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Foodomics perspective on sweetpotato [*Ipomoea batatas* (L.) Lam.] roots and leaves: composition, processing, and functional ingredient applications

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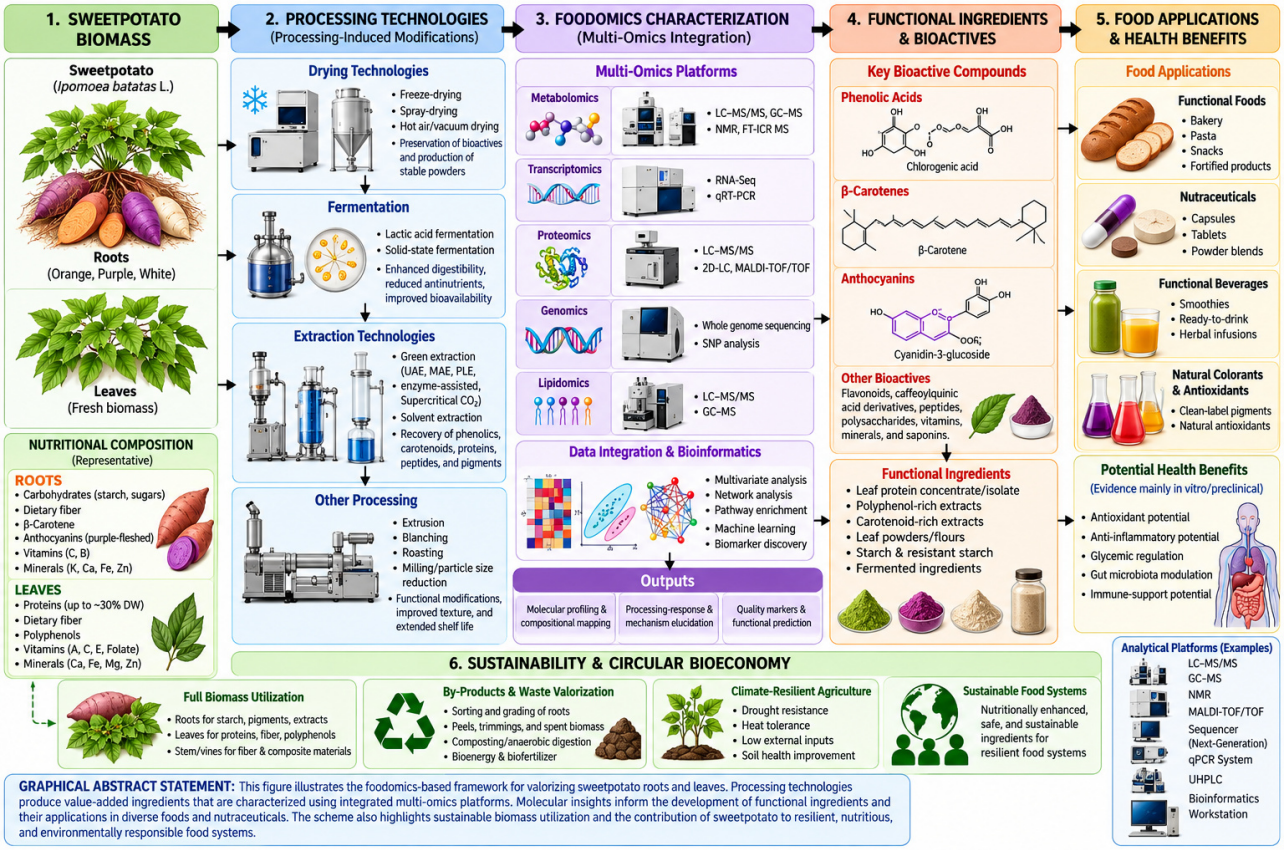
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Abstract

Sweetpotato [*Ipomoea batatas* (L.) Lam.] is increasingly recognized as a multifunctional, climate-resilient crop with substantial potential to contribute to sustainable food systems and functional ingredient development. This review provides a comprehensive, foodomics-oriented evaluation of the compositional, techno-functional, and biofunctional properties of sweetpotato storage roots and leaves, with particular emphasis on their complementary roles in food and nutraceutical applications. Storage roots are rich in complex carbohydrates, resistant starch, carotenoids, and anthocyanins, making them suitable for incorporation into staple and processed foods to improve texture, color, and nutritional quality. In contrast, sweetpotato leaves represent an underutilized yet nutrient-dense biomass rich in protein, dietary fiber, essential minerals, and diverse polyphenolic compounds that have demonstrated strong antioxidant and other biological activities primarily in vitro and preclinical studies. Recent advances in sweetpotato metabolomics, transcriptomics, proteomics, genomics, and emerging multi-omics approaches have improved understanding of cultivar-specific phytochemical composition, processing-induced molecular transformations, metabolic pathway regulation, and ingredient functionality. Current foodomics applications include compositional fingerprinting, biomarker discovery, quality authentication, and evaluation of processing effects, whereas integrated multi-omics strategies for precision breeding and nutritional prediction remain emerging research directions. Recent advances in functional food applications derived from sweetpotato roots and leaves, including bakery products, gluten-free formulations, beverages, fermented foods, nutraceutical ingredients, and plant-based foods, are critically evaluated. The review further discusses processing technologies, bioavailability constraints, consumer acceptance, safety considerations, and sustainability from an evidence-based perspective, recognizing that quantitative lifecycle and industrial-scale assessments remain limited. By integrating current foodomics evidence with functional ingredient research, this review identifies knowledge gaps and future research

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priorities while highlighting the potential contribution of sweetpotato to sustainable food innovation, circular bioeconomy strategies, and global nutritional security.



Graphical abstract. Foodomics-guided valorization of sweetpotato (*Ipomoea batatas* (L.) Lam.) roots and leaves for functional ingredient development and sustainable food systems. DW: dry weight; FT-ICR: Fourier transform ion cyclotron resonance; GC-MS: gas chromatography-mass spectrometry; LC-MS/MS: liquid chromatography-tandem mass spectrometry; MALDI-TOF: matrix-assisted laser desorption/ionization time-of-flight; MAE: microwave-assisted extraction; NMR: nuclear magnetic resonance; PLE: pressurized liquid extraction; qRT-PCR: quantitative reverse transcription polymerase chain reaction; SNP: single nucleotide polymorphism; UAE: ultrasound-assisted extraction; UHPLC: ultra-high-performance liquid chromatography.

Keywords

sweetpotato, foodomics, metabolomics, transcriptomics, proteomics, functional foods, nutraceuticals, sustainability

Introduction

Global demand for nutrient-dense, health-promoting, and environmentally sustainable food ingredients continues to rise, driving scientific and industrial interest in underutilized, climate-resilient crops such as sweetpotato [*Ipomoea batatas* (L.) Lam.] [1–3]. Traditionally regarded as an energy-rich staple, sweetpotato is now increasingly recognized as a multifunctional food resource with significant potential for value addition from both its storage roots and aerial biomass [4]. This shift reflects a growing emphasis on circular bioeconomy principles, sustainable food production, clean-label ingredients, and evidence-based functional food development. Recent advances in foodomics, including metabolomics, transcriptomics, proteomics, genomics, lipidomics, and chemometric analyses, have substantially expanded understanding of sweetpotato composition, cultivar diversity, processing responses, and the potential of functional ingredients. Unlike conventional compositional analyses, foodomics integrates multiple analytical platforms to investigate molecular composition, biological function, processing-induced transformations, and quality attributes at a systems level. Although integrated multi-omics datasets for sweetpotato remain limited, the

available evidence shows increasing use of targeted metabolomics, transcriptomics, and genomic analyses to elucidate carotenoid biosynthesis, anthocyanin accumulation, starch metabolism, stress adaptation, and phytochemical diversity. Both sweetpotato storage roots and leaves are increasingly recognized as complementary raw materials for functional food development. While storage roots have long been used in traditional diets and industrial food processing, leaves, once considered agricultural by-products, are now recognized as nutrient-rich ingredients with considerable potential for food and nutraceutical applications [5–7]. However, commercialization of leaf-derived ingredients remains constrained by limited consumer familiarity, lack of standardized processing, sensory challenges, and regulatory considerations. Consequently, a comprehensive evaluation of both edible organs within a unified foodomics framework is needed to facilitate their sustainable utilization. Storage roots contain high concentrations of starch, typically 60–80% of dry matter [8]. They also contain glucose, fructose, sucrose, dietary fiber, vitamin C, potassium, magnesium, and carotenoids, particularly β-carotene in orange-fleshed cultivars [8–11]. These nutritional characteristics have contributed to the growing use of sweetpotato flour, starch, puree, and resistant starch ingredients in modern food systems. In contrast, sweetpotato leaves contain relatively high levels of protein (approximately 20–30% dry weight), dietary fiber, vitamins A, C, and E, essential minerals, and abundant phenolic compounds, particularly caffeoylquinic acid derivatives [5, 9]. Experimental studies have demonstrated antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and hepatoprotective activities associated with these phytochemicals; however, most evidence currently comes from biochemical assays, cell culture experiments, and animal studies, while robust human clinical evidence remains comparatively limited. This distinction is important when interpreting reported biological activities and evaluating potential functional food applications [12–15].

Sweetpotato also contains numerous phytochemicals that contribute to nutritional quality and ingredient functionality. Phenolic acids, flavonoids, carotenoids, and anthocyanins have attracted increasing attention for their antioxidant properties, technological functionality, and potential as natural food ingredients [2, 4, 16]. Nevertheless, considerable variability exists among cultivars because phytochemical composition is strongly influenced by genotype, environmental conditions, agronomic management, maturity stage, postharvest handling, and processing conditions. Consequently, foodomics-assisted characterization has become increasingly important for cultivar authentication, quality standardization, biomarker discovery, and optimization of ingredient functionality. Storage roots are widely processed into flour, starch, puree, syrups, noodles, chips, and snack foods, whereas leaves are increasingly used in dried powders, functional beverages, bakery products, and nutraceutical formulations [3, 5, 6, 17–24]. Recent processing research has shifted from conventional preservation to understanding processing-induced molecular transformations that affect phytochemical stability, resistant starch formation, protein functionality, and overall ingredient quality. This knowledge provides an important foundation for foodomics-based optimization of sweetpotato-derived food ingredients [25, 26].

Foodomics provides an analytical framework linking molecular composition, processing behavior, ingredient functionality, and nutritional quality. Targeted metabolomics has already been successfully used to characterize cultivar-specific phytochemical fingerprints, while transcriptomic and genomic studies have elucidated genes that regulate carotenoid accumulation, anthocyanin biosynthesis, starch metabolism, and stress adaptation. Emerging proteomic investigations have improved understanding of protein composition, digestibility, enzymatic modification, and allergenicity. Although fully integrated multi-omics approaches remain relatively limited, they represent an important future direction for precision breeding, quality authentication, predictive food processing, and personalized nutrition. Accordingly, this review aims to critically evaluate current evidence on nutritional composition, foodomics characterization, processing technologies, functional ingredient development, health-related biological activities, industrial applications, sustainability, and future research priorities of sweetpotato roots and leaves. Unlike previous reviews that primarily emphasize storage roots, leaves, isolated phytochemicals, or nutritional composition, this review integrates available evidence within a comprehensive foodomics framework and critically distinguishes established scientific knowledge from emerging research opportunities. Emphasis is

placed on evidence-based interpretation, sustainability limitations, processing-induced molecular transformations, and future multi-omics research priorities relevant to functional food innovation.

Methodology of literature review

This review was prepared using literature retrieved from Web of Science, Scopus, PubMed, ScienceDirect, and Google Scholar. Searches used combinations of the following keywords: "sweetpotato" OR "Ipomoea batatas" AND "roots," "leaves," "foodomics," "metabolomics," "transcriptomics," "proteomics," "genomics," "multi-omics," "processing," "functional foods," "bioactive compounds," "nutraceuticals," "sustainability," "valorization," "phytochemicals," and "food processing." The literature search was conducted between January and March 2026. Priority was given to peer-reviewed original research articles, systematic reviews, authoritative review articles, and book chapters published primarily between 2000 and 2026, with earlier landmark publications retained if they were foundational to sweetpotato chemistry, food processing, or utilization. Studies were included if they reported nutritional composition, phytochemical characterization, foodomics analyses, processing technologies, functional ingredient development, biological activities, food applications, consumer acceptance, safety, or sustainability related to sweetpotato roots, leaves, or derived products.

Studies focused exclusively on agronomic performance without relevance to food; reports lacking sufficient methodological detail; conference abstracts without full publication; duplicate datasets; and publications unrelated to food, nutrition, or ingredient development were excluded. For health-related evidence, findings were interpreted according to the hierarchy of evidence, distinguishing biochemical assays, cell-based studies, animal experiments, and human clinical investigations. Throughout this review, reported biological activities are discussed in relation to the strength of available evidence, and therapeutic interpretations are intentionally avoided unless supported by clinical data. To minimize citation bias, literature from multiple independent research groups was included whenever possible. Primary experimental studies were prioritized over secondary reviews for quantitative compositional data, processing outcomes, and food applications. When conflicting values were reported, greater emphasis was placed on studies that employed validated analytical methods, clearly described experimental designs, provided quantitative measurements, and included independent verification. Sustainability-related conclusions were interpreted cautiously, based on currently available evidence on biomass utilization, waste valorization, processing feasibility, industrial applicability, and reported environmental impacts. Because relatively few life cycle assessments (LCAs) and techno-economic analysis (TEA) studies are available for sweetpotato-derived food systems, sustainability discussions should be viewed as evidence-informed perspectives rather than definitive environmental assessments. The biomass allocation, nutritional composition, bioactive compounds, and foodomics relevance of sweetpotato roots and leaves are shown in Figure 1.

Botanical characteristics and edible components

Sweetpotato [*Ipomoea batatas* (L.) Lam.] is a dicotyledonous species in the family Convolvulaceae. The plant has storage roots, vines, stems, leaves, and fibrous roots, with storage roots and young leaves being the principal edible components consumed worldwide. Storage roots develop from adventitious roots through secondary thickening and function primarily as carbohydrate storage organs, rich in starch and energy reserves. In contrast, leaves and young shoots contain substantially higher concentrations of protein, dietary fiber, vitamins, minerals, and polyphenolic compounds, making them nutritionally comparable to several commonly consumed leafy vegetables [5, 9]. Although sweetpotato roots are widely used commercially, leaves remain underutilized in many countries despite their high nutritional value. Recent interest in sustainable food systems has prompted renewed evaluation of leaf biomass as a valuable food resource that can improve whole-plant utilization and reduce agricultural waste. From a foodomics perspective, both storage roots and leaves exhibit substantial metabolic diversity shaped by genotype, developmental stage, environmental conditions, agronomic management, and postharvest handling. Metabolomic studies have revealed cultivar-specific variation in carotenoids, anthocyanins, caffeoylquinic

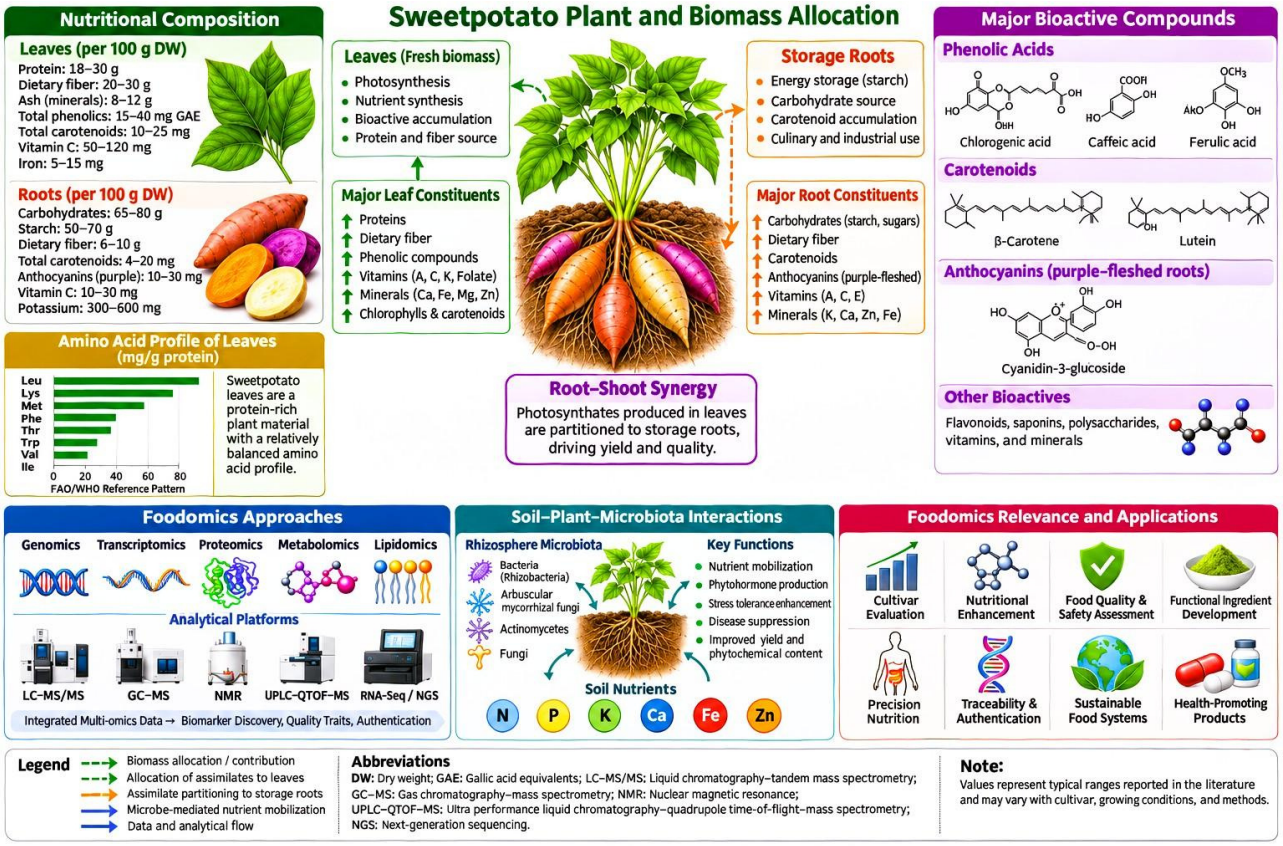


Figure 1. Biomass allocation, nutritional composition, bioactive compounds, and foodomics relevance of sweetpotato roots and leaves.

acid derivatives, flavonoids, sugars, amino acids, and volatile compounds, underscoring the importance of molecular characterization for food quality and ingredient standardization. This complementary distribution of carbohydrates in roots and bioactive phytochemicals in leaves provides the scientific basis for the integrated use of both edible organs in functional food development.

Sweetpotato storage roots as food and functional ingredients

Conventional and processed food uses

Sweetpotato storage roots are consumed in various forms, including boiled, steamed, baked, roasted, fried, dried, and fermented products, as well as other processed foods [4, 27, 28]. Beyond traditional consumption, roots are increasingly processed into value-added products including flour, starches, purees, chips, noodles, syrups, and functional ingredients suitable for industrial food applications. The technological versatility of sweetpotato results primarily from its starch composition, natural sweetness, attractive pigmentation, and favorable processing characteristics. Flour derived from storage roots has received considerable attention as a gluten-free ingredient because it improves nutritional quality, moisture retention, texture, color, and consumer acceptability in bakery and snack products [29]. However, considerable variability exists among cultivars with respect to starch composition, sugar profiles, carotenoid concentrations, anthocyanin content, and functional performance. Consequently, direct comparison among studies requires careful consideration of cultivar identity, analytical methodology, and processing conditions. Table 1 summarizes functional ingredients derived from sweetpotato storage roots and leaves, together with representative compositional ranges, selected cultivar examples, techno-functional properties, and major food applications supported by the cited literature.

Starch and carbohydrate-based ingredients

Starch is the primary component of sweetpotato storage roots and a critical functional ingredient in food processing. Sweetpotato starch is known for its high viscosity, strong water-binding capacity, favorable

Table 1. Functional ingredients derived from sweetpotato storage roots and leaves, with representative compositional ranges, selected cultivar examples, techno-functional properties, and food applications.

Source	Functional ingredient	Representative quantitative ranges/selected cultivar examples	Techno-functional properties	Food applications
Storage root	Flour	Starch in whole-root flours commonly ranged from 31.68 to 64.90% dry weight (DW) across seven varieties [30]; white-fleshed cultivars in a broad panel contained about 52.0 to 83.4% starch DW, while orange cultivars showed β-carotene around 47.2 mg/100 g DW in high-carotenoid lines [31].	Water absorption, bulking, natural sweetness, moderate viscosity; cultivar-dependent pasting, gelatinization, and texture behavior [30].	Bakery products, gluten-free formulations, snack foods.
	Native starch	Amylose in seven cultivars ranged from about 15.7% to 40.3%; resistant starch in native starch ranged from < 5% to > 30% depending on cultivar, e.g., Jeonmi about 30.75%, Pungwonmi < 5% [32].	Thickening, gelatinization, gel formation, film-forming ability, granule structure, and amylose/amylopectin ratio strongly affect swelling, pasting, and digestibility [32].	Soups, sauces, gravies, processed foods.
	Modified starch	Heat-moisture and enzyme-debranching treatments increased resistant starch to about 14.23–17.16% in purple sweetpotato starch systems, while decreasing swelling power from 26.21 to 17.21 g/g and solubility from 9.46% to 7.41% [33].	Improved thermal stability, altered swelling and solubility, greater shear resistance, freeze-thaw stability, and tailored digestibility [33].	Industrial food systems, instant foods, specialty starch applications.
	Resistant starch	Native resistant starch varied markedly by cultivar, from < 5% to > 30% [32]; processed purple sweetpotato starch reached about 14.23–17.16% after heat-moisture or enzyme-assisted treatment [33]; resistant starch content and physicochemical properties vary with cultivar, starch structure, and processing conditions.	Low digestibility, prebiotic potential, reduced glycemic response, and texture modification in formulated foods [32, 33].	Functional foods, dietary supplements, and low-glycemic formulations.
	Syrups/Sweeteners	Produced by enzymatic hydrolysis of starch-rich roots; root starch substrate typically ranges from about 31.68–64.90% DW in flour studies and 52.0–83.4% DW in high-starch white cultivars, supporting syrup yield potential [30].	Sweetening, humectancy, viscosity adjustment, flavor enhancement through oligosaccharide-rich hydrolysates.	Beverages, confectionery, bakery fillings.
	Carotenoid extracts	Orange/yellow-fleshed cultivars are richest; β-carotene in orange-fleshed panels has been reported around 47.2 mg/100 g DW in orange cultivars, and cultivar studies identified Kamalasundari [Bangladesh Agricultural Research Institute Sweet Potato-2 (BARI SP-2)] and BARI SP-5 as high-carotene types [31].	Natural colorant, antioxidant activity, provitamin A activity; useful in fortification and color enhancement [31].	Fortified foods, dairy products, and beverages.
	Anthocyanin extracts	Purple-fleshed cultivars contain acylated anthocyanins; purple sweetpotato anthocyanin extracts are dominated by cyanidin/peonidin 3,5-diglucoside derivatives, and extraction studies report totals around 1.36 mg/g DW or higher, depending on process and cultivar [34].	High color stability, antioxidant capacity, pH-responsive coloration, improved suitability as natural food colorants due to acylation [34].	Functional beverages, confectionery, and natural colorants.
Leaves	Leaf powder	Crude protein is commonly about 16.69–31.08 g/100 g DW across 40 cultivars; total polyphenols are reported at about 2.73–21.39% DW in cultivar surveys and more conservatively about 3–12% DW in review summaries [9].	Nutrient enrichment, water binding, antioxidant activity, color contribution; useful in protein- and micronutrient fortification [5].	Bakery products, pasta, fortified snacks.
	Protein concentrates	Leaf protein is often about 20–30% DW and may reach about 31.08 g/100 g DW depending on cultivar; incorporation of leaf material significantly raises product protein content, e.g., flakes increased from 6.6% to 15.4% protein with 50% leaf inclusion [9].	Emulsifying, foaming, gel-forming potential; supports plant-based formulation and nutritional fortification [35].	Plant-based foods, protein supplements.

Table 1. Functional ingredients derived from sweetpotato storage roots and leaves, with representative compositional ranges, selected cultivar examples, techno-functional properties, and food applications. (*continued*)

Source	Functional ingredient	Representative quantitative ranges/selected cultivar examples	Techno-functional properties	Food applications
	Polyphenol extracts	Total polyphenols in sweetpotato leaves ranged from about 2.73% to 21.39% DW across 40 cultivars, with caffeoylquinic acid derivatives and flavonoids as major compounds [9, 12, 21].	Antioxidant, antimicrobial, and anti-inflammatory activity in experimental studies; oxidative stability enhancement in formulated systems [5, 36].	Functional beverages, nutraceutical formulations.
	Dietary fiber fractions	Leaf carbohydrate/fiber-rich material contains crude carbohydrate about 42.03–61.36 g/100 g DW, and prior comparisons indicate leaf dietary fiber may be about fivefold higher than in roots in some studies [9].	Water retention, bulking, gut health support, matrix stabilization in composite foods [9].	Fiber-enriched foods, functional formulations.

Representative compositional ranges are compiled from published studies and may vary with cultivar, flesh color, leaf maturity, agronomic conditions, analytical method, and processing status. Health-related activities associated with leaf polyphenol are based mainly on in vitro and preclinical evidence. Bracketed references are included to improve traceability of ingredient composition, functionality, and application claims.

gelatinization behavior, and excellent gel-forming properties, making it suitable as a thickener, stabilizer, and texturizer in soups, sauces, bakery products, noodles, confectionery, and other processed foods [2]. These techno-functional attributes have contributed to the growing use of sweetpotato starch in gluten-free foods, clean-label formulations, and other value-added food products. In addition to native starch, modified starches derived from sweetpotato through thermal, enzymatic, physical, or chemical treatments are increasingly used to improve freeze-thaw stability, rheological properties, thermal resistance, digestibility, and processing performance under diverse industrial conditions. Such modifications enhance the versatility of sweetpotato starch for commercial food manufacturing while improving product quality and processing stability. Recent advances in foodomics have shown that starch functionality cannot be explained solely by amylose and amylopectin composition. Instead, starch behavior is shaped by complex interactions among cultivar-specific metabolic traits, starch granule architecture, endogenous proteins, lipid-starch interactions, enzyme activities, and processing-induced molecular transformations. Integrated metabolomic, proteomic, lipidomic, and chemometric approaches have provided new insights into starch biosynthesis, molecular organization, gelatinization behavior, retrogradation, and functional performance, thereby extending conventional physicochemical characterization toward a systems-level understanding of starch functionality.

Resistant starch fractions, formed naturally or through retrogradation and controlled processing, have attracted considerable attention for their potential nutritional significance. Experimental studies suggest that resistant starch may reduce the rate of starch digestion, attenuate postprandial glycemic responses, and serve as a fermentable substrate for intestinal microorganisms, potentially contributing to short-chain fatty acid production and gut microbial metabolism [32, 33]. However, these reported physiological effects are influenced by starch structure, processing conditions, food matrix interactions, and individual metabolic variability. Furthermore, the current evidence is derived primarily from mechanistic studies, in vitro digestion models, nutritional investigations, and animal experiments, whereas robust, large-scale human clinical evidence remains comparatively limited. Consequently, these observations should be interpreted as promising biological activities rather than established therapeutic effects. The comparative phytochemical composition of sweetpotato roots and leaves, including the principal bioactive compounds and their shared functional properties relevant to reported biological activities, is presented in Figure 2. This comparison illustrates the complementary nutritional roles of storage roots, which are rich in starch and carotenoids, and leaves, which contain higher concentrations of proteins, chlorogenic acid derivatives, flavonoids, vitamins, and minerals. Despite extensive research on sweetpotato starch functionality, reported physicochemical properties vary substantially among cultivars and analytical methodologies. Differences in amylose content, granule morphology, starch extraction protocols, environmental conditions, harvest maturity, and processing techniques often complicate direct comparison among studies. This variability highlights the importance of interpreting published data within the context of the experimental

design and analytical methods employed. Furthermore, many reported functional advantages of sweetpotato starch remain based primarily on laboratory-scale investigations and require validation under commercial manufacturing conditions. Studies should therefore prioritize standardized analytical protocols, harmonized starch characterization methods, comparative evaluation of genetically diverse cultivars, and industrial-scale processing trials. Integration of foodomics with rheological analysis, molecular characterization, artificial intelligence (AI), and predictive modeling will further improve understanding of starch functionality, facilitate precision selection of cultivars for targeted food applications, and strengthen the translation of laboratory findings into commercially viable sweetpotato-based ingredients.

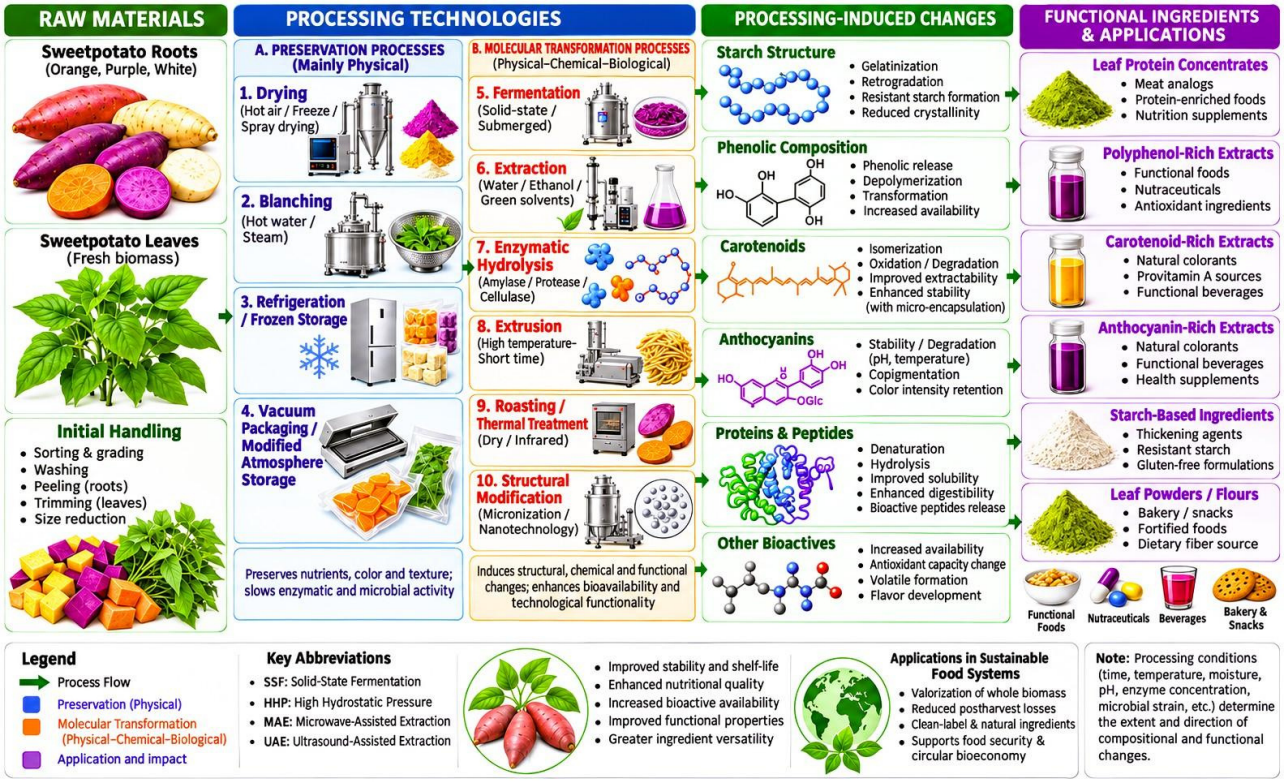


Figure 2. Foodomics-guided valorization of sweetpotato roots and leaves through integrated processing, multi-omics characterization, and functional ingredient development.

Natural sweeteners and syrups

Sweetpotato storage roots are increasingly processed into natural syrups and sweeteners via controlled enzymatic hydrolysis of starch, yielding glucose-, maltose-, and oligosaccharide-rich products suitable for a wide range of food applications. These sweeteners are used in beverages, confectionery, bakery products, dairy formulations, and processed foods as natural alternatives to refined sugars because of their desirable sweetness profile, favorable viscosity, functional stability, and consumer preference for clean-label ingredients [37, 38]. Recent advances in foodomics have substantially improved understanding of carbohydrate transformation during enzymatic hydrolysis by integrating metabolomics, carbohydrate profiling, high-performance chromatography, mass spectrometry, and chemometric analyses. These approaches enable detailed characterization of mono-, di-, and oligosaccharide composition, enzyme specificity, intermediate carbohydrate metabolites, and processing-induced molecular changes that collectively influence sweetness, viscosity, fermentability, storage stability, and overall product quality.

Sweetpotato syrups contain varying proportions of glucose, maltotriose, and other oligosaccharides, depending on cultivar, starch composition, enzymatic treatment, and processing conditions. These compositional differences influence both sensory characteristics and technological functionality, making cultivar selection and process optimization important considerations for industrial manufacturing.

Oligosaccharides in sweetpotato-derived syrups have attracted increasing interest in their potential physiological significance. Experimental evidence suggests that certain oligosaccharides may serve as fermentable substrates for beneficial intestinal microorganisms and may help modulate postprandial glycemic responses compared with highly refined sugars. However, these reported effects depend on syrup composition, processing conditions, dosage, overall dietary context, and individual metabolic variability. Furthermore, much of the available evidence comes from mechanistic investigations, in vitro digestion studies, and experimental nutritional models, whereas well-controlled human clinical studies remain comparatively limited. Consequently, these observations should be interpreted as promising biological activities rather than established health benefits. Despite growing commercial interest, relatively few studies have comprehensively evaluated the physicochemical stability, sensory performance, storage behavior, and economic feasibility of sweetpotato-derived syrups under industrial manufacturing conditions. Variability in cultivars, enzymatic hydrolysis protocols, sugar profiles, and analytical methods also complicates direct comparisons across published studies. Research should prioritize standardized processing protocols, comprehensive carbohydrate fingerprinting using foodomics technologies, comparative evaluation of diverse sweetpotato cultivars, and industrial-scale validation of syrup production systems. Integrating foodomics with AI, predictive processing models, and advanced quality-control strategies will optimize sweetness profiles, nutritional quality, ingredient consistency, and commercial scalability, while supporting evidence-based development of sweetpotato-derived natural sweeteners for functional food applications.

Pigments and bioactive ingredients

Sweetpotato contains a diverse array of phytochemicals that contribute to its nutritional quality, technological functionality, and reported biological activities. Among these compounds, phenolic acids, particularly chlorogenic acid and related caffeoylquinic acid derivatives, are the predominant phenolic constituents and have been associated with modulation of oxidative stress pathways, inflammatory signaling, glucose metabolism, and other cellular processes in experimental studies [4, 31]. Flavonoids, including quercetin, kaempferol, and their glycosides, further contribute to the in vitro free radical-scavenging capacity and cellular protective effects reported for sweetpotato extracts. However, the magnitude of these biological responses depends on phytochemical composition, bioavailability, food matrix interactions, dosage, and individual physiological variability. Orange-fleshed cultivars are particularly rich in β-carotene, an important provitamin A carotenoid widely incorporated into biofortification and nutrition intervention programs aimed at reducing vitamin A deficiency in vulnerable populations [2, 16, 39]. Purple-fleshed cultivars contain high concentrations of acylated anthocyanins, which exhibit excellent thermal, pH, and storage stability compared with many naturally occurring anthocyanins. These pigments have attracted considerable industrial interest as clean-label natural colorants for beverages, dairy products, confectionery, bakery products, and other processed foods, while also contributing antioxidant capacity and product differentiation [40, 41]. Recent advances in foodomics have substantially expanded understanding of sweetpotato pigmentation beyond conventional compositional analyses. Integrated metabolomics, transcriptomics, proteomics, and chemometric analyses have enabled comprehensive characterization of carotenoid, anthocyanin, flavonoid, and phenolic metabolic networks, identification of cultivar-specific molecular biomarkers, elucidation of biosynthetic pathways, and evaluation of processing-induced molecular transformations. These system-level approaches facilitate improved quality assurance, cultivar authentication, ingredient standardization, and optimization of processing technologies for functional food development. Although numerous studies report high concentrations of carotenoids, anthocyanins, chlorogenic acid derivatives, and other phenolic compounds in sweetpotato tissues, considerable compositional variability has been observed among cultivars due to differences in genotype, environmental conditions, agronomic management, maturity stage, postharvest handling, storage conditions, and analytical methodologies [24–26]. Processing techniques, including thermal treatment, drying, fermentation, and extraction methods, may further modify phytochemical composition and stability, thereby influencing both technological functionality and nutritional quality. Consequently, direct comparisons among published studies remain challenging, and phytochemical

abundance should not be assumed to directly translate into biological efficacy or clinical benefit. Although carotenoids, anthocyanins, and phenolic compounds have demonstrated antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and other health-related activities in biochemical assays, cell culture systems, and animal models, the strength of evidence varies considerably across biological endpoints, and relatively few well-designed human clinical trials have confirmed these effects. Accordingly, the reported health-promoting properties of sweetpotato-derived pigments should be viewed as promising scientific evidence rather than definitive therapeutic outcomes.

The growing use of sweetpotato-derived pigments aligns with rising consumer demand for natural, clean-label ingredients that can replace synthetic colorants while delivering added nutritional value. However, successful commercialization requires consistent pigment composition, standardized extraction methods, validated quality-control protocols, regulatory compliance, and economic feasibility to ensure reliable industrial performance. Research should prioritize foodomics-assisted standardization of pigment profiles, biomarker-guided quality assessment, integrated multi-omics investigations of pigment biosynthesis, comparative evaluation of genetically diverse cultivars, optimization of processing technologies to preserve phytochemical stability, and comprehensive studies on bioavailability and human health outcomes. Furthermore, integrating AI, predictive metabolomics, and advanced chemometric modeling offers significant opportunities to accelerate cultivar selection, improve quality assurance, and support the industrial translation of sweetpotato-derived pigments and bioactive ingredients for functional food applications. The foodomics-guided valorization of sweetpotato roots and leaves through integrated processing, multi-omics characterization, and functional ingredient development is presented in Figure 2.

Sweetpotato leaves as emerging functional food ingredients

Leafy vegetable and culinary applications

Sweetpotato leaves have long been consumed as nutritious leafy vegetables in many regions of Asia, Africa, and parts of Oceania, where they are commonly used in soups, stir-fries, steamed dishes, curries, salads, and other traditional foods. Their mild flavor, tender texture, quick cooking time, and favorable nutritional profile make them suitable for a wide range of culinary applications [18, 42, 43]. In addition to their culinary versatility, sweetpotato leaves provide substantial amounts of dietary fiber, high-quality protein, vitamins, minerals, chlorogenic acid derivatives, flavonoids, and other bioactive compounds that contribute to their value as functional food ingredients. Recent foodomics investigations have deepened understanding of the molecular composition of sweetpotato leaves by integrating metabolomics, proteomics, transcriptomics, and advanced phytochemical profiling. These approaches have revealed considerable diversity in phenolic compounds, flavonoids, carotenoids, amino acids, and other metabolites across cultivars, and have also shown that cooking, drying, blanching, and other processing methods can substantially influence phytochemical retention, nutritional quality, sensory attributes, and ingredient functionality. Such system-level characterization provides valuable information for optimizing cultivar selection, processing technologies, and product development. Although sweetpotato leaves are widely consumed in many developing regions, their use remains limited in North America and Europe, representing a significant yet largely underexploited opportunity for developing functional foods, plant-based ingredients, and sustainable vegetable products [9, 43–45]. Growing consumer interest in nutrient-dense leafy vegetables, clean-label ingredients, and plant-based diets may create favorable conditions for expanding their commercial adoption. However, broader market acceptance will require improvements in consumer awareness, sensory optimization, standardized postharvest handling, quality assurance, and reliable supply chains.

Despite growing interest in their nutritional composition, relatively few studies have systematically evaluated how genotype, environmental conditions, harvest maturity, storage, and culinary processing affect the retention of bioactive compounds and overall product quality under commercial conditions. Furthermore, many reported health-related properties of sweetpotato leaves are supported primarily by compositional analyses, in vitro assays, and preclinical investigations rather than large-scale human

intervention studies. Studies should prioritize foodomics-assisted characterization of cultivar diversity, standardized evaluation of processing effects on nutritional quality and sensory characteristics, optimization of postharvest preservation technologies, and industrial-scale validation of leaf-based food products. Integrating multi-omics technologies with consumer sensory analysis, AI, and predictive quality modeling will further facilitate cultivar selection, quality standardization, and the commercialization of sweetpotato leaves as high-value functional ingredients for modern food systems.

Protein-rich functional ingredients

One of the most distinctive nutritional attributes of sweetpotato leaves is their relatively high protein content, which has been reported to reach approximately 20–30% on a dry-weight basis, depending on cultivar, maturity stage, environmental conditions, and cultivation practices. This relatively high protein concentration distinguishes sweetpotato leaves from many commonly consumed leafy vegetables and highlights their potential as a sustainable plant-derived protein source. Consequently, sweetpotato leaves have attracted growing interest for use in protein-enriched flour, bakery products, snacks, beverages, meat analogues, and other plant-based food formulations. The amino acid composition of sweetpotato leaf proteins is relatively balanced and contains appreciable levels of several essential amino acids, supporting their nutritional quality and potential contribution to diversified dietary protein intake [5]. In addition to protein, sweetpotato leaves provide dietary fiber, vitamins, minerals, chlorogenic acid derivatives, flavonoids, and carotenoids, creating opportunities for developing multifunctional food ingredients with both nutritional and technological value. Recent advances in foodomics have deepened understanding of sweetpotato leaf proteins beyond conventional compositional analysis. Integrated proteomics, metabolomics, transcriptomics, and amino acid profiling have enabled detailed characterization of protein composition, cultivar-dependent variation, post-translational modifications, interactions with phytochemicals, and processing-induced molecular changes that affect protein functionality, digestibility, and ingredient performance. These system-level approaches provide valuable information for optimizing cultivar selection, improving extraction efficiency, and developing standardized protein ingredients for food applications.

Leaf protein concentrates and protein isolates are emerging as promising functional ingredients for plant-based foods because of their emulsifying capacity, water-holding ability, foaming properties, and nutritional profile. These ingredients are increasingly being investigated as sustainable alternatives to conventional plant proteins in response to growing consumer demand for environmentally responsible, plant-based food systems and diversified protein sources [46]. Considerable variability in protein content and functional characteristics has been reported among sweetpotato cultivars due to differences in genotype, environmental conditions, agronomic practices, harvest maturity, processing methods, and protein extraction technologies. This variability complicates direct comparisons across studies and underscores the need for standardized analytical methodologies and harmonized evaluation protocols. Although sweetpotato leaf proteins exhibit promising nutritional quality and functional properties, relatively little information is available on protein digestibility after industrial processing, amino acid bioavailability, allergenic potential, sensory acceptance, long-term storage stability, and commercial-scale manufacturing. Most published investigations remain at the laboratory or pilot scale, and additional validation under industrial processing conditions is required before widespread commercial implementation. Research should prioritize foodomics-assisted characterization of protein quality, integration of proteomics with metabolomics and transcriptomics, optimization of sustainable extraction and purification technologies, comparative evaluation of genetically diverse cultivars, and comprehensive assessment of digestibility, bioavailability, and sensory performance. The application of AI, predictive protein modeling, and advanced chemometric approaches may further accelerate ingredient optimization, quality assurance, and industrial translation of sweetpotato leaf proteins for next-generation plant-based food systems.

Polyphenol-rich extracts and in vitro free radical-scavenging capacity ingredients

Sweetpotato leaves are among the richest plant sources of polyphenolic compounds, particularly chlorogenic acid and related caffeoylquinic acid derivatives, along with flavonoids and other phenolic constituents that substantially contribute to their antioxidant potential [4]. These phytochemicals have attracted considerable interest as natural functional ingredients for incorporation into nutraceuticals, functional beverages, dietary supplements, and health-oriented food products because of their reported biological activities and favorable consumer perception of plant-derived antioxidants.

Recent advances in foodomics have substantially improved the characterization of sweetpotato leaf polyphenols through integrated metabolomics, high-resolution mass spectrometry, chromatographic fingerprinting, and chemometric analyses. These approaches enable comprehensive identification and quantification of individual phenolic compounds, evaluation of cultivar-specific metabolite profiles, monitoring of processing-induced molecular transformations, and the development of molecular biomarkers for quality assurance and ingredient standardization. Such systems-level characterization provides a stronger scientific foundation for selecting cultivars and optimizing extraction technologies for industrial applications. Sweetpotato leaf extracts have shown strong in vitro free radical-scavenging capacity, largely attributed to synergistic interactions among caffeoylquinic acid derivatives, flavonoids, and other phenolic compounds. Experimental studies suggest that incorporating these extracts into food systems may improve oxidative stability, delay lipid oxidation, extend shelf life, and reduce reliance on synthetic antioxidants [17, 27]. These characteristics have increased interest in sweetpotato leaf extracts as clean-label natural antioxidants for a variety of processed food applications. However, antioxidant activity measured by in vitro chemical assays should not be taken as direct evidence of physiological efficacy in humans. The biological effects of polyphenols are influenced by bioavailability, gastrointestinal metabolism, food matrix interactions, individual metabolic variability, dosage, and biotransformation by the gut microbiota, factors that conventional antioxidant assays do not adequately capture. Consequently, high in vitro free radical-scavenging capacity does not necessarily translate into proportional in vivo biological activity or clinical benefit. Although numerous studies report anti-inflammatory, antidiabetic, antimicrobial, hepatoprotective, and other health-related activities of sweetpotato leaf extracts, the current evidence is derived predominantly from in vitro investigations and preclinical animal studies, whereas well-designed randomized human clinical trials remain comparatively limited. Therefore, these biological activities should be regarded as promising experimental observations rather than established therapeutic outcomes. Considerable variability in polyphenol composition has also been reported among sweetpotato cultivars due to differences in genotype, environmental conditions, agronomic practices, harvest maturity, postharvest handling, extraction procedures, and analytical methodologies. This variability underscores the need for foodomics-assisted standardization, validated analytical protocols, and biomarker-guided quality assessment to improve reproducibility and facilitate industrial use. Studies should prioritize integrated metabolomic and transcriptomic investigations of polyphenol biosynthesis; optimization of environmentally sustainable extraction technologies; comprehensive studies of bioavailability and pharmacokinetics; randomized human intervention trials; and industrial validation of polyphenol-rich ingredients under commercial processing conditions. Furthermore, integrating AI, predictive metabolomics, and advanced chemometric modeling may improve cultivar selection, extraction efficiency, quality control, and the commercialization of sweetpotato leaf polyphenols for next-generation functional food and nutraceutical applications.

Leaf powders and fortification applications

Drying and milling sweetpotato leaves produce nutrient-dense powders that can be readily incorporated into a variety of food products as multifunctional ingredients. Sweetpotato leaf powders have been successfully used to fortify bakery products, pasta, noodles, snacks, composite flours, beverages, and other plant-based foods, thereby enhancing protein, dietary fiber, vitamin, mineral, and phytochemical levels while improving the overall nutritional profile of finished products [46, 47]. These attributes have generated growing interest in sweetpotato leaf powders as sustainable ingredients for clean-label and

functional food formulations. Beyond their nutritional value, sweetpotato leaf powders contain substantial levels of chlorogenic acid derivatives, flavonoids, carotenoids, and other bioactive compounds that may enhance the antioxidant capacity and functional properties of fortified foods. However, the retention of these compounds depends heavily on drying technology, milling conditions, storage, packaging, and subsequent food processing, underscoring the importance of optimizing processing parameters to preserve ingredient quality. Recent advances in foodomics have substantially improved the characterization of sweetpotato leaf powders through integrated metabolomics, proteomics, chromatographic profiling, and chemometric analyses. These technologies enable comprehensive evaluation of nutrient composition, phytochemical fingerprinting, processing-induced molecular transformations, and cultivar-specific variability, while supporting biomarker-guided quality assurance and ingredient standardization. These systems-level approaches facilitate the development of standardized leaf powders with consistent nutritional composition and functional performance for industrial applications. Sweetpotato leaf powders have potential as nutrient-rich ingredients for food fortification and may provide an additional value-added use for sweetpotato foliage, although their nutritional contribution depends on formulation, processing conditions, and consumption levels [4, 6, 46–49]. Incorporating them into food systems also supports whole-plant utilization and can reduce biomass waste by converting edible leaves into value-added ingredients. Nevertheless, the magnitude of these sustainability benefits depends on production efficiency, consumer acceptance, supply-chain logistics, processing technologies, and economic feasibility, and therefore requires quantitative validation.

The processing pathways for converting sweetpotato into functional food ingredients, including drying, extraction, and structural modification processes leading to diverse food, nutraceutical, and industrial applications, are illustrated in Figure 3. This framework highlights the integration of processing technologies with ingredient functionality and provides a conceptual basis for foodomics-guided development of value-added sweetpotato products. Although promising nutritional characteristics, several challenges remain for the commercial utilization of sweetpotato leaf powders. Considerable variability in nutrient composition, protein content, polyphenol concentration, color, and sensory properties has been reported among cultivars because of differences in genotype, environmental conditions, harvest maturity, drying methods, storage conditions, and analytical methodologies. Furthermore, increased inclusion levels may adversely affect color, flavor, texture, and overall consumer acceptance of fortified foods, emphasizing the need to optimize formulation strategies. Additionally, many reported nutritional and functional advantages of sweetpotato leaf powders are supported primarily by compositional analyses, laboratory-scale product development, and pre-clinical investigations. Evidence from industrial-scale manufacturing, long-term storage studies, consumer acceptance trials, and randomized human intervention studies remains comparatively limited. Research should prioritize standardized processing protocols, comparative foodomics evaluation of diverse cultivars, optimization of drying and stabilization technologies, comprehensive assessment of nutrient bioavailability following food processing, and industrial validation of fortified food products. Integration of AI, predictive quality modeling, multi-omics technologies, and sensory analytics will further strengthen ingredient standardization, quality assurance, formulation optimization, and commercialization of sweetpotato leaf powders as sustainable functional food ingredients [50, 51].

Foodomics approaches in sweetpotato functional ingredient research

Recent advances in foodomics have substantially transformed research on sweetpotato functional ingredients by enabling comprehensive, systems-level characterization of their molecular composition, processing behavior, nutritional quality, safety, and biological functionality. Foodomics integrates metabolomics, genomics, transcriptomics, proteomics, lipidomics, bioinformatics, chemometrics, and computational biology to provide a holistic understanding of food systems from crop production through processing, digestion, and human health outcomes [52–57]. Unlike conventional compositional analyses that quantify individual nutrients or phytochemicals in isolation, foodomics investigates the complex interactions among genes, proteins, metabolites, environmental factors, processing technologies, and food

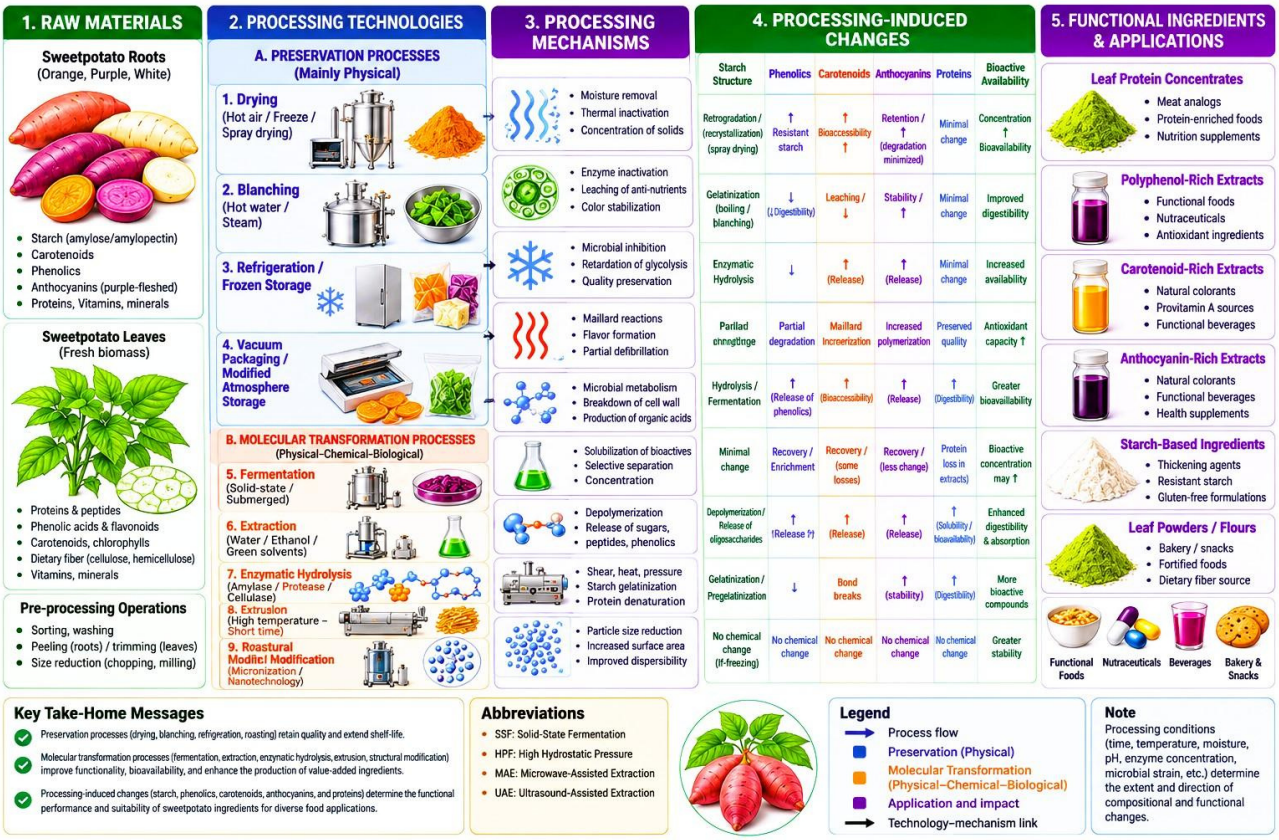


Figure 3. Processing pathways for conversion of sweetpotatoes into functional food ingredients, including drying, extraction, and structural modification routes leading to diverse food and nutraceutical applications. Roasting is grouped with preservation processes because of its dehydrating, shelf-life-extending effect; its molecular transformation effects (e.g., Maillard reactions) are shown in the processing-mechanism column and in Figure 2. Vacuum packaging/modified atmosphere storage (Figure 2) is not shown because it does not involve a distinct processing mechanism.

matrices that collectively determine ingredient functionality and product quality [52–55]. Among these approaches, metabolomics has become one of the most widely used analytical platforms in sweetpotato research. High-resolution liquid chromatography-mass spectrometry (LC-MS), gas chromatography-mass spectrometry (GC-MS), nuclear magnetic resonance (NMR), and related technologies have enabled comprehensive profiling of phenolic acids, chlorogenic acid derivatives, anthocyanins, carotenoids, flavonoids, amino acids, sugars, organic acids, volatile compounds, and numerous secondary metabolites linked to nutritional quality, sensory characteristics, and reported biological activities [52–54]. Metabolomic fingerprinting also facilitates cultivar authentication, biomarker discovery, quality assurance, geographical origin verification, and the evaluation of processing-induced molecular transformations, thereby supporting standardized ingredient development for food and nutraceutical applications [52, 54, 58, 59]. Transcriptomic and genomic investigations have substantially advanced understanding of the molecular mechanisms regulating anthocyanin accumulation, carotenoid biosynthesis, starch metabolism, stress tolerance, nutrient partitioning, and other metabolic pathways underlying cultivar-specific variation. Integrating transcriptomics with metabolomics enables identification of regulatory genes and metabolic networks that influence phytochemical accumulation and processing performance, providing valuable information for precision breeding, marker-assisted selection, and the development of nutritionally enhanced sweetpotato cultivars.

Proteomics has emerged as an important complementary platform for characterizing sweetpotato proteins and peptides, including the evaluation of amino acid composition, protein digestibility, enzymatic modifications, allergenic potential, post-translational modifications, and processing-induced structural alterations. Combined proteomic and metabolomic analyses further enhance understanding of protein-polyphenol interactions, food matrix effects, and ingredient functionality during food processing and storage. More recently, integrated multi-omics approaches that combine metabolomics, transcriptomics, proteomics, lipidomics, microbiomics, and advanced bioinformatics have enabled comprehensive

investigation of genotype × environment × management interactions that influence sweetpotato quality and functionality [54, 55, 60]. These multidisciplinary strategies facilitate the identification of molecular biomarkers for cultivar authentication, prediction of processing behavior, optimization of ingredient functionality, and evaluation of food quality and safety throughout the production chain [53–55, 58].

Foodomics also offers valuable opportunities to advance understanding of the bioavailability, biotransformation, metabolic fate, and biological interactions of sweetpotato-derived bioactive compounds in complex food matrices and human physiological systems [55–57, 61, 62]. Integration with nutrigenomics, microbiome research, and precision nutrition has begun to elucidate how dietary phytochemicals interact with the intestinal microbiota, host metabolism, and genetic variability, thereby providing a more comprehensive understanding of potential nutritional outcomes. Nevertheless, these investigations remain in the early stages, and additional human intervention studies are required before many mechanistic observations can be translated into evidence-based dietary recommendations.

AI, machine learning (ML), deep learning, and advanced chemometric modeling increasingly complement foodomics by enabling automated interpretation of high-dimensional datasets, predicting metabolite profiles, identifying quality biomarkers, optimizing processing conditions, and precisely selecting superior cultivars [50, 51, 55]. These computational approaches offer new opportunities to accelerate quality control, product development, and decision-making across the sweetpotato value chain. Despite remarkable progress, several important challenges remain. Significant variability among cultivars, environmental conditions, agricultural practices, processing technologies, analytical platforms, and data-processing pipelines frequently limit reproducibility and direct comparison across studies. In addition, the lack of standardized foodomics methodologies, harmonized metabolite databases, validated molecular biomarkers, and integrated multi-center datasets constrains broader application of foodomics in industrial settings. Furthermore, relatively few investigations have linked foodomics-derived molecular signatures to long-term clinical outcomes, consumer acceptance, industrial scalability, or regulatory evaluation [55–57]. Future research should prioritize standardized multi-omics protocols, harmonized analytical workflows, robust biomarker libraries, integration of AI with predictive foodomics, comprehensive studies of processing-induced molecular transformations, quantitative evaluation of bioavailability and gut microbiome interactions, and randomized human clinical trials. Equally important are LCA, TEA, and industrial validation to ensure that foodomics-driven innovations are scientifically robust, economically feasible, environmentally sustainable, and commercially translatable. Collectively, these multidisciplinary advances provide a transformative framework for developing next-generation sweetpotato functional foods with improved nutritional quality, ingredient consistency, processing stability, safety, and consumer acceptance, while strengthening the scientific foundation for evidence-based utilization of this globally important crop.

Processing technologies for functional ingredient development

Processing technologies play a fundamental role in transforming sweetpotato roots and leaves into high-value functional food ingredients with enhanced nutritional quality, physicochemical functionality, storage stability, and industrial applicability. Rather than serving solely as preservation methods, modern processing technologies induce complex molecular, structural, and biochemical transformations that affect starch functionality, protein characteristics, phytochemical stability, bioaccessibility, sensory quality, and overall ingredient performance [4]. Consequently, understanding these processing-induced changes through foodomics approaches has become increasingly important for developing evidence-based functional food ingredients and optimizing industrial utilization. Foodomics provides an integrated analytical framework that combines metabolomics, proteomics, transcriptomics, lipidomics, chemometrics, and advanced analytical chemistry to characterize processing-induced molecular transformations. These technologies enable comprehensive monitoring of changes in carotenoids, anthocyanins, polyphenols, resistant starch, proteins, peptides, sugars, volatile compounds, and other metabolites throughout food processing. Consequently, foodomics has shifted process optimization from empirical trial-and-error approaches to molecularly informed processing strategies that maximize nutritional retention while

maintaining desirable technological functionality [63]. The major processing technologies currently employed for sweetpotato-derived ingredients are summarized in Table 2, together with representative processing conditions, physicochemical modifications, measurable quality outcomes, functional property changes, and industrial applications.

Table 2. Effects of processing technologies on functional properties of sweetpotato-derived ingredients.

Processing method	Raw material	Representative processing parameters (examples)	Key physicochemical changes	Measurable outcomes (examples)	Functional property modification	Food industry implication
Sun/Cabinet/Tunnel drying [64]	Roots and leaves	Hot-air or cabinet drying typically occurs at 50–60°C for 4–8 h; open-air sun drying is highly variable; some OFSP cultivars were dried at 58°C for 4 h.	Moisture reduction; partial degradation of vitamin C and carotenoids; concentration of minerals, fiber, and carbohydrate due to water loss.	Sun-drying of OFSP slices caused trans-β-carotene losses up to ~83% in some cultivars, whereas cabinet drying gave lower losses (~28–47%); tunnel/solar dryers retained ~87–90% provitamin A (~10–13% loss).	Improved shelf life and bulk density, but with reduced retention of heat-sensitive nutrients under higher temperature or uncontrolled sun exposure; nutritional changes depend strongly on time-temperature profile and dryer type.	Flour and powder production where moderate losses of carotenoids and vitamin C are acceptable; more controlled cabinet/tunnel drying is preferred for high β-carotene retention.
Freeze-drying [65, 66]	Roots and leaves	Typical protocol: blanch (optional), freeze to about –28 to –33°C, then vacuum freeze-dry at ~35–80 Pa for 12–20 h.	Minimal thermal degradation; sublimation preserves cell structure; limited oxidation; good retention of color and rehydration capacity.	Under optimized conditions, dehydration below 60°C (including freeze-drying) can retain approximately 70–90% of β-carotene and 75–90% of overall vitamins in sweetpotato products.	High retention of bioactive compounds and natural color; excellent rehydration; near-fresh sensory quality compared with hot-air and sun drying.	Premium functional powders for nutraceuticals, high-value ingredients, and applications where maximal retention of carotenoids, phenolics, and vitamin C is required.
Spray drying [67]	Extracts (juices, purees, polyphenol or carotenoid extracts)	Inlet temperatures often ~140–180°C; outlet temperatures ~70–90°C; carrier solids (e.g., maltodextrin) ~5–20%.	Rapid dehydration into microencapsulated powders; reduced water activity; potential partial loss of heat-sensitive compounds, but improved handling and stability.	Spray-dried sweetpotato starch or extract shows reduced bulk density, a narrower particle-size distribution, and improved flow; encapsulation of carotenoids/phenolics can maintain a higher proportion of antioxidant activity during storage compared with non-encapsulated liquids (values are formulation-dependent).	Enhanced stability, flowability, and dispersibility of bioactive compounds; enables controlled release and improved shelf life compared with liquid forms.	Encapsulated carotenoid and polyphenol ingredients, instant beverages, powdered flavors and colorants, and nutraceutical powders.
Extrusion cooking [68]	Root flour/starch, composite flours	Barrel temperature often ~100–155°C (multi-zone	Starch gelatinization and loss of crystallinity; protein denaturation;	At 150–155°C during extrusion, products can achieve high expansion, with a specific volume of	Improved expansion, texture, and digestibility; modified	Snacks, breakfast cereals, instant porridges, and

Table 2. Effects of processing technologies on functional properties of sweetpotato-derived ingredients. (*continued*)

Processing method	Raw material	Representative processing parameters (examples)	Key physicochemical changes	Measurable outcomes (examples)	Functional property modification	Food industry implication
		profiles), moisture ~15–25%, screw speed ~80–140 rpm, die diameter ~4–10 mm.	partial dextrinization; formation of porous expanded structures; potential formation of some resistant starch fractions.	around 2.44 mL/g and reduced hardness (~985 g), compared with unextruded flour (2.17 mL/g; hardness ~1,637 g). Resistant starch formation depends on formulation and cooling, with some systems reporting increased slowly digestible/resistant fractions.	glycemic response; formation of ready-to-eat snack structures while retaining acceptable micronutrient levels when parameters are optimized.	ready-to-eat products based on sweetpotato flour or composite blends.
Fermentation (lactic, mixed) [63]	Roots and leaves; juices or purees	Lactic acid bacteria fermentation typically 24–72 h at ~30–37°C; inoculum ≥ 10^6 CFU/mL; possible co-fermentation with yeast or other microbes.	Microbial hydrolysis of macromolecules; changes in phenolic profiles; reduction of some antinutritional factors; acidification and flavor development.	In lactic-fermented purple sweetpotato juice, ABTS [2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)] radical scavenging activity increased by ~20%; DPPH and ·OH scavenging increased by ~11–20%; total phenolic and flavonoid contents increased relative to unfermented juice. Fermented sweetpotato matrices show sustained high phenolic content and antioxidant activity over 24–72 h.	Improved bioavailability of phenolics, enhanced antioxidant capacity, and reduced selected antinutritional factors; development of acidic, mildly effervescent sensory profiles.	Functional beverages, fermented purees, probiotic or symbiotic products based on sweetpotato roots or juices, and, potentially, leaf-containing formulations.
Blanching [69]	Leaves (and sometimes roots prior to drying)	Hot-water blanching is typically ~85–95°C for 1–5 min; steam blanching is also used before drying or freezing.	Enzyme (e.g., polyphenol oxidase, peroxidase) inactivation; partial leaching of soluble solids; pigment stabilization; partial loss of vitamin C, depending on severity.	Proper blanching before drying preserves more color and vitamin A activity than unblanched sun-drying; cabinet/hot-air drying after blanching retains more ascorbic acid than sun-drying in several sweetpotato studies (exact losses depend on the time-temperature regime).	Improved color retention, reduced enzymatic browning and bitterness, better flavor and texture in rehydrated leaves and root slices.	Pre-treatment for vegetable-type leaf products and powders, frozen or dried root slices, and intermediate ingredients for further processing.
Roasting/baking [70, 71]	Roots (whole, sliced, or pureed)	Baking commonly ~180–220°C for 20–60 min; roasting conditions vary with product thickness and desired browning.	Maillard reactions and caramelization; moisture loss; partial starch gelatinization and dextrinization; increased sweetness via maltose formation.	Baking at ~200°C reduces starch and markedly increases maltose, which becomes the major sugar of baked roots; antioxidant levels can be maintained or slightly increased in some conditions, but vitamin C and some carotenoids may decline; crust color and aroma intensify.	Flavor enhancement, aroma development, desirable browning, and softer texture contribute to consumer-acceptable baked and roasted products.	Bakery and snack products such as baked sweetpotato chips, wedges, breads, and purees.

Table 2. Effects of processing technologies on functional properties of sweetpotato-derived ingredients. (*continued*)

Processing method	Raw material	Representative processing parameters (examples)	Key physicochemical changes	Measurable outcomes (examples)	Functional property modification	Food industry implication
Enzymatic hydrolysis [72, 73]	Roots (starch-based substrates, purees)	Liquefaction and saccharification using α-amylase, glucoamylase, or other carbohydrases; typical conditions ~50–65°C, 1–4 h, pH optimized for the enzyme used.	Starch breaks down into dextrins and oligosaccharides; reduced viscosity; increased soluble solids and sweetness; potential formation of resistant oligosaccharides depending on enzyme and time.	Conversion of sweetpotato starch to syrups with high dextrose equivalent; viscosity can drop several-fold; increasing soluble solids and sweetness enables direct use as sweeteners or fermentation substrates.	Increased sweetness, reduced viscosity, improved processability in beverages and syrups; generation of substrates for fermentation or prebiotic applications.	Syrups, beverages, confectionery, and substrates for bioethanol, organic acids, or probiotic fermentations.
Solvent/green extraction [74]	Leaves and roots (polyphenols, carotenoids, anthocyanins)	Conventional solvent extraction with aqueous ethanol/methanol (often 50–80% v/v) at ~25–60°C; advanced green methods may use ultrasound, microwave, or pressurized liquids.	Isolation and concentration of phytochemicals; possible structural modification of sensitive compounds depending on solvent, temperature, and time.	Optimization studies on purple sweetpotato report anthocyanin yields of 1.0–1.5 mg/g DW in dehydrated material under optimal conditions, with improved color stability due to acylated structures; leaf extractions can yield total polyphenols of several g GAE/100 g DW depending on the solvent and cultivar.	Concentration of antioxidants and pigments; improved control over dosage and formulation; potential to tailor antioxidant and color intensity in final products.	Nutraceuticals, functional beverages, natural colorants, antioxidant food additives, and ingredient systems for clean-label formulations.

Drying technologies

Drying remains one of the most widely used preservation technologies for sweetpotato roots and leaves because it substantially reduces moisture content, inhibits microbial growth, and extends shelf life. Conventional drying methods, including sun drying, cabinet drying, tunnel drying, and hot-air drying, are widely used because of their relatively low cost and operational simplicity [64, 65]. However, drying also induces numerous physicochemical and molecular changes. Heat-sensitive compounds, including vitamin C, carotenoids, chlorophylls, and certain phenolic compounds, may degrade depending on drying temperature, oxygen exposure, drying duration, and moisture removal kinetics. Conversely, water removal concentrates minerals, dietary fiber, carbohydrates, and some relatively stable phytochemicals on a dry-weight basis. Freeze-drying is widely regarded as the most effective method for preserving bioactive compounds because water is removed by sublimation under reduced pressure and low temperature. Compared with conventional thermal drying, freeze-drying minimizes oxidation, pigment degradation, structural collapse, and loss of volatile compounds, while maintaining superior rehydration capacity, color retention, and functional ingredient quality. Consequently, freeze-dried sweetpotato powders are increasingly used in premium functional foods and nutraceutical formulations. Foodomics studies have shown that drying affects not only nutrient concentrations but also metabolite composition. Metabolomic profiling has revealed cultivar-dependent changes in carotenoid isomers, phenolic metabolites, sugars, amino acids, and volatile compounds after thermal dehydration, underscoring that processing effects cannot be generalized across all sweetpotato varieties.

Fermentation

Fermentation has emerged as an important processing strategy for improving both nutritional quality and functional properties of sweetpotato-derived ingredients. Lactic acid bacteria and mixed microbial cultures hydrolyze complex carbohydrates, modify phenolic compounds, reduce selected antinutritional factors, and

generate desirable flavor compounds. Fermentation also alters metabolite composition through microbial enzymatic activity, increasing the bioavailability of selected phenolic compounds while simultaneously modifying carbohydrate metabolism, organic acid production, amino acid profiles, and antioxidant capacity. Several studies have reported increased antioxidant activity and improved phenolic availability following controlled fermentation of sweetpotato juices and purees. Nevertheless, the magnitude of these improvements depends on microbial strain, fermentation conditions, substrate composition, cultivar, and analytical methodology. Although fermentation has demonstrated promising improvements in nutrient bioavailability and functional quality under laboratory conditions, additional industrial-scale validation remains necessary before generalized processing recommendations can be established.

Extrusion processing

Extrusion cooking is widely used to manufacture expanded snacks, breakfast cereals, instant porridges, and composite flour products. High temperature, pressure, and shear simultaneously gelatinize starch, denature proteins, reduce microbial contamination, and generate expanded structures with desirable texture. Processing-induced starch transformations include gelatinization, dextrinization, disruption of crystalline structure, amylose reassociation, and formation of resistant starch fractions during subsequent cooling. These molecular changes influence digestibility, glycemic response, texture, water absorption, expansion characteristics, and shelf stability. Foodomics-assisted investigations have demonstrated that extrusion also modifies metabolite profiles, volatile compounds, Maillard reaction products, and antioxidant composition. Consequently, optimization requires balancing desirable technological characteristics with retention of nutritionally important bioactive compounds.

Extraction technologies

Extraction technologies are increasingly used to isolate carotenoids, anthocyanins, chlorogenic acid, caffeoylquinic acid derivatives, flavonoids, proteins, dietary fiber fractions, and other functional ingredients from sweetpotato tissues. Conventional solvent extraction remains widely used, whereas ultrasound-assisted extraction, microwave-assisted extraction, pressurized liquid extraction, and other green extraction technologies are attracting growing attention for their higher extraction efficiency and reduced solvent consumption. Foodomics has substantially improved the optimization of extraction processes by comprehensively characterizing metabolite composition, extraction selectivity, phytochemical stability, and biomarker recovery. High-resolution chromatography coupled with mass spectrometry enables identification of cultivar-specific phytochemical fingerprints and facilitates quality control and ingredient standardization. Nevertheless, extraction efficiency varies considerably with solvent composition, extraction temperature and time, plant tissue, cultivar, maturity stage, and analytical platform. Therefore, standardized extraction protocols remain an important research priority.

Processing-induced molecular transformations

One of the most significant advances in recent sweetpotato research has been the recognition that food processing fundamentally alters molecular composition rather than merely preserving existing nutrients.

Thermal treatments affect carotenoid isomerization, anthocyanin degradation, vitamin stability, starch digestibility, protein denaturation, volatile formation, and Maillard reaction pathways. Drying affects moisture sorption characteristics, oxidation reactions, pigment retention, and phytochemical stability. Fermentation alters microbial metabolites, organic acids, phenolic bioavailability, and carbohydrate utilization. Extrusion alters starch crystallinity, resistant starch formation, and textural functionality. These processing-induced molecular transformations can now be comprehensively evaluated using integrated foodomics approaches that combine metabolomics, proteomics, chemometrics, and advanced statistical modeling. These approaches provide mechanistic insight into how processing affects nutritional quality, functional ingredient performance, and product stability.

Current limitations and future research needs

Despite substantial progress, several important knowledge gaps remain. First, quantitative data on processing-induced degradation kinetics of carotenoids, anthocyanins, phenolic compounds, proteins, and vitamins remain limited for many commercially important cultivars. Second, standardized protocols for comparing processing technologies across laboratories are still lacking, making direct comparisons among published studies difficult. Third, industrial-scale validation of many laboratory-scale processing technologies, including green extraction methods, advanced encapsulation systems, and precision fermentation, remains limited. Finally, future research should integrate foodomics, AI, ML, predictive process modeling, LCA, and TEA to optimize sweetpotato processing and improve nutritional quality, sustainability, economic feasibility, and industrial scalability. Overall, processing technologies should be viewed not merely as preservation tools but as molecular engineering strategies that shape nutritional composition, functional performance, quality attributes, and commercial value of sweetpotato-derived food ingredients. Integrating foodomics with advanced processing science will substantially strengthen the future development of evidence-based functional foods derived from both sweetpotato roots and leaves.

Safety, antinutritional factors, and sensory considerations

Despite the considerable nutritional, functional, and industrial potential of sweetpotato roots and leaves, their successful incorporation into commercial food systems requires careful evaluation of food safety, antinutritional constituents, processing effects, sensory quality, regulatory compliance, and consumer acceptance. Although sweetpotato has a long history of safe consumption worldwide, ingredient quality and safety may vary considerably depending on cultivar, agronomic practices, environmental conditions, processing technologies, storage conditions, and product formulation. Therefore, comprehensive quality assurance and evidence-based safety assessment are essential for the development of standardized sweetpotato-derived functional ingredients.

Antinutritional factors

Sweetpotato leaves naturally contain several antinutritional compounds, including oxalates, phytates, tannins, and trypsin inhibitors, whereas storage roots generally contain substantially lower concentrations of these compounds. The concentrations of these compounds are influenced by genotype, leaf maturity, environmental conditions, fertilizer management, irrigation practices, and harvest stage [6]. Oxalates may reduce calcium bioavailability by forming insoluble calcium oxalate complexes, while phytates can chelate essential minerals such as iron, zinc, calcium, and magnesium, thereby decreasing their intestinal absorption. Tannins may reduce protein digestibility by forming protein complexes and can contribute to bitterness and astringency. Although these compounds may reduce nutrient bioavailability at high concentrations, they are also recognized for beneficial biological activities, including antioxidant and antimicrobial properties, emphasizing the importance of balanced interpretation rather than considering them exclusively undesirable constituents. Current evidence indicates that antinutritional compound concentrations in edible sweetpotato tissues are generally lower than those reported for many other leafy vegetables and are substantially reduced by conventional household processing. Nevertheless, quantitative concentrations vary considerably among cultivars and analytical methods, highlighting the need for standardized compositional databases.

Effects of processing on safety and antinutritional components

Processing is central to improving the nutritional quality and safety of sweetpotato-derived ingredients. Conventional processing methods, including blanching, boiling, steaming, fermentation, drying, and extrusion, substantially reduce antinutritional factors while improving digestibility, palatability, and storage stability. Blanching effectively inactivates oxidative enzymes, including polyphenol oxidase and peroxidase, thereby reducing enzymatic browning, bitterness, and undesirable color changes, while partially reducing soluble oxalates and other heat-labile antinutritional compounds. Fermentation further improves nutritional quality by degrading phytates and selected tannins, modifying phenolic composition,

and increasing mineral bioavailability. Thermal processing may simultaneously reduce certain heat-sensitive nutrients, including vitamin C and some carotenoids; therefore, optimizing processing conditions requires balancing nutrient retention with reductions in antinutritional constituents. Foodomics approaches have recently provided new insights into processing-induced molecular transformations by simultaneously monitoring degradation products, metabolite profiles, phytochemical stability, and changes in nutritional composition throughout processing. These integrated analytical approaches enable more precise optimization of processing parameters than conventional compositional analyses alone.

Microbiological safety

The microbiological quality of sweetpotato-derived ingredients is an important consideration, particularly for dehydrated leaf powders, protein concentrates, minimally processed products, and functional beverages. Potential microbial hazards include bacterial contamination at harvest, during washing, drying, grinding, storage, transportation, and packaging. Hygienic processing practices, Good Manufacturing Practices (GMP), Hazard Analysis and Critical Control Point (HACCP) systems, and appropriate moisture control are essential to minimize microbial risks. Low moisture content, achieved through properly controlled drying, substantially improves microbial stability during storage. Nevertheless, inadequate drying or improper storage conditions may permit mold growth, mycotoxin production, and deterioration of product quality. Future studies should investigate shelf-life stability, microbial ecology, and preservation technologies for emerging sweetpotato-based functional ingredients intended for commercial distribution.

Environmental contaminants

The safety of sweetpotato-derived food ingredients may also be affected by environmental contaminants originating from agricultural production systems. Heavy metals, including cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg), may accumulate in edible plant tissues when crops are grown in contaminated soils. Likewise, pesticide residues may persist when agricultural chemicals are misapplied or when pre-harvest intervals are insufficient. Current literature indicates that sweetpotato generally has an acceptable safety profile when cultivated under recommended agricultural practices; however, contamination risks remain site-specific and should not be generalized. Therefore, routine monitoring of heavy metals, pesticide residues, and other environmental contaminants should be incorporated into quality assurance programs for commercial sweetpotato ingredients.

Allergenicity and consumer safety

Sweetpotato is generally regarded as a low-allergen food with a long history of safe dietary consumption. Nevertheless, processing-induced modifications to proteins and peptides may influence allergenic potential, digestibility, and biological activity. Current proteomic investigations remain limited, and additional research is needed to characterize protein composition, potential allergenic proteins, digestibility, and processing-induced structural modifications relevant to food safety. Future foodomics studies that integrate proteomics, peptidomics, and immunological analyses may substantially improve understanding of protein safety and support the development of standardized plant-based protein ingredients.

Sensory quality and consumer acceptance

Sensory quality remains a principal determinant of the successful commercialization of sweetpotato-derived functional ingredients. Storage roots are generally characterized by desirable sweetness, attractive color, pleasant aroma, and soft texture, contributing to their broad consumer acceptance across diverse food products. In contrast, sweetpotato leaves often have a bitter, astringent, grassy flavor and intense green pigmentation, characteristics that may reduce consumer acceptance in certain food applications. These sensory attributes are largely associated with polyphenolic compounds, chlorophylls, organic acids, and other secondary metabolites, whose concentrations vary substantially among cultivars and maturity stages. Processing technologies, including blanching, fermentation, drying, ingredient blending, and encapsulation, can effectively reduce undesirable sensory attributes while maintaining acceptable nutritional quality. Consumer acceptance studies further indicate that product success depends not only on

nutritional composition but also on appearance, texture, flavor, aroma, convenience, cultural familiarity, and price competitiveness. Consequently, successful commercialization requires multidisciplinary approaches that integrate food science, sensory evaluation, consumer behavior, and market research.

Regulatory considerations

Commercial use of sweetpotato-derived functional ingredients must comply with national and international food safety regulations governing ingredient identity, compositional standards, contaminant limits, labeling requirements, health claims, and manufacturing practices. Importantly, many biological activities reported for sweetpotato phytochemicals are supported primarily by in vitro experiments and animal studies rather than by human clinical investigations. Therefore, health-related marketing claims should remain consistent with the available scientific evidence and applicable regulatory frameworks. Foodomics technologies can substantially support regulatory compliance by enabling ingredient authentication, molecular fingerprinting, adulteration detection, biomarker verification, compositional standardization, and quality assurance.

Future perspectives

Future research should prioritize standardized analytical methods for quantifying antinutritional compounds, comprehensive foodomics characterization of safety-related metabolites, improved contaminant monitoring, industrial-scale shelf-life evaluation, and integrated risk assessment. Greater integration of metabolomics, proteomics, microbiomics, and AI will enable predictive safety assessment, ingredient authentication, contaminant detection, and quality standardization across sweetpotato production and processing systems. Overall, the nutritional and functional advantages of sweetpotato roots and leaves substantially outweigh the identified safety concerns when appropriate cultivars, processing technologies, quality assurance systems, and regulatory standards are used. Continued research that integrates foodomics with food safety science will further strengthen the development of safe, standardized, and commercially viable sweetpotato-derived functional ingredients for sustainable food systems.

Integration into functional food systems

The integration of sweetpotato-derived ingredients into modern food systems has expanded considerably over the past decade, owing to their favorable nutritional profile, technological functionality, natural pigmentation, and compatibility with clean-label product development. Storage roots and leaves provide complementary functional attributes that support the formulation of diverse food products while improving nutritional quality and enabling more sustainable use of whole-plant biomass [1, 6]. However, successful commercialization depends not only on nutrient composition but also on ingredient stability, processing compatibility, sensory acceptability, regulatory compliance, and economic feasibility. The application landscape of sweetpotato-derived functional ingredients in modern food systems, illustrating their integration into bakery products, beverages, dairy systems, nutraceuticals, snacks, and infant nutrition, is presented in Figure 4.

Bakery and cereal-based products

Sweetpotato flour has become one of the most widely used root-derived ingredients in bakery applications because of its natural sweetness, desirable color, starch functionality, and gluten-free characteristics. It has been successfully incorporated into bread, cakes, biscuits, cookies, muffins, noodles, pasta, composite flours, and breakfast cereals. Root flour contributes to water absorption, starch gelatinization, moisture retention, natural pigmentation, and improved textural characteristics, while increasing dietary fiber, carotenoids, and resistant starch relative to conventional cereal products. Orange-fleshed cultivars further enhance provitamin A content, whereas purple-fleshed cultivars provide anthocyanins that serve as natural colorants and antioxidants [1, 6]. Leaf powders have also been incorporated into bakery formulations to increase protein, dietary fiber, minerals, and polyphenolic compounds. However, excessive substitution

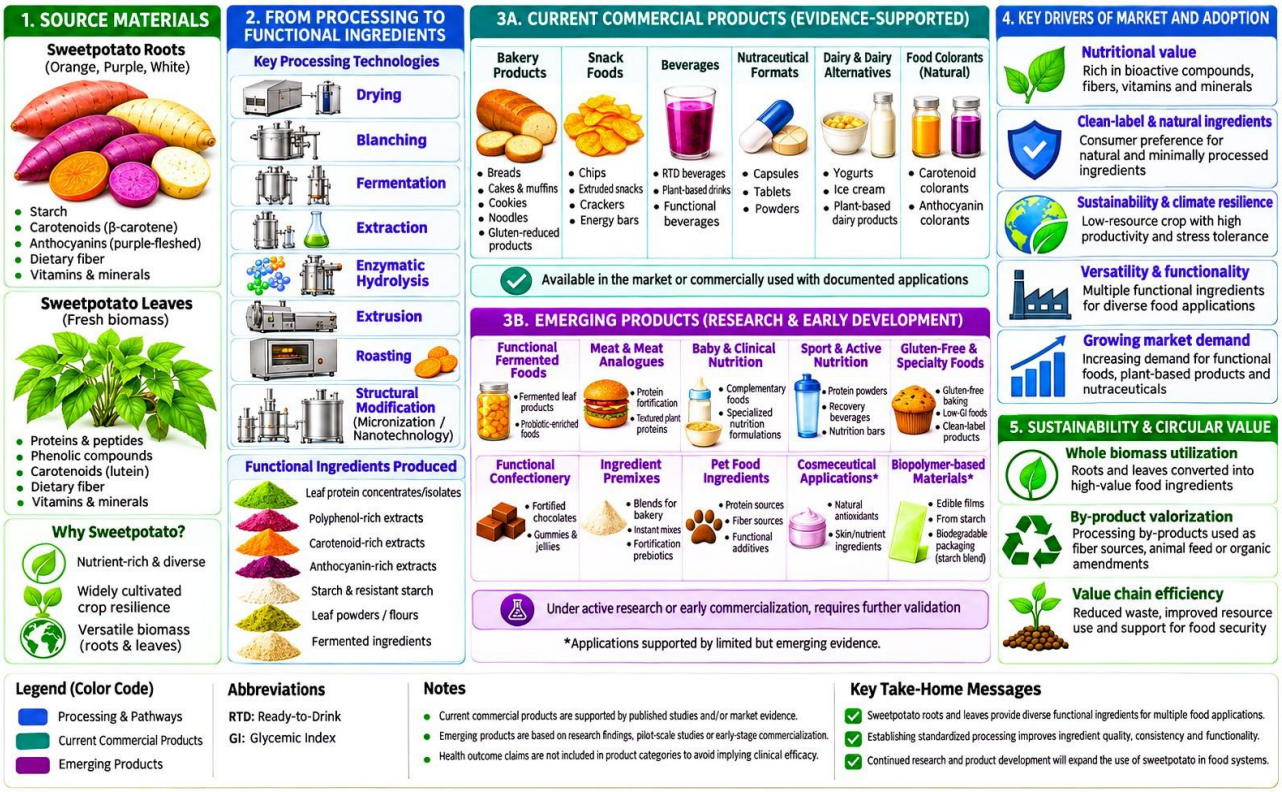


Figure 4. Applications and commercialization of sweetpotato-derived functional ingredients.

levels may negatively affect dough rheology, product volume, color, flavor, and overall consumer acceptance due to increased bitterness and green pigmentation. Current evidence suggests that optimal substitution levels depend on product type, cultivar, processing conditions, and consumer preferences, underscoring the importance of formulation-specific optimization rather than universal recommendations.

Gluten-free and specialty foods

Sweetpotato-derived ingredients are particularly attractive for gluten-free product development because root starch provides desirable thickening, binding, and structural properties without gluten proteins.

Commercial and experimental applications include gluten-free breads, noodles, pasta, crackers, snacks, and composite flour blends. Foodomics investigations have improved understanding of starch molecular structure, gelatinization behavior, amylose-amylopectin interactions, resistant starch formation, and processing-induced physicochemical changes that influence gluten-free product quality.

Future studies integrating foodomics with predictive processing models may facilitate cultivar selection optimized for gluten-free applications.

Functional beverages and fermented foods

Sweetpotato-derived ingredients are increasingly incorporated into functional beverages, smoothies, fermented juices, probiotic products, and nutraceutical drinks. Root-derived syrups provide natural sweetness, whereas anthocyanin-rich extracts function as natural colorants and antioxidant ingredients. Leaf extracts contribute polyphenols, chlorogenic acid derivatives, caffeoylquinic acids, vitamins, and minerals that enhance nutritional quality. Controlled fermentation further modifies phytochemical composition, organic acid production, aroma compounds, and antioxidant activity, creating opportunities for developing novel fermented functional beverages. However, many beverage applications remain at laboratory or pilot scale, and additional industrial validation is needed to establish long-term stability, consumer acceptance, and commercial feasibility.

Dairy and plant-based food systems

Natural pigments extracted from orange- and purple-fleshed sweetpotato have been incorporated into yogurt, dairy desserts, ice cream, flavored milk, and plant-based dairy alternatives. Anthocyanins and carotenoids provide stable natural coloration while simultaneously contributing to antioxidant activity, thereby supporting current consumer demand for clean-label ingredients. Leaf proteins and fiber-rich fractions are also receiving increasing attention as ingredients for plant-based meat analogs, protein beverages, soups, and fortified foods. Although preliminary results are encouraging, large-scale processing technologies for producing standardized leaf protein concentrates remain underdeveloped.

Nutraceutical and functional ingredient applications

The diverse phytochemical composition of sweetpotato supports the development of nutraceutical ingredients including polyphenol extracts, anthocyanin concentrates, carotenoid-rich preparations, resistant starch, dietary fiber concentrates, and protein-rich leaf powders. These ingredients have demonstrated promising biological activities in experimental studies, including antioxidant, anti-inflammatory, antimicrobial, and antidiabetic properties. Nevertheless, most supporting evidence currently comes from biochemical assays, cell culture experiments, and animal studies, whereas well-controlled human intervention studies remain comparatively limited. Consequently, health-related applications should be interpreted according to the strength of available evidence, and reported biological activities should not be considered equivalent to clinically established therapeutic effects.

Foodomics-driven functional ingredient development

Foodomics has emerged as an essential platform for optimizing functional ingredient development by integrating metabolomics, proteomics, transcriptomics, chemometrics, and advanced analytical chemistry. These technologies enable (i) cultivar authentication through molecular fingerprinting; (ii) identification of nutritional biomarkers; (iii) monitoring of processing-induced metabolite transformations; (iv) quality assurance and compositional standardization; (v) prediction of ingredient functionality; and (vi) evaluation of phytochemical stability during storage and processing. Compared with conventional compositional analyses, foodomics provides a systems-level understanding of how genotype, environment, processing conditions, and food matrices collectively influence ingredient performance.

Consumer acceptance and market translation

Despite the considerable nutritional advantages of sweetpotato-derived ingredients, successful market adoption depends heavily on consumer perception. Storage-root ingredients generally exhibit excellent consumer acceptance because of their desirable sweetness, attractive color, and familiar sensory properties. Conversely, leaf-derived ingredients frequently exhibit bitterness, grassy flavor, astringency, and dark green coloration that may limit consumer acceptance in some food categories. Consumer preference studies indicate that formulation optimization, appropriate substitution levels, flavor masking strategies, fermentation, ingredient blending, and product-specific processing significantly improve sensory acceptance while maintaining nutritional quality. Future product development should therefore integrate sensory science, consumer behavior research, and market analysis with foodomics-guided ingredient optimization.

Translation and future opportunities

Although numerous sweetpotato-derived functional ingredients have demonstrated promising laboratory-scale performance, commercial translation varies substantially among application categories. Root flour, starch, puree, and chips are already commercially established worldwide, whereas many leaf-derived ingredients, protein concentrates, polyphenol extracts, and specialty nutraceutical products remain at the experimental or pilot scale. Successful commercialization will require standardized raw-material quality, improved shelf-life characterization, scalable processing technologies, regulatory approval, economic feasibility, and consistent consumer acceptance. Integration of AI, predictive foodomics, ML, digital

manufacturing, and precision quality control offers significant opportunities to accelerate the commercialization of next-generation sweetpotato-derived functional foods. Overall, the complementary utilization of storage roots and leaves provides substantial opportunities for developing sustainable, nutrient-dense, and value-added food products. However, future innovation should emphasize evidence-based formulation, standardized quality assessment, realistic industrial scalability, and multidisciplinary integration of foodomics, processing science, nutrition, sensory evaluation, and sustainability assessment. Such an integrated approach will strengthen the role of sweetpotato as a strategically important crop for future functional food systems and circular bioeconomy development.

Industrial translation, commercialization, and future perspectives

The commercial application of sweetpotato has evolved substantially from its traditional role as a staple food to an increasingly important source of functional ingredients, natural colorants, nutraceuticals, and value-added food products. This transition has been driven by growing consumer demand for clean-label foods, plant-based ingredients, sustainable production systems, and naturally derived bioactive compounds. Nevertheless, successful industrial translation requires integration of scientific innovation with scalable processing technologies, regulatory compliance, quality assurance, consumer acceptance, and economic feasibility.

Current commercial applications

Sweetpotato roots are widely utilized commercially in the production of fresh foods, frozen products, dehydrated powders, starch, flour, purees, chips, noodles, beverages, confectionery products, and infant foods. Orange-fleshed cultivars are increasingly incorporated into provitamin A-enriched food products, while purple-fleshed cultivars serve as important sources of natural anthocyanin colorants for beverages, dairy products, bakery products, and confectionery applications. In contrast, commercial utilization of sweetpotato leaves remains comparatively limited despite their high concentrations of proteins, dietary fiber, minerals, vitamins, and polyphenolic compounds. Current industrial applications primarily involve dehydrated vegetable products, functional teas, dietary supplements, and specialty health foods, whereas broader commercialization remains constrained by processing, sensory, and supply-chain challenges.

Opportunities for value addition and circular bioeconomy

Whole-plant utilization represents one of the most promising strategies for increasing the economic and environmental sustainability of sweetpotato production. In addition to storage roots, leaves, vines, peels, and processing by-products can serve as valuable raw materials to produce functional food ingredients, dietary fiber concentrates, natural pigments, protein-rich ingredients, animal feed, biodegradable materials, fermentation substrates, and bioenergy products. Such integrated biomass utilization aligns with circular bioeconomy principles by reducing agricultural waste, improving resource-use efficiency, and generating additional revenue streams throughout the sweetpotato value chain. However, quantitative LCA and TEA remain relatively limited for many proposed valorization pathways. Consequently, sustainability benefits should be interpreted as promising but requiring further industrial validation.

Challenges to industrial commercialization

Despite substantial scientific progress, several technical and commercial barriers continue to limit broader industrial utilization of sweetpotato-derived functional ingredients. First, considerable variability exists among cultivars with respect to starch composition, phytochemical profiles, protein content, processing characteristics, and functional properties. This biological variability complicates ingredient standardization and quality assurance across production systems. Second, processing technologies capable of preserving heat-sensitive phytochemicals while remaining economically competitive at industrial scale remain under continuous development. Third, leaf-derived ingredients frequently exhibit bitterness, astringency, and green coloration that may reduce consumer acceptance without appropriate formulation strategies. Additional challenges include seasonal raw-material availability, postharvest deterioration, supply-chain

logistics, regulatory approval of novel ingredients, manufacturing costs, and market competitiveness. Addressing these constraints requires multidisciplinary collaboration among plant scientists, food engineers, food chemists, nutritionists, sensory scientists, economists, and industrial partners.

Foodomics for industrial quality assurance

Foodomics technologies provide powerful tools for improving industrial quality control and ingredient standardization. Advanced metabolomic and chemometric approaches enable comprehensive molecular fingerprinting of sweetpotato cultivars, facilitating authentication of raw materials, detection of adulteration, geographical traceability, and verification of ingredient consistency. Transcriptomic and genomic analyses contribute to cultivar selection by identifying genes associated with carotenoid biosynthesis, anthocyanin accumulation, starch metabolism, stress tolerance, and nutritional quality. Proteomic analyses further improve understanding of protein composition, enzymatic activity, digestibility, and processing-induced structural modifications relevant to functional ingredient development. Collectively, these integrated omics platforms support evidence-based quality assurance systems that extend beyond conventional compositional analyses by linking molecular composition with technological functionality and nutritional performance.

Artificial intelligence and digital foodomics

The integration of AI, ML, and digital foodomics represents an emerging frontier in sweetpotato research and industrial manufacturing. AI-assisted predictive models can integrate metabolomic, genomic, proteomic, processing, environmental, and quality-control datasets to optimize cultivar selection, ingredient formulation, process parameters, and product stability. ML algorithms may also facilitate prediction of nutritional quality, shelf life, sensory attributes, processing performance, and consumer preferences using multidimensional analytical datasets. Although these computational approaches remain at relatively early stages for sweetpotato applications, continued integration of AI with foodomics is expected to substantially accelerate precision food manufacturing, automated quality assurance, and data-driven product development.

Regulatory and market considerations

Commercial expansion of sweetpotato-derived functional ingredients requires compliance with national and international food regulations governing ingredient identity, contaminant limits, labeling requirements, manufacturing standards, and substantiation of health claims. Importantly, many reported biological activities of sweetpotato phytochemicals originate from laboratory and preclinical investigations rather than human clinical trials. Therefore, regulatory approval of health claims requires additional high-quality clinical evidence and should remain consistent with applicable regulatory frameworks. Consumer interest in plant-based nutrition, natural food colorants, sustainable agriculture, and minimally processed foods continues to create favorable market opportunities for sweetpotato-derived ingredients. Successful commercialization ultimately depends on balancing nutritional value, sensory quality, affordability, product stability, and consumer confidence.

Future research priorities

Future research should emphasize multidisciplinary integration of foodomics, food engineering, nutrition, computational biology, sensory science, sustainability assessment, and industrial processing.

Priority research areas include:

- development of standardized foodomics databases for major sweetpotato cultivars;
- harmonization of analytical methodologies for metabolomic and proteomic characterization;
- long-term evaluation of processing-induced molecular transformations;
- large-scale clinical studies evaluating bioavailability and physiological effects of sweetpotato-derived functional ingredients;

- integration of AI-assisted predictive modeling with precision food manufacturing;
- comprehensive LCA and TEA of sweetpotato processing systems;
- improved utilization of leaves and processing by-products within circular bioeconomy frameworks.

Greater collaboration among academic researchers, food industries, regulatory agencies, and agricultural producers will facilitate translation of laboratory discoveries into commercially viable products that contribute to sustainable food systems.

Concluding perspectives

Sweetpotato possesses exceptional potential as a multifunctional food crop capable of simultaneously contributing to nutrition, sustainable agriculture, functional ingredient development, and circular bioeconomy initiatives. Advances in foodomics have substantially improved understanding of the molecular composition, processing behavior, quality characteristics, and functional properties of both storage roots and leaves. However, several important challenges including cultivar variability, processing optimization, ingredient standardization, industrial scalability, consumer acceptance, and limited human clinical evidence must be addressed before the full commercial potential of sweetpotato-derived functional ingredients can be realized. Future progress will depend on integrating multi-omics technologies, AI, advanced food processing, standardized quality assurance systems, and sustainability assessment into comprehensive research and industrial development programs. Such multidisciplinary approaches will enable evidence-based commercialization of safe, nutritious, and high-value sweetpotato-derived products while supporting global food security, environmental sustainability, and the transition toward resilient circular food systems.

Health benefits

The consumption of sweetpotato roots and leaves has been associated with numerous potential health-promoting properties, primarily owing to their rich composition of dietary fiber, vitamins, minerals, carotenoids, anthocyanins, phenolic acids, flavonoids, and other bioactive phytochemicals [29, 75, 76]. Recent advances in foodomics, including metabolomics, transcriptomics, proteomics, and chemometric analyses, have substantially improved understanding of the molecular composition of sweetpotato and the biochemical mechanisms underlying these reported biological activities. These integrated approaches facilitate the identification of bioactive metabolites, elucidation of molecular pathways, evaluation of processing-induced compositional changes, and discovery of biomarkers associated with nutritional quality and physiological responses. Polyphenols, carotenoids, anthocyanins, and flavonoids present in sweetpotato exhibit substantial in vitro free-radical scavenging activity and may contribute to modulating oxidative stress and inflammatory signaling pathways [1, 3, 4, 27, 77–79]. Metabolomic investigations have demonstrated that antioxidant capacity results from the collective interactions among multiple phytochemicals rather than the activity of a single compound, with considerable variation observed among cultivars, growing environments, maturity stages, and processing conditions.

Several experimental studies have reported antidiabetic properties associated with sweetpotato-derived bioactive compounds, including improved insulin sensitivity, modulation of glucose metabolism, inhibition of carbohydrate-hydrolyzing enzymes, and regulation of signaling pathways involved in glucose homeostasis [10, 76, 80, 81]. Additional laboratory and preclinical investigations have suggested anti-inflammatory, antimicrobial, hepatoprotective, cardiometabolic, neuroprotective, and anticancer activities of sweetpotato phytochemicals. Transcriptomic and proteomic studies have further begun to identify molecular targets associated with these physiological responses, although mechanistic understanding remains incomplete. The high dietary fiber content of sweetpotato roots also contributes to digestive health by promoting normal gastrointestinal function and providing fermentable substrates for beneficial intestinal microorganisms, which may contribute to the production of short-chain fatty acids associated with gut health [6, 33, 82]. Emerging foodomics studies integrating metabolomics with microbiome analyses have begun to elucidate interactions between sweetpotato-derived carbohydrates, microbial metabolism, and host physiological responses; however, this research area remains in its early stages.

Importantly, the strength of evidence supporting the reported health-related effects differs substantially among biological endpoints. Antioxidant activities are primarily supported by biochemical assays, chemical antioxidant tests, and cell-based experiments. Antidiabetic, anti-inflammatory, hepatoprotective, cardiometabolic, antimicrobial, and anticancer activities are supported predominantly by in vitro investigations and animal studies. In contrast, robust human clinical evidence remains comparatively limited for most reported health outcomes. Therefore, the term "health benefits" used throughout this review should be interpreted cautiously. Unless specifically supported by well-designed human clinical investigations, these observations should be regarded as reported biological activities rather than established therapeutic effects. To improve scientific clarity and avoid overinterpretation, the available evidence may be categorized into four complementary levels: (i) biochemical antioxidant and enzyme-inhibitory assays, (ii) cell culture studies, (iii) animal experiments, and (iv) human observational studies or clinical interventions where available. Such classification provides a more balanced interpretation of the current literature and better aligns mechanistic evidence with its translational significance. Although the existing body of evidence strongly supports the nutritional value of sweetpotato as part of a healthy dietary pattern, further multidisciplinary research is required to establish causal relationships between sweetpotato consumption and specific health outcomes. Future investigations should prioritize standardized foodomics methodologies, comprehensive bioavailability assessments, dose-response studies, long-term randomized clinical trials, and integrated multi-omics approaches capable of linking phytochemical composition with clinically relevant physiological responses. Such studies will facilitate the evidence-based development of sweetpotato-derived functional foods and nutraceutical ingredients while strengthening scientific support for future dietary recommendations.

Applications and functional foods

Sweetpotato has emerged as a highly versatile raw material for the development of functional foods owing to its rich composition of dietary fiber, resistant starch, carotenoids, anthocyanins, phenolic acids, flavonoids, vitamins, minerals, and other bioactive phytochemicals present in storage roots and leaves [16, 83]. Recent advances in foodomics, including metabolomics, proteomics, transcriptomics, and chemometric analyses, have substantially enhanced understanding of the molecular composition, processing behavior, ingredient functionality, and quality characteristics of sweetpotato-derived products. These multidisciplinary approaches facilitate the identification of cultivar-specific biomarkers, evaluation of processing-induced molecular transformations, and optimization of ingredient quality for functional food applications. The storage roots, particularly orange- and purple-fleshed cultivars, are widely utilized in bakery products, gluten-free foods, noodles, pasta, breakfast cereals, beverages, purees, snacks, natural colorants, and nutraceutical ingredients, where their high concentrations of β-carotene and anthocyanins improve nutritional quality while providing desirable technological properties [18, 84, 85]. Orange-fleshed cultivars are primarily valued as sources of provitamin A carotenoids, whereas purple-fleshed cultivars provide anthocyanins with excellent potential as natural food colorants and antioxidant ingredients. In addition to their nutritional attributes, sweetpotato starch contributes favorable gelatinization behavior, water-holding capacity, and textural functionality, making root flour an attractive ingredient for gluten-free and clean-label food formulations. Concurrently with the increasing utilization of storage roots, sweetpotato leaves have gained attention as valuable functional food ingredients because of their high concentrations of polyphenols, chlorogenic acid, caffeoylquinic acid derivatives, flavonoids, dietary fiber, vitamins, and minerals [5, 86, 87]. Leaf powders, aqueous extracts, protein-rich concentrates, and fermented leaf products have been investigated for incorporation into functional beverages, herbal teas, bakery products, soups, dietary supplements, and green vegetable formulations. These applications are supported by their high nutritional density and favorable phytochemical composition. Numerous laboratory and preclinical investigations have reported antioxidant, anti-inflammatory, antimicrobial, antihypertensive, hepatoprotective, antidiabetic, and anticancer activities associated with sweetpotato-derived phytochemicals. However, most of these reported biological activities are supported primarily by biochemical assays, cell culture studies, and animal experiments, whereas human clinical evidence remains

comparatively limited. Therefore, these observations should be interpreted as promising biological activities rather than established therapeutic effects, and future clinical investigations are required to substantiate health-related claims associated with functional food products. Foodomics technologies have become increasingly important for functional ingredient development by enabling comprehensive characterization of phytochemical composition, monitoring processing-induced metabolite transformations, evaluating ingredient stability during storage, authenticating cultivar identity, and standardizing quality across production systems. Such molecular-level information facilitates evidence-based formulation strategies that optimize nutritional quality while maintaining desirable physicochemical and sensory properties.

Furthermore, incorporating sweetpotato-derived ingredients into emerging food systems, including plant-based meat analogs, fermented foods, probiotic beverages, dairy alternatives, protein-enriched formulations, edible films, biodegradable packaging materials, and clean-label functional snacks, highlights their considerable potential to support sustainable, nutrient-dense, and health-oriented food systems [6]. These innovative applications also align with circular bioeconomy principles by promoting the utilization of underexploited plant materials, particularly leaves and processing by-products, thereby improving resource-use efficiency and reducing agricultural waste. Despite these promising opportunities, the level of technological readiness differs substantially among application categories. Commercial utilization of root flour, starch, puree, chips, and natural colorants is already well established in many regions, whereas numerous applications involving leaf proteins, polyphenol extracts, specialty nutraceuticals, and advanced functional formulations remain largely at the laboratory or pilot scale. Consequently, additional industrial-scale validation, shelf-life studies, process optimization, sensory evaluation, economic assessment, and regulatory approval are required before widespread commercialization can be achieved. Successful translation of sweetpotato-derived functional ingredients into commercial food systems further depends on multiple factors beyond nutritional composition, including ingredient stability, dosage optimization, bioavailability, sensory compatibility, consumer acceptance, manufacturing scalability, supply-chain consistency, cost-effectiveness, and compliance with national and international food regulations. Therefore, formulation strategies should be developed using multidisciplinary approaches integrating food science, foodomics, processing engineering, sensory evaluation, nutrition, regulatory science, and market analysis. Overall, the complementary utilization of sweetpotato roots and leaves represents a promising strategy for value addition, diversification of plant-based food products, reduction of agricultural waste, and development of next-generation functional foods with potential contributions to sustainable food systems [88–94]. Not all reported applications have progressed beyond proof-of-concept or laboratory-scale formulation studies. Accordingly, the applications discussed in this review are interpreted according to their current level of scientific and technological maturity by distinguishing established commercial ingredients from emerging experimental formulations. This evidence-based perspective provides a more balanced assessment of the current state of sweetpotato functional food research while identifying priorities for future industrial translation. Table 3 summarizes representative applications of sweetpotato-derived ingredients across diverse food systems, highlighting their principal functional components, technological roles, reported biological activities, current level of commercial development, and future opportunities for foodomics-guided innovation.

Table 3. Food applications of sweetpotato-derived ingredients in different food systems.

Food category	Application status	Functional ingredient	Technological function	Example products	Supporting references
Bakery products	Commercially established/widely adopted	Root flour, root puree, leaf powder	Structure formation, partial wheat-flour replacement, color enhancement, fiber, and micronutrient enrichment	Bread, cakes, biscuits, muffins, composite-flour bakery products	[8, 18]
Gluten-free foods	Commercially established/widely	Root flour, starch	Texture improvement, binding, moisture	Gluten-free bread, noodles, pasta,	[3, 90]

Table 3. Food applications of sweetpotato-derived ingredients in different food systems. (*continued*)

Food category	Application status	Functional ingredient	Technological function	Example products	Supporting references
	adopted		retention, starch-based structure formation	composite flour products	
Snack foods	Commercially established/widely adopted	Extruded root flour, starch, dehydrated root powder	Expansion, crispiness, texture modification, bulk formation, and color development	Chips, puffs, extruded snacks, breakfast-type products	[3, 91]
Beverages	Experimental/Prototype formulations	Syrups, fermented root juice, leaf extracts, anthocyanin-rich extracts	Sweetening, antioxidant enrichment, natural coloring, and fermentation substrate	Functional drinks, smoothies, fermented beverages	[63, 74]
Dairy and dairy-style products	Experimental/Prototype formulations	Carotenoid-rich root extracts, anthocyanin-rich purple sweetpotato extracts	Natural colorants, antioxidant enrichment, pigment stabilization	Yogurt, ice cream, flavored milk, plant-based dairy alternatives	[2, 4]
Infant and complementary foods	Commercially established/widely adopted	Root puree, orange-fleshed sweetpotato flour	Smooth texture, digestibility, provitamin A enrichment, energy supply	Baby foods, purees, porridges, complementary foods	[8, 95]
Functional foods	Experimental/Prototype formulations	Resistant starch, dietary fiber concentrates, polyphenols, anthocyanins	Prebiotic potential, antioxidant activity, glycemic modulation, bioactive enrichment	Nutrition bars, fortified snacks, functional powders	[4, 38]
Plant-based foods	Experimental/Prototype formulations	Leaf protein, leaf powder, fiber-rich fractions	Protein fortification, emulsification support, mineral enrichment, color and antioxidant enhancement	Meat analogs, protein shakes, fortified soups, plant-based patties	[5, 72]
Nutraceuticals	Experimental/Prototype formulations	Leaf extracts, caffeoylquinic acid derivatives, anthocyanin pigments	Bioactive delivery, antioxidant support, polyphenol concentration, encapsulation potential	Capsules, powders, tablets, concentrated extracts	[5, 74]
Traditional foods	Commercially established/widely adopted	Whole roots, cooked leaves, boiled or steamed roots	Basic nutrition, sensory attributes, household-level preparation, and cultural food use	Boiled roots, baked roots, cooked leaves, soups, stir-fried leaves	[1, 96]

"Commercially established/widely adopted" refers to applications already common in household, traditional, industrial, or retail food systems. "Experimental/Prototype formulations" refers to products mainly reported in laboratory, pilot-scale, or emerging functional food studies.

Sustainability and future perspectives

Sweetpotato possesses several characteristics that make it an attractive crop for supporting more sustainable food systems, including the production of both edible storage roots and nutrient-rich leaves, broad environmental adaptability, relatively high biomass productivity, and opportunities for whole-plant utilization [93]. Unlike many conventional food crops in which only a single plant component is consumed, sweetpotato offers the potential for complementary utilization of roots, leaves, vines, peels, and processing by-products, thereby improving resource-use efficiency and contributing to circular bioeconomy strategies. Despite their exceptional nutritional composition, sweetpotato leaves remain considerably underutilized in many regions, particularly in developed countries, where commercial production has traditionally focused on storage roots. Greater utilization of leaf biomass could diversify plant-based food resources while reducing unnecessary biomass losses and generating additional value throughout the production chain. However, the extent of these sustainability benefits depends on regional production systems, consumer acceptance, processing infrastructure, economic feasibility, and market demand rather than on crop characteristics alone. Recent advances in foodomics including metabolomics, proteomics, transcriptomics, and chemometric analyses, provide valuable tools for improving sustainable utilization of sweetpotato resources. Foodomics facilitates molecular characterization of both roots and leaves, identification of

cultivar-specific nutritional biomarkers, optimization of processing technologies, monitoring of processing-induced compositional changes, and quality standardization of functional food ingredients. These approaches support evidence-based utilization of underexploited biomass while reducing quality variability across production systems. Future research should prioritize developing standardized harvesting, processing, storage, and quality-control protocols for both roots and leaves to improve product consistency and industrial scalability. Additional efforts are needed to optimize drying, fermentation, extraction, encapsulation, and preservation technologies that maintain phytochemical stability, nutritional quality, and sensory acceptability while remaining economically feasible for commercial production. Although numerous laboratory and preclinical studies have demonstrated promising biological activities associated with sweetpotato-derived phytochemicals, human clinical evidence remains comparatively limited. Consequently, future research should prioritize randomized controlled clinical trials, comprehensive bioavailability studies, dose-response investigations, and long-term dietary intervention studies to establish stronger evidence supporting the physiological relevance of sweetpotato-derived functional foods.

The complementary nutritional characteristics of storage roots and leaves provide important opportunities for integrated food utilization. Storage roots primarily contribute complex carbohydrates, dietary fiber, carotenoids, and energy, whereas leaves provide higher concentrations of protein, vitamins, minerals, chlorogenic acid derivatives, flavonoids, and other polyphenolic compounds [1, 9, 16]. This complementary nutrient distribution supports whole-plant utilization strategies capable of improving nutritional diversity while increasing agricultural resource efficiency. Advances in food processing technologies, growing consumer interest in plant-based nutrition, increasing demand for clean-label ingredients, and expanding knowledge of sweetpotato phytochemistry are expected to accelerate the development of innovative sweetpotato-derived functional foods [72]. However, successful industrial translation depends not only on nutritional quality but also on ingredient standardization, processing efficiency, shelf-life stability, sensory compatibility, regulatory approval, manufacturing scalability, economic competitiveness, and consumer acceptance. The comparative functional roles of sweetpotato storage roots and leaves within food systems are summarized in Table 4, highlighting their complementary nutritional composition, principal functional ingredients, representative food applications, and opportunities for value-added utilization.

Table 4. Comparative functional roles of sweetpotato storage roots and leaves in food systems.

Functional aspect	Storage roots	Leaves
Primary role	Energy source, typically starch-dominant roots with total starch commonly about 22.6–69.7 g/100 g dry weight (DW); many starch-rich cultivars exceed 50 g/100 g DW, and individual high-starch accessions reach up to 69.7 g/100 g DW [11]	Micronutrient-, fiber-, polyphenol-, and protein-rich leafy biomass; crude protein commonly 16.69–31.08 g/100 g DW, with many reports around 20–30% DW [9]
Protein content	Typically low relative to leaves, generally < 5 g/100 g DW in storage-root-focused compositional comparisons; roots are not the major protein fraction of the crop [11]	Typically high, about 16.69–31.08 g/100 g DW across 40 cultivars; representative reviews also report about 20–30% DW [9]
Carbohydrate content	Typically high, with total starch about 22.6–69.7 g/100 g DW and often 45.8–67.5% in cultivar studies; carbohydrate is the dominant dry-matter fraction [11]	Moderate relative to roots, with crude carbohydrate about 42.03–61.36 g/100 g DW in leaf compositional surveys, but leaves remain functionally distinguished by higher protein, minerals, fiber, and phenolics rather than starch dominance [9]
Bioactive compounds	Carotenoids and anthocyanins are the signature root bioactives; root carotenoids in orange-fleshed cultivars have been reported at about 50–260 μg/g FW, while anthocyanins in purple roots vary with cultivar and may be absent in white/orange roots [97]	Polyphenols, especially caffeoylquinic acid derivatives and flavonoids, dominate; total phenolic content in leaves has been reported at about 3–12% DW and 6.3–13.5 g GAE/100 g DW depending on cultivar and method [9]
Functional ingredient	Strong for starch, flour, syrup, carotenoid, and anthocyanin ingredient development, defined	Strong for protein-, antioxidant-, and fiber-oriented ingredients, defined here as leaves being the principal

Table 4. Comparative functional roles of sweetpotato storage roots and leaves in food systems. (*continued*)

Functional aspect	Storage roots	Leaves
potential	here as roots being the principal source of starch-rich bulk ingredients and natural pigments used for texturizing, sweetening, fortification, and coloring [98]	source of protein concentrates, polyphenol-rich extracts, and micronutrient-dense powders; this is supported by protein values of about 16.69–31.08 g/100 g DW and phenolics of about 3–12% DW [9]
Industrial utilization	Well-established, defined here as broad and long-standing use of roots in flour, starch, puree, chips, noodles, syrups, and pigment applications across traditional and industrial food systems [6]	Emerging and expanding, defined here as increasing but still less standardized use of leaf powder, polyphenol extracts, and protein-rich materials in bakery products, beverages, nutraceuticals, and plant-based foods [5, 6]
Value-added products	Flour, starch, syrup, puree, chips, noodles, carotenoid extracts, anthocyanin colorants [58]	Leaf powders, polyphenol extracts, antioxidant ingredients, protein concentrates, fiber-rich fortificants [5, 6]
Sustainability contribution	Moderate-to-high when roots are integrated with by-product valorization, defined here as use of an already established staple biomass with opportunities for further peel, starch, and processing-stream utilization [6]	High waste-valorization potential, defined here as upgrading underused aerial biomass into food ingredients, especially where leaves are currently discarded or underutilized [6]

Representative ranges are compiled from published studies and may vary with cultivar, flesh or leaf type, maturity, agronomic conditions, analytical method, and processing status. “Industrial utilization” and “sustainability contribution” are expressed as evidence-based interpretive criteria rather than absolute quantitative values because the literature does not provide a single standardized numerical metric for these categories.

Sweetpotato demonstrates considerable potential to contribute to sustainable agriculture through efficient biomass utilization, diversification of food resources, and valorization of agricultural by-products. Nevertheless, broad sustainability claims including circularity, climate resilience, waste reduction, carbon mitigation, and full biomass utilization efficiency should be interpreted cautiously because quantitative evidence remains limited. The magnitude of these benefits depends strongly on local agronomic practices, cultivar selection, environmental conditions, postharvest management, processing technologies, supply-chain logistics, market structure, and socioeconomic factors. Likewise, although whole-plant utilization aligns conceptually with circular bioeconomy principles, relatively few studies have comprehensively quantified lifecycle environmental impacts, greenhouse gas emissions, carbon footprints, water footprints, energy consumption, or industrial-scale economic performance of sweetpotato-based food systems. Consequently, many proposed sustainability advantages remain promising hypotheses requiring further validation rather than universally established outcomes. Future multidisciplinary research should therefore integrate foodomics, systems biology, AI, precision agriculture, food engineering, environmental assessment, and computational modeling to optimize sweetpotato production and utilization. Emphasis should be placed on developing standardized foodomics databases, predictive quality models, cultivar-specific nutritional fingerprints, and intelligent processing systems capable of maximizing both nutritional quality and industrial efficiency. Furthermore, objective evaluation of sustainability should incorporate comprehensive LCA, TEA, material-flow analysis, carbon accounting, water-use efficiency, and sustainability performance indicators. These complementary approaches will enable quantitative comparison of alternative production and processing systems while supporting evidence-based sustainability claims and informed decision-making for industry and policymakers. Thus, sweetpotato represents one of the most promising multifunctional crops for future sustainable food systems because of its exceptional nutritional diversity, adaptability, processing versatility, and potential for whole-plant utilization. Realizing its full potential will require coordinated advances in foodomics, processing technologies, clinical nutrition, sustainability science, consumer research, industrial engineering, and regulatory science. Such multidisciplinary integration will facilitate the development of safe, standardized, nutritionally optimized, and environmentally sustainable sweetpotato-derived foods that contribute meaningfully to global food security, human health, and circular bioeconomy development.

Future foodomics research priorities

Future advances in sweetpotato research will increasingly depend on integrating foodomics technologies to move beyond conventional compositional analysis toward a system-level understanding of crop

functionality, nutritional quality, food processing, ingredient performance, and health-promoting potential. Although substantial progress has been achieved in characterizing individual phytochemicals, proteins, carbohydrates, and metabolites, comprehensive multi-omics frameworks linking genotype, environmental conditions, agronomic management, food processing, food matrix interactions, bioavailability, and human physiological responses remain comparatively underdeveloped. Consequently, integrated food-making approaches are expected to become central tools for advancing both fundamental research and industrial innovation. The integration of metabolomics, transcriptomics, proteomics, lipidomics, microbiomics, genomics, phenomics, and computational biology provides unprecedented opportunities to elucidate the molecular mechanisms underlying sweetpotato quality, nutritional functionality, processing behavior, and biological activities while accelerating the development of next-generation functional foods and nutraceutical ingredients [58–60, 62, 99]. Compared with single-omics investigations, integrated multi-omics platforms enable simultaneous characterization of molecular composition, regulatory pathways, protein expression, metabolic networks, and food-processing responses, thereby providing a more comprehensive understanding of sweetpotato biology and functionality.

One of the highest research priorities is identifying robust molecular biomarkers for cultivar authentication, quality assurance, geographical traceability, breeding selection, and compositional standardization. Advanced metabolomic fingerprinting, combined with chemometric analyses and ML algorithms, can facilitate rapid discrimination among sweetpotato genotypes based on carotenoid profiles, anthocyanin composition, caffeoylquinic acid derivatives, volatile metabolites, amino acid signatures, lipid composition, and other nutritional biomarkers. Such molecular authentication systems could substantially improve supply-chain transparency, reduce food adulteration, enhance regulatory compliance, and enable precision selection of cultivars for specific food, nutritional, pharmaceutical, or industrial applications [24, 31, 59]. A second major research priority involves understanding processing-induced molecular transformations using integrated foodomics platforms. Thermal processing, drying, extrusion, fermentation, storage, encapsulation, and emerging green-processing technologies significantly influence the stability, bioaccessibility, digestibility, and biological activity of sweetpotato-derived phytochemicals. Future investigations should integrate metabolomics, proteomics, lipidomics, and advanced analytical chemistry to quantify dynamic changes in carotenoids, anthocyanins, chlorogenic acid derivatives, polyphenols, resistant starch fractions, proteins, peptides, lipid metabolites, volatile compounds, and Maillard reaction products during processing and storage. Such mechanistic understanding will facilitate evidence-based optimization of processing conditions capable of maximizing nutritional retention, ingredient functionality, shelf-life stability, and sensory quality while minimizing degradation of valuable bioactive compounds [43, 63, 74, 100].

Greater emphasis should also be placed on multi-omics characterization of genotype × environment × management (G × E × M) interactions. Sweetpotato nutritional quality and phytochemical composition are strongly influenced by cultivar genetics, environmental conditions, soil characteristics, agronomic practices, irrigation, fertilization, harvest maturity, and postharvest handling. Future systems biology investigations integrating genomic, transcriptomic, metabolomic, proteomic, and phenomic datasets will provide deeper understanding of regulatory networks governing nutrient accumulation, stress adaptation, secondary metabolite biosynthesis, processing behavior, and yield stability. Such knowledge will support breeding programs aimed at developing climate-resilient cultivars with improved nutritional quality, functional properties, and environmental adaptability [26, 101]. Nevertheless, future studies should recognize that crop performance remains highly environment-dependent and that predictive models require extensive validation across diverse production systems. Another rapidly emerging research frontier is the application of AI, ML, deep learning, and predictive foodomics. Predictive computational models integrating omics datasets with physicochemical measurements, sensory properties, processing variables, environmental data, and quality attributes may enable accurate forecasting of starch functionality, phytochemical stability, antioxidant capacity, shelf life, consumer acceptance, and processing performance. AI-assisted foodomics also has considerable potential for automated cultivar classification, ingredient authentication, quality prediction, anomaly detection, digital quality control, and intelligent process optimization. However, the

robustness and generalizability of AI models depend on the availability of representative, standardized, high-quality datasets, appropriate model development and validation procedures, and independent external evaluation across relevant laboratories, instruments, and production environments [102, 103].

Human nutrition research represents another critical priority. Despite extensive evidence generated from in vitro experiments and animal studies, relatively few randomized controlled human intervention studies have incorporated foodomics biomarkers to investigate physiological responses following sweetpotato consumption. Future clinical investigations should integrate metabolomics, lipidomics, microbiome profiling, nutritional phenotyping, and systems biology approaches to identify biomarkers of dietary exposure, bioavailability, metabolic response, and long-term health outcomes. Such studies will improve understanding of interindividual variability, dietary response, nutrient metabolism, and precision nutrition while providing stronger evidence for evaluating reported biological activities of sweetpotato-derived functional ingredients [47]. Importantly, future research should continue distinguishing experimental biological activities from clinically established therapeutic effects until stronger human evidence becomes available. The interaction between sweetpotato bioactive compounds and the human gut microbiome also warrants extensive investigation. Emerging evidence suggests that resistant starch, dietary fiber, anthocyanins, chlorogenic acid derivatives, and other polyphenols may influence microbial diversity, microbial metabolism, and short-chain fatty acid production, thereby affecting host metabolism, immune function, and intestinal health. Integrated microbiome-metabolome-transcriptome investigations may provide valuable mechanistic insights into host-microbe interactions and facilitate development of microbiome-targeted functional foods. Nevertheless, this research field remains relatively immature, and many mechanistic hypotheses require confirmation through well-controlled longitudinal human studies.

Future foodomics research should further expand beyond nutritional characterization by incorporating sustainability-oriented analytical frameworks. Integration of LCA, TEA, digital agriculture, precision farming, environmental footprint assessment, carbon accounting, resource-use efficiency metrics, and circular bioeconomy principles will enable comprehensive evaluation of sweetpotato production systems and value chains. Combining molecular quality indicators derived from foodomics with environmental, economic, and social sustainability metrics will facilitate objective comparison of alternative production systems while supporting evidence-based sustainability assessments. At present, relatively few studies have integrated foodomics with LCA or TEA, representing an important opportunity for future interdisciplinary research. Another important priority involves improving standardization and data harmonization across foodomics investigations. Future progress will require standardized analytical protocols, harmonized sample preparation procedures, validated reference materials, interoperable databases, common reporting guidelines, and open-access multi-omics repositories. Such standardization will improve reproducibility, facilitate meta-analyses, enable cross-study comparisons, and accelerate collaborative international research.

Greater collaboration among plant scientists, food chemists, nutritionists, microbiologists, food engineers, computational biologists, clinicians, regulatory agencies, and industrial stakeholders will be essential for translating foodomics discoveries into practical food innovations. Such multidisciplinary partnerships can accelerate the development of standardized functional ingredients, evidence-based dietary recommendations, precision breeding strategies, and sustainable commercial applications.

Overall, the convergence of foodomics, systems biology, AI, microbiome science, precision nutrition, sustainability science, and computational modeling provides a transformative framework for future sweetpotato research. By integrating comprehensive molecular characterization, predictive analytics, clinical nutrition, environmental assessment, and industrial processing, future investigations can enable precision utilization of sweetpotato roots and leaves, strengthen evidence supporting functional food development, improve supply-chain quality assurance, facilitate sustainable commercialization, and reinforce the role of sweetpotato as a nutritionally strategic, climate-adaptive, and economically valuable crop for future global food systems. Continued emphasis on methodological standardization, external

validation, multidisciplinary collaboration, and high-quality human clinical evidence will be essential to translate these scientific advances into robust public health, industrial, and sustainability outcomes.

Conclusions

Sweetpotato is a uniquely versatile crop whose storage roots and leaves perform complementary roles in modern food systems through their distinct yet synergistic nutritional, technological, and functional properties. Storage roots, characterized by high concentrations of complex carbohydrates, resistant starch, carotenoids, anthocyanins, and other phytochemicals, serve as valuable raw materials for energy-rich foods and functional ingredients that enhance texture, color, nutritional quality, and processing performance in a broad range of products, including bakery goods, gluten-free foods, fermented products, snacks, beverages, and natural food colorants. In contrast, the leaves, which remain underutilized in many regions despite their exceptional nutritional composition, provide concentrated sources of high-quality protein, dietary fiber, vitamins, minerals, chlorogenic acid derivatives, flavonoids, and other polyphenolic compounds, making them promising ingredients for functional beverages, dietary supplements, plant-based foods, and nutraceutical formulations. A central theme emerging from this review is that the complementary utilization of both storage roots and leaves provides opportunities to maximize the nutritional, functional, and economic value of the entire crop while supporting more efficient biomass utilization. However, the successful implementation of whole-plant utilization strategies depends on appropriate cultivar selection, standardized processing technologies, quality assurance systems, consumer acceptance, regulatory compliance, and economic feasibility. Foodomics has fundamentally transformed sweetpotato research by shifting investigations from descriptive compositional analyses toward comprehensive systems-level understanding of molecular composition, processing-induced transformations, ingredient functionality, and nutritional performance. The integration of metabolomics, transcriptomics, proteomics, lipidomics, chemometrics, and computational biology has enabled improved characterization of cultivar-specific phytochemical profiles, identification of molecular biomarkers for quality assurance and authenticity, monitoring of processing-induced changes, and optimization of functional ingredient development. These multidisciplinary approaches provide a robust scientific framework for linking genotype, environmental conditions, processing technologies, food matrix interactions, and nutritional functionality, thereby supporting evidence-based innovation throughout the sweetpotato value chain. Importantly, this review also highlights several critical knowledge gaps that should be considered when interpreting the current literature. Although numerous studies report antioxidant, anti-inflammatory, antidiabetic, antimicrobial, hepatoprotective, cardiometabolic, neuroprotective, and anticancer activities associated with sweetpotato-derived phytochemicals, the strength of supporting evidence differs substantially across biological endpoints. Antioxidant activities are supported primarily by biochemical and cell-based assays, whereas many antidiabetic, anti-inflammatory, hepatoprotective, and anticancer effects originate predominantly from animal experiments and mechanistic laboratory investigations. Robust evidence from well-designed randomized human clinical trials remains comparatively limited for most reported health outcomes. Consequently, the biological activities summarized in this review should be interpreted as promising scientific evidence rather than established therapeutic effects, and health-related claims should remain consistent with the available level of clinical evidence. Similarly, while sweetpotato demonstrates considerable potential to contribute to sustainable food systems through whole-plant utilization, biomass valorization, and diversification of plant-based food resources, sustainability benefits should not be regarded as universally established. The magnitude of these benefits depends on agronomic practices, environmental conditions, processing technologies, postharvest management, supply-chain logistics, consumer behavior, and economic viability. Relatively few investigations have comprehensively quantified life-cycle environmental impacts, carbon footprints, resource-use efficiency, greenhouse gas emissions, or industrial-scale economic performance. Therefore, future sustainability assessments should incorporate quantitative LCA, TEA, and standardized sustainability performance metrics to provide objective evaluation of sweetpotato-based food systems. Future research should prioritize integrated multi-omics investigations, standardized analytical methodologies, harmonized processing protocols, quantitative

comparisons between storage roots and leaves, comprehensive bioavailability studies, randomized controlled human intervention trials, microbiome-foodomics integration, and AI-assisted predictive modeling. Emphasis should also be placed on developing standardized molecular biomarkers for cultivar authentication, improving quality assurance systems, optimizing processing technologies, enhancing ingredient stability, and strengthening industrial scalability. Furthermore, multidisciplinary collaboration among plant scientists, food chemists, nutritionists, food engineers, computational biologists, clinicians, environmental scientists, regulatory agencies, and industry partners will be essential for translating laboratory discoveries into commercially viable and scientifically validated food innovations.

Overall, the convergence of foodomics, systems biology, advanced food processing, AI, precision nutrition, sustainability science, and circular bioeconomy principles provides a transformative framework for the future utilization of sweetpotato. By integrating comprehensive molecular characterization with evidence-based processing strategies, rigorous clinical evaluation, and quantitative sustainability assessment, future research can facilitate the development of safe, standardized, nutritionally optimized, and environmentally sustainable sweetpotato-derived functional foods. Such multidisciplinary integration will not only strengthen scientific understanding of this globally important crop but also enhance its contribution to food security, human nutrition, public health, and resilient food systems in the coming decades.

Abbreviations

AI: artificial intelligence

LCAs: life cycle assessments

ML: machine learning

TEA: techno-economic analysis

Declarations

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Figure preparation and AI use: All figures in this manuscript were created using GraphPad Prism and Microsoft PowerPoint. The auther used AI-assisted tools (Photon and Gemini) solely for image enhancement and visual refinement. All figures are original works created by the author. The author reviewed and edited the content as necessary and assume full responsibility for the final content of the publication.

Author contributions

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The author declares no conflict of interest associated with this manuscript.

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Consent to participate

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