with the promotion of human health and overall well-being.

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