

Review

Fermented Agri-Food By-Products from Tubers and Legumes as Next-Generation Functional Ingredients: From Waste Valorisation to Precision Nutrition

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Abstract

Processing tubers such as potato, sweet potato, cassava, and yam, as well as legumes such as soybean, pea, chickpea, bean, and lentil, generates substantial quantities of peels, pulps, husks, and press cakes that retain considerable nutritional and functional value despite often being discarded. Microbial fermentation has emerged as a low-cost and scalable approach for valorising these residues into functional ingredients with improved digestibility and enhanced bioactive-compound content. This study synthesises the composition of major tuber and legume by-products, the solid-state and submerged fermentation systems employed for their bioconversion, and the biochemical and functional transformations achieved through fermentation, including improvements in antioxidant activity, prebiotic potential, antihyperglycaemic properties, and protein quality. The emerging applications of these fermented by-products in bakery products, dairy alternatives, snacks, nutraceuticals, and the conceptually related field of gut-microbiome-guided precision nutrition are also examined. Persistent challenges, including compositional variability, safety monitoring, and regulatory classification, are critically evaluated alongside strategies for addressing these limitations. Overall, fermentation-based valorisation of tuber and legume residues represents a scientifically credible and environmentally sustainable strategy for transforming agri-food waste streams into value-added, functional nutrition ingredients.

Keywords: agri-food by-products; tuber and legume residues; solid-state fermentation; functional ingredients; bioactive compounds; gut microbiome; precision nutrition; circular bioeconomy



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1. Introduction

Global agri-food systems generate an estimated one-third of all food produced for human consumption as loss or waste, equivalent to about 1.3 billion tonnes [1]. Processing operations for starchy tubers and grain legumes are among the largest contributors of solid residues, including peels, pulps, husks, hulls and press cakes [2,3]. Potato processing alone leaves behind peels, pulp, and fruit-juice fractions that can represent up to a quarter of the raw tuber mass, while cassava, sweet potato, and yam processing generate peels, bagasse, and press cakes rich in residual carbohydrate, fibre, and phenolic compounds [2,4,5]. Legume processing, particularly the manufacture of soymilk, tofu, protein isolates, and pulse flours, similarly produces high volumes of okara, husks, hulls, and seed coats that retain considerable protein, fibre, and phytochemical content but are commonly diverted to landfills, low-value animal feed, or composting [3,6,7].

These agri-food by-products present both a challenge and an opportunity. On the one hand, their high moisture content makes them highly susceptible to rapid microbial spoilage, leading to environmental concerns and increased disposal costs. On the other hand, they are rich sources of valuable nutrients and bioactive compounds that remain largely underutilized [6,8]. Their valorisation therefore supports the principles of the circular economy and zero-waste strategies by transforming what is traditionally regarded as waste into valuable raw materials for the food, feed, cosmetic, and pharmaceutical industries [9–11]. Although physical and chemical extraction methods can recover specific bioactive compounds, microbial fermentation has emerged as a more sustainable and cost-effective approach. It requires less energy, preserves the integrity of the food matrix, and simultaneously enhances the safety, digestibility, nutritional value, and functional properties of the entire by-product [12,13]. However, head-to-head quantitative cost comparisons between fermentation and physical or chemical extraction methods remain scarce in the peer-reviewed literature. Therefore, the sustainability and cost advantages described here are primarily based on qualitative, process-level considerations, such as lower energy and equipment requirements, rather than on published techno-economic analyses.

Fermentation, whether carried out through solid-state fermentation (SSF) or submerged fermentation (SmF), harnesses the metabolic and enzymatic activities of microorganisms such as lactic acid bacteria, yeasts, and filamentous fungi, including *Rhizopus*, *Aspergillus*, and *Pleurotus* species. During fermentation, these microorganisms break down complex polysaccharides, release bound phenolic compounds, reduce antinutritional factors such as phytates, tannins, trypsin inhibitors, and cyanogenic glucosides, and produce a range of beneficial metabolites, including short-chain organic acids, exopolysaccharides, and bioactive peptides [14,15]. These transformations are well documented for isolated by-products such as soybean okara and cassava peel, where fermentation increases soluble fibre, antioxidant capacity and protein digestibility while reducing raw-fibre content and toxicant load [16,17].

Similarly, nutrition science has moved decisively toward the recognition that dietary responses are highly individual, shaped by genetics, gut microbiome composition, health status, and lifestyle, giving rise to the field of precision (or personalized) nutrition [18,19]. Fermented foods, by virtue of their viable microbial content, structured food matrices, and diverse metabolite profiles, are increasingly discussed as potential tools for microbiome-targeted dietary strategies, although the evidence base for population-specific responses remains heterogeneous [20,21]. This creates a natural, but so far only partially explored, convergence between two research paths: the fermentation-based valorisation of tuber and legume by-products, and the design of foods adapted to individual metabolic and microbial profiles.

This review summarises the composition and volumes of major tuber and legume agri-food by-products, critically appraises the fermentation technologies and microbial systems used for their bioconversion, synthesises the biochemical, nutritional and functional transformations that fermentation confers, examines current and emerging food applications, explores the conceptual and mechanistic links between fermented by-product ingredients and precision nutrition, and discusses the technological, safety and regulatory barriers that must be addressed before these ingredients can be deployed at scale.

The scope of this review is deliberately narrative, given the breadth of substrates (multiple tuber and legume species), fermentation configurations (solid-state, submerged, spontaneous, and defined-culture), and outcome measures (compositional, functional, sensory, and emerging microbiome-related endpoints) reported across the literature. Sources were identified through targeted searches of peer-reviewed journals and recent review articles addressing tuber and legume by-product valorisation, solid-state and submerged

fermentation, functional food ingredient development, and precision or personalised nutrition, with an emphasis on publications from the past decade.

A further motivation for this study is economic and environmental. Life-cycle and techno-economic assessments of agri-food by-product valorisation consistently identify fermentation as one of the lower-capital-intensity routes for converting a disposal cost into a revenue-generating ingredient stream, particularly relative to chromatographic purification or advanced extraction technologies that require substantial capital investment and solvent management [9,11]. Although these assessments are largely qualitative or infrastructure-based, specific capital-cost comparisons between fermentation and alternative extraction methods for tuber and legume by-product streams remain limited. This gap highlights the need for future techno-economic studies to quantify the economic feasibility and comparative cost-effectiveness of these valorisation approaches. Because fermentation can often be implemented with modest infrastructure, it is also attracting attention as a valorisation route accessible to small and medium-sized processors in regions where tuber crops such as cassava and sweet potato are dietary staples and where formal waste-management infrastructure is limited [5,22].

2. Review Methodology

This review adopted a narrative approach to capture the wide range of agri-food by-products, fermentation strategies, and functional outcomes reported in the literature. Relevant studies were identified through systematic searches of Scopus, Web of Science, PubMed, and Google Scholar using combinations of keywords, including tuber by-product, legume by-product, okara, cassava peel, potato peel, solid-state fermentation, submerged fermentation, functional ingredient, bioactive compound, gut microbiome, and precision nutrition. These search terms were combined using the Boolean operators AND and OR to ensure comprehensive retrieval of relevant publications. The review included peer-reviewed original research articles, systematic and narrative reviews, and relevant book chapters published in English between 2000 and 2026. This timeframe was selected to encompass both the early developments in solid-state fermentation research and the more recent advances in precision nutrition, gut microbiome modulation, and the development of functional food ingredients.

Records were screened by title and abstract for relevance to tuber or legume by-product valorisation, fermentation technology, or precision/personalised nutrition, and full texts were retrieved where the abstract indicated a direct bearing on these themes.

Articles were excluded where they addressed fermentation of primary (non-by-product) crops without a clear by-product focus, where they were not available in full text, or where they duplicated findings already captured in a more recent or more comprehensive source. Reference lists of key reviews were also hand-searched to identify additional primary studies, an approach consistent with the narrative-synthesis method appropriate to a field this heterogeneous in substrates, methods, and outcome measures.

3. Tuber and Legume Agri-Food By-Products: Sources, Volumes, Composition and Handling

Tubers and legumes differ substantially in the chemical nature of their processing residues; however, these crops share a common profile of underexploited macronutrients such as residual starch, protein, and fibre, and micronutrient and phytochemical fractions such as polyphenols, carotenoids, saponins, and glycoalkaloids that survive primary processing [2,3]. Potato peel, generated during peeling for chips, crisps, and starch manufacture, is particularly rich in chlorogenic acid and related phenolics, as well as glycoalkaloids such as α -solanine and α -chaconine, which confer antimicrobial activity but

require monitoring at higher concentrations [2]. Potato pulp and fruit juice, by-products of starch extraction, retain *patatin* and protease-inhibitor proteins of high nutritional quality, comparable in amino acid balance to egg or soy protein, although native extraction methods can denature these proteins or cause them to complex with phenolics and glycoalkaloids, thereby reducing digestibility [23,24].

Sweet potato processing residues remain valuable sources of starch, non-starch polysaccharides, and, in coloured varieties, anthocyanins. Reported fermentation studies generally describe increases in soluble dietary fiber and in phenolic-associated antioxidant activity, although the magnitude varies with cultivar and process conditions [16]. For cassava peels, the safety relevance of cyanogenic compounds is clearer when numerical values are reported: one mixed-culture study reduced cyanide from 40.33 ± 2.80 mg/kg in unsoaked unfermented peels to 7.35 ± 0.81 mg/kg, while another study reported a decrease from 152 ± 2.02 to 5 ± 2.03 mg/kg after 168 h of inoculated *Aspergillus niger* fermentation [4,25]. Also, mixed-culture fermentation of sweet potato residue with *Lactocaseibacillus rhamnosus* and *Pediococcus pentosaceus* (48 h, 37 °C) has been reported to raise soluble dietary fibre to approximately 15.0 g/100 g dry weight and total polyphenol content to approximately 95.7 mg/100 g dry weight, alongside lactic acid and acetic acid concentrations of approximately 58.0 and 1.7 mg/g, respectively, relative to the unfermented residue [16]. Similarly, cassava peels and bagasse, generated in large quantities during cassava starch processing in tropical regions, contain substantial amounts of fermentable carbohydrates. However, they also contain cyanogenic glucosides, including linamarin and *lotaustralin*, which must be detoxified before use. Fermentation, particularly solid-state fermentation using fungi such as *Rhizopus oligosporus* or mixed bacterial–yeast cultures, has shown potential to reduce cyanide levels while enhancing protein content and antioxidant activity. Reported reductions in hydrogen cyanide (HCN) content of approximately 79–80% have been achieved after 5–15 days of fermentation, although the extent of cyanide reduction varies with the microbial strain and fermentation duration [5,10].

Among legume by-products, soybean okara, the insoluble residue remaining after soymilk and tofu production, is one of the most abundant and nutritionally valuable. On a dry-weight basis, okara contains approximately 50% dietary fibre, 20–30% protein, and moderate amounts of lipids, together with isoflavones that are predominantly present as glucosides before fermentation [6,8]. Other legume processing residues, such as hulls, husks, and seed coats from peas, chickpeas, lentils, and beans, generally contain lower levels of protein but are rich in insoluble dietary fibre, resistant starch, and phenolic compounds. As a result, these by-products are increasingly being explored as sustainable sources of functional fibre and natural hydrocolloid alternatives for food applications [3,26].

As handling and logistics are closely linked to the composition and volume of the by-products, their physical characteristics directly influence the requirements for collection, transportation, storage, and pre-treatment. Beyond proximate composition, the physical form and moisture content of these residues determine the likely processing route. Dry fibrous residues such as potato and cassava peels are generally more compatible with solid-state fermentation, whereas wet streams such as potato fruit juice and fresh okara require rapid stabilisation or immediate processing. These characteristics are relevant to the sources and composition of the by-products because moisture and physical form affect measured nutrient concentrations, shelf stability, and the feasibility of subsequent fermentation [6,8]. Seasonality and geographic concentration of processing influence the consistency of the available feedstock and, therefore, the composition of material entering fermentation. These factors can cause variation in moisture, fibre, protein, and phytochemical concentrations between batches and are therefore important when interpreting composition data and designing standardised fermentation processes [5,22].

While many agri-food by-products offer considerable nutritional and functional value, some also present safety concerns that must be carefully managed before they can be used as food ingredients. For example, potato peels and sprouted tubers may contain elevated levels of glycoalkaloids, particularly when potatoes have been exposed to light or stored under unsuitable conditions. Although fermentation can reduce these compounds, their concentrations still need to be monitored to ensure food safety [2,23].

Also, cassava peels and bagasse contain cyanogenic glucosides, whose levels vary with the cassava cultivar (sweet or bitter) and the processing methods employed. As a result, by-products classified in the same category may differ substantially in their safety profiles depending on their origin and processing history [5,10]. This variability highlights the importance of interpreting the compositional values presented in Table 1 as representative ranges rather than fixed values, reflecting the natural diversity of these by-products.

Table 1. Some proximate compositions for major tuber and legume by-products.

By-Product	Process	Protein (%)	Fibre (%)	Important Bioactives/ Antinutrients	References
Potato peel	Peeling for chips/crisps/starch	4–10	15–30	Chlorogenic acid, glycoalkaloids	[2,27–29]
Potato pulp/fruit juice	Starch extraction	40–65 (protein isolate)	10–20	Patatin, protease inhibitors, phenolics	[23,24,30,31]
Sweet potato residue	Starch processing	3–7	20–35	Anthocyanins, polyphenols, and resistant starch	[16,32,33]
Cassava peel/bagasse	Peeling, starch/flour processing	3–9	15–25	Cyanogenic glucosides, phenolics	[4,5,17]
Soybean okara	Soymilk/tofu manufacture	20–30	45–55	Isoflavone glucosides, saponins	[6,8,12]
Pulse hulls/husks	Dehulling, flour/protein processing	5–15	40–60	Tannins, phytates, phenolics	[3,7,26]

4. Fermentation Technologies for By-Product Valorisation

Two main fermentation approaches are widely used to convert tuber and legume by-products into value-added functional ingredients: solid-state fermentation (SSF) and submerged fermentation (SmF) [11,14]. In SSF, microorganisms grow on moist solid substrates with little or no free water, making this approach particularly suitable for fibrous residues such as cassava peels, pulse hulls, and dried okara. Compared with SmF, SSF requires less water, provides higher productivity per unit volume, and closely resembles many traditional fermentation practices. In contrast, SmF involves suspending the substrate in a liquid medium, allowing better control of factors such as pH, aeration, and nutrient availability. This method is therefore more appropriate for liquid by-products, including potato fruit juice [4,14].

Lactic acid bacteria (LAB), particularly *Lactobacillus plantarum*, *Lactocaseibacillus rhamnosus*, and *Pediococcus pentosaceus*, are among the most commonly used starter cultures for fermenting tuber by-products. These microorganisms lower the pH by producing organic acids, synthesise exopolysaccharides, and modify starch granules, resulting in fermented starches with improved pasting and gelling characteristics [15,16]. Studies have shown that fermenting sweet potato residues with mixed LAB cultures increases soluble dietary fibre, total polyphenol content, and the production of lactic and acetic acids, while also en-

hancing antioxidant activity. Fermentation further alters the substrate's physical structure, producing a looser, more porous matrix, as observed by scanning electron microscopy [16].

Filamentous fungi also play an important role in the fermentation of tuber by-products. Species such as *Rhizopus oligosporus*, *Aspergillus* spp., and edible *Pleurotus* (oyster mushroom) are widely employed in the solid-state fermentation of cassava residues and cassava–soybean mixtures. These fungi produce extracellular enzymes, including amylases, cellulases, and proteases, which break down complex carbohydrates and proteins, reduce cyanogenic glucosides, and increase soluble protein levels (Figure 1). In addition, fungal biomass contributes extra protein and bioactive compounds to the fermented product, further improving its nutritional quality [10,17]. Yeasts such as *Saccharomyces cerevisiae* are also used, either alone or in combination with bacteria, to detoxify cassava peels and enhance their protein content for food and animal feed applications [5,17].

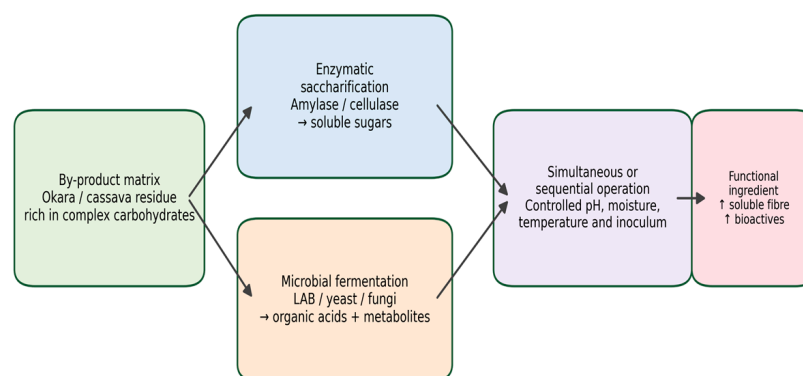


Figure 1. Integrated enzymatic saccharification and microbial fermentation pathway.

Among legume by-products, soybean okara has received the greatest research attention. During solid-state fermentation, fungi such as *Rhizopus* and *Aspergillus* produce β -glucosidase enzymes that convert isoflavone glucosides, including *daidzin* and *genistin*, into the more readily absorbed aglycone forms, *daidzein* and *genistein*. At the same time, fermentation reduces fibre content and improves protein digestibility [12,13]. Probiotic LAB fermentation, sometimes combined with enzymatic saccharification, further increases the concentrations of free sugars and amino acids, making fermented okara suitable for developing functional beverages, sauces, and probiotic food products [6,8]. Increasingly, researchers are using mixed microbial cultures rather than single strains because they more closely resemble the microbial diversity of traditional fermented foods and provide complementary enzymatic activities that improve substrate utilisation [26,34]. The specific strain composition and, in sequential (back-slopped or two-stage) processes, the order in which microorganisms are introduced can substantially influence fermentation outcomes. Co-inoculation of lactic acid bacteria (LAB) with amylolytic or cellulolytic fungi can promote complementary interactions, whereby fungal hydrolytic enzymes release fermentable sugars that are subsequently utilised by LAB to produce organic acids. The resulting decrease in pH may further influence enzyme activity while suppressing competing and spoilage microorganisms. In contrast, introducing the fungal stage first allows substrate hydrolysis to occur before acidification, potentially maximising the release of fermentable sugars for subsequent bacterial fermentation. Simultaneous inoculation, however, may result in substrate competition, particularly when rapidly acidifying LAB inhibits fungal growth before sufficient hydrolysis has occurred. These interactions are mediated by several mechanisms, including competition for fermentable carbohydrates and nitrogen, interspecies signaling and cross-feeding, and pH- and metabolite-mediated inhibition. For example, fungal hydrolysis products can serve as substrates for LAB, whereas organic acids

and bacteriocins produced by LAB may inhibit competing or undesirable microorganisms. Because these interactions are highly strain- and sequence-dependent, similar substrates fermented with ostensibly comparable mixed cultures may exhibit markedly different metabolic, functional, and safety profiles. This highlights the importance of carefully selecting starter cultures and optimising inoculation sequence and process conditions for the targeted valorisation of tuber and legume by-products.

The success of fermentation depends largely on process conditions. Moisture content and water activity determine which microorganisms can grow and how efficiently fermentation proceeds. In solid-state fermentation, particularly with cassava peels and pulse hulls, maintaining an optimal moisture level is essential to provide sufficient water for microbial activity while preventing substrate compaction and poor oxygen diffusion [4]. Temperature and fermentation time also vary according to the microorganism and substrate. LAB fermentation of sweet potato residues is generally carried out at moderate temperatures for one to two days, whereas fungal fermentation of cassava peels with *Rhizopus oligosporus* often requires several days to achieve effective detoxification and enzyme production [16,17]. Also, inoculum size and, in mixed-culture fermentations, the relative proportions of individual microorganisms influence whether acid production, protein degradation, or polysaccharide hydrolysis becomes the dominant metabolic process [16].

Another important consideration is the choice between spontaneous fermentation and the use of defined starter cultures. Spontaneous fermentation relies on naturally occurring microorganisms and has traditionally been used for processing many cassava- and legume-based foods. Although this approach is inexpensive and requires minimal infrastructure, its outcomes are often inconsistent because the native microbial population varies with factors such as season, storage conditions, and hygiene practices [4,11]. In contrast, defined starter cultures provide greater control over fermentation, resulting in more consistent acidification, enzyme production, and metabolite formation. Consequently, starter-culture fermentation is generally preferred for producing food-grade functional ingredients with predictable quality, despite the additional costs associated with starter production, storage, and maintenance [13].

Scaling fermentation processes from laboratory to industrial throughput introduces distinct engineering challenges that cannot be fully addressed by the process advantages demonstrated at bench scale. In solid-state fermentation (SSF), the shallow-bed and tray configurations commonly used in laboratory studies do not necessarily scale linearly because increasing bed depth and reactor volume can intensify heat- and mass-transfer limitations. Microbial metabolism generates heat that is difficult to dissipate in poorly conductive solid matrices, potentially leading to temperature and moisture gradients, heterogeneous microbial growth, substrate compaction, and non-uniform oxygen distribution. Consequently, industrial SSF often requires purpose-designed bioreactor configurations, including packed-bed, rotating-drum, stirred-bed, and fluidised-bed systems, together with controlled aeration, moisture management, and temperature regulation [35,36].

In submerged fermentation (SmF), scale-up is governed primarily by mixing and gas–liquid mass-transfer constraints. These challenges become particularly important when processing viscous or particulate-rich by-product slurries, such as potato fruit juice or okara-based suspensions, because changes in broth rheology can reduce mixing efficiency and oxygen-transfer capacity. As reactor volume increases, maintaining adequate oxygen transfer requires careful optimisation of impeller configuration, agitation, aeration rate, and reactor geometry, commonly using parameters such as the volumetric oxygen-transfer coefficient and power input per unit volume as scale-up criteria [37,38]. Foaming can also become increasingly problematic during large-scale aerated fermentation, as excessive foam

may reduce effective gas–liquid mass transfer and necessitate the addition of antifoam agents, which can subsequently affect downstream processing and process economics [39].

Importantly, process conditions optimized at laboratory scale, including inoculum concentration, substrate moisture content, aeration, agitation, and temperature, cannot generally be transferred directly to industrial equipment because hydrodynamic, heat-transfer, and mass-transfer conditions change with scale. Successful scale-up therefore requires systematic re-optimisation at intermediate or pilot scales, guided by appropriate engineering criteria and consideration of the physiological responses of the production microorganism [38,40]. Failure to account for these scale-dependent interactions can result in reduced productivity, inconsistent product quality, and diminished process efficiency, underscoring the importance of integrated bioreactor design, process monitoring, and scale-up strategies in the industrial valorisation of tuber and legume by-products.

The overall workflow linking by-product characterisation, fermentation processing and functional-ingredient output is illustrated in Figure 2, while representative fermentation systems reported for each substrate, together with the organisms and principal outcomes involved, are summarised in Table 2.

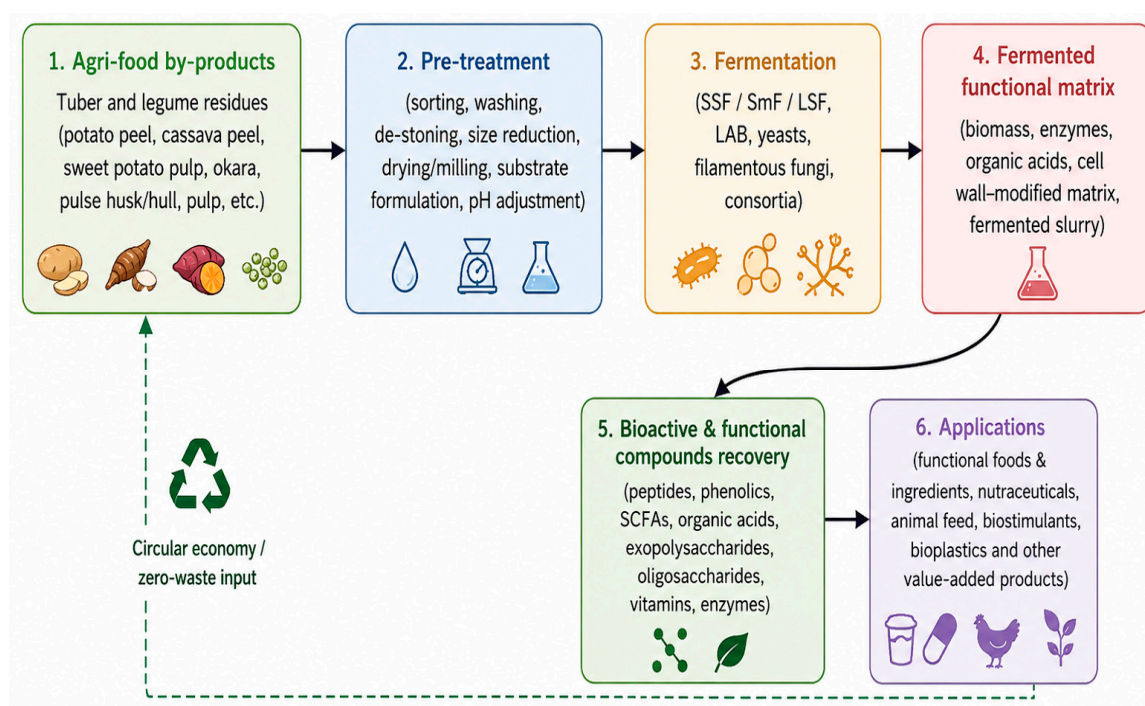


Figure 2. Fermentation-based valorisation pipeline for tuber and legume agri-food by-products. Source Adapted from [41,42].

Table 2. Representative fermentation systems applied to tuber and legume by-product valorisation.

Substrate	Fermentation Type	Representative Organism	Principal Outcome	References
Potato starch/pulp	Submerged Fermentation (SmF)	<i>Lactobacillus plantarum</i>	Fermented starch with modified pasting properties	[15,43,44]
Sweet potato residue	Submerged Fermentation (SmF)	<i>Lactocaseibacillus rhamnosus</i> and <i>Pediococcus pentosaceus</i>	Increased soluble fibre, polyphenols, organic acids, antioxidant activity	[16,32,45]
Cassava peel	Solid-State Fermentation (SSF)	<i>Rhizopus oligosporus</i>	Reduced cyanogenic glucosides; increased soluble protein; α -amylase production	[4,17,46]

Table 2. Cont.

Substrate	Fermentation Type	Representative Organism	Principal Outcome	References
Cassava and soybean residue	Solid-State Fermentation (SSF)	<i>Pleurotus ostreatus mycelium</i>	Improved nutrient profile for safe animal feed	[14,47,48]
Soybean okara	Solid-State Fermentation (SSF)	<i>Aspergillus/Rhizopus</i> spp.	Isoflavone glucoside-to-aglycone bioconversion; reduced raw fibre	[12,13,48]
Okara (biotransformation)	Enzymatic saccharification and LAB fermentation	Mixed LAB cultures	Higher free sugars, amino acids, prebiotic dietary fibre	[6,8,12,49]
Pulse husks/hulls	Solid-State Fermentation (SSF)/Submerged Fermentation (SmF)	LAB and fungal co-culture	Lactic acid production; techno-functional replacement of fats, eggs, hydrocolloids	[7,26,50]

5. Biochemical and Nutritional Transformations During Fermentation

Across substrates, fermentation consistently drives the same handful of biochemical changes. Starch and non-starch polysaccharides are partially hydrolysed, raising soluble fibre and fermentable oligosaccharide content. Bound, matrix-associated phenolic compounds are released through microbial esterase and glycosidase activity, lifting measurable total phenolic content and radical-scavenging capacity. Storage and structural proteins undergo proteolysis into peptides and free amino acids, some of which exhibit antioxidant, antihypertensive, or antimicrobial activity. Antinutritional and toxic constituents, including phytic acid, tannins, trypsin inhibitors, and, in cassava substrates, cyanogenic glucosides, are broken down [4,13].

These transformations are interdependent. Cell-wall-degrading enzymes released during fungal or bacterial growth loosen the plant matrix, which both liberates bound phenolics and improves access of proteolytic and amylolytic enzymes to their substrates, producing the looser, more porous microstructure documented by microscopy in fermented sweet potato residue and okara [12]. In cassava-based by-products, fermentation provides dual benefits by simultaneously improving nutritional quality and enhancing safety. The enzymatic activities of fermenting microorganisms increase protein solubility and antioxidant capacity and promote the breakdown of cyanogenic glucosides via the enzyme *linamarase*. As a result, fermentation serves as both a nutritional enhancement and detoxification process in a single step [4].

One of the best-documented examples of fermentation-induced improvement in bioactivity is the conversion of isoflavones during okara fermentation. β -Glucosidase enzymes produced by fermenting fungi and bacteria hydrolyse the sugar groups attached to the isoflavone glucosides *daidzin* and *genistin*, converting them into the aglycone forms daidzein and genistein. These aglycones are more readily absorbed in the human gastrointestinal tract and have been linked to greater antioxidant activity and beneficial estrogen-modulating effects [4,13]. Similar transformations have also been reported in potato-derived by-products, where fermentation converts glycoside-bound phytochemicals into more bioavailable aglycones and breaks down chlorogenic acid derivatives into low-molecular-weight phenolic acids. These changes increase the availability of health-promoting compounds without requiring expensive extraction or purification processes [2,13].

However, the nutritional benefits of fermentation are strongly influenced by processing conditions, particularly fermentation time and intensity. Under optimal conditions, fermentation generally increases soluble phenolic compounds and antioxidant capacity by releasing phytochemicals that were previously bound within the food matrix. If fer-

mentation is prolonged or excessively intensive, however, microorganisms may further metabolise these released phenolic compounds into smaller molecules that exhibit lower antioxidant activity or are less readily detected by conventional analytical methods. Consequently, the biochemical changes that occur during fermentation do not always increase continuously over time; instead, they depend on carefully balancing the fermentation conditions to maximise the nutritional and functional quality of the final product [2].

Process optimisation, rather than fermentation per se, is what ultimately determines whether a target functional profile is reached, which is likely why comparable substrates fermented with different starter cultures or for different durations so often produce divergent reported outcomes. The interconnected biochemical and nutritional changes described above are summarised schematically in Figure 3.

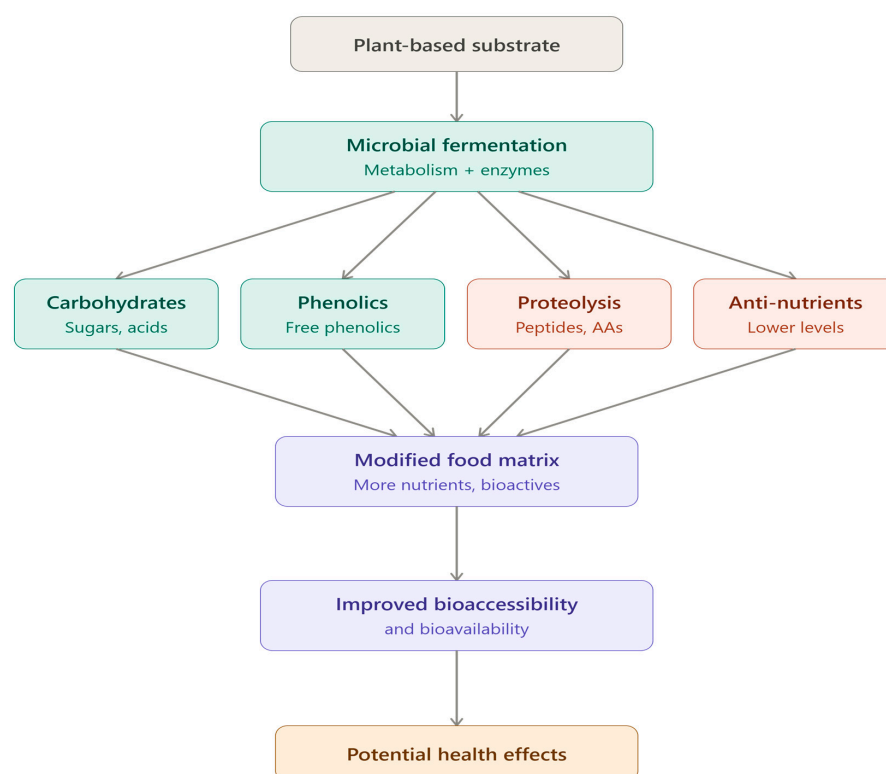


Figure 3. Integrated Biochemical and nutritional transformations during fermentation.

6. Functional and Bioactive Properties of Fermented By-Products

The functional consequences of these biochemical changes have been evaluated across a range of *in vitro* and, less frequently, *in vivo* or clinical models. Fermented potato peel and sweet potato residue extracts consistently show elevated DPPH and related radical-scavenging activity relative to unfermented controls, attributable to both the increased free phenolic content and to newly formed melanoidin and peptide-type antioxidants [16]. Fermented okara has been reported in the literature to exhibit antidiabetic, anti-obesity, anti-hyperlipidaemic, and antioxidant activities, generally attributed to the combined effects of increased soluble fibre, released isoflavone aglycones, and bioactive peptides generated during proteolysis [6].

From a protein-quality perspective, fermentation of potato pulp, okara, and pulse hulls has been reported to increase the proportion of soluble and low-molecular-weight nitrogenous fractions, which is generally interpreted as improved digestibility and reduced potential for complexation between protein and phenolic or glycoalkaloid constituents that otherwise depress protein bioavailability [23]. The reduction in trypsin-inhibitor activity

and phytate content further supports improved amino acid and mineral bioaccessibility in fermented legume by-products [3].

The soluble dietary fibre and oligosaccharide fractions generated during fermentation are of particular interest for their prebiotic potential: increased soluble fibre in fermented sweet potato residue, alongside residual viable lactic acid bacteria, has been linked in vitro to favourable simulated colonic fermentation profiles, including short-chain fatty acid-supportive substrate availability [16]. Comparable prebiotic reasoning underlies interest in fermented okara and pulse husk fractions as functional fibre ingredients capable of selectively supporting beneficial gut taxa [6].

Sensory and techno-functional attributes are equally important determinants of whether a fermented by-product ingredient can be adopted at a commercial scale, independent of its nutritional or bioactive merit. Fermentation typically shifts the flavour profile toward mild acidity and, depending on the dominant organism, can reduce beany or earthy off-notes associated with unfermented okara and certain pulse fractions, while fungal SSF of cassava-derived substrates can introduce characteristic fermented aromas that are acceptable in some traditional food contexts but may require masking or blending for other applications [4]. Water- and oil-holding capacity, viscosity and gelling behaviour are also altered by fermentation-induced polysaccharide and protein modification, which is the basis for the reported use of fermented pulse by-products as replacers for fat, egg or hydrocolloid functionality in reformulated food products [26]. The principal functional and bioactive properties documented for fermented tuber and legume by-products, together with their proposed mechanistic basis, are summarised in Table 3.

Table 3. Principal functional and bioactive properties of fermented tuber and legume by-product ingredients.

Functional Property	Substrate Examples	Mechanistic Basis	References
Antioxidant/radical-scavenging activity	Potato peel, sweet potato residue, okara	Release of bound phenolics; formation of peptide and Maillard-type antioxidants	[2,12,16]
Improved protein digestibility/quality	Potato pulp, okara, pulse hulls	Proteolysis to peptides/free amino acids; reduced protein–phenolic/tannin complexation	[3,23,24]
Isoflavone bioactivation	Soybean okara	β -glucosidase-mediated glucoside-to-aglycone conversion (daidzein, genistein)	[12,13]
Antinutrient/toxicant reduction	Cassava peel, pulse hulls	<i>Linamarase</i> -mediated cyanogenic glucoside breakdown; phytase and tannase activity	[2,3,16]
Prebiotic/soluble fibre enrichment	Sweet potato residue, okara, pulse husks	Polysaccharide hydrolysis increases soluble and fermentable fibre fractions	[6,16,26]
Techno-functional replacement of fat, egg, hydrocolloids	Pulse by-products	Modified water/oil-holding and gelling properties post-fermentation/processing	[7,26]

7. Applications in Functional Foods and Nutraceuticals

Fermented tuber and legume by-product ingredients are being explored across several food categories. In bakery and cereal-based products, fermented potato and sweet potato starches are used as functional replacements for cassava starch in gluten-free formulations, exploiting their modified pasting and gelling behaviour to improve crumb structure without the need for conventional yeast leavening [15]. Fermented okara flour and pulse husk fractions are incorporated into biscuits, bread and extruded snacks as fibre- and

protein-fortifying ingredients, simultaneously supporting waste reduction and product reformulation toward higher-fibre, lower-glycaemic-index profiles [6].

In dairy-alternative and fermented-beverage applications, potato protein isolates combined with high-pressure homogenisation have been used to create stabiliser-free, yogurt-like fermented products, addressing the poor solubility and sensory limitations that commonly affect plant-protein-based analogues [24]. Okara has similarly been developed into fermented sauces, functional beverages, and, when combined with lactic acid bacteria-fermented whey, into bioactive edible films incorporating sweet potato flour and potato starch as prebiotic and probiotic-carrier matrices for food packaging [6].

Fermented cassava peel and cassava-soybean residue systems have been directed principally toward safe, nutrient-enriched animal feed, reflecting both the technical maturity of detoxification-oriented fermentation and the comparative cost sensitivity of feed markets relative to human food ingredients [14]. Nonetheless, the same detoxification and protein-enrichment principles are increasingly being adapted for human-food-grade cassava-derived ingredients, including fermented flours and composite baked goods, particularly in regions where cassava is a dietary staple [22].

Beyond direct food incorporation, fermentation-derived extracts from these by-products are being explored as nutraceutical and cosmeceutical ingredients, leveraging their concentrated phenolic and peptide fractions for antioxidant and skin-health applications, and as substrates for single-cell protein, enzymes, and other high-value biomolecules within integrated biorefinery concepts [9].

Effective incorporation of fermented by-product ingredients into mainstream products depends on formulation strategies that manage inclusion level, particle size, and interaction with other recipe components, since excessive inclusion of fibre- and phenolic-rich fermented material can adversely affect texture, colour and mouthfeel even where nutritional and functional benefits are clearly demonstrated at the ingredient level [26]. Research on consumer acceptance of foods containing by-product-derived ingredients suggests that consumers may initially be hesitant because these ingredients are associated with food waste [9,27]. However, this perception can be improved through clear communication about their sustainability benefits and nutritional or functional value. These findings indicate that effective labelling and marketing are just as important as product formulation in encouraging consumer acceptance and supporting the successful commercialisation of these ingredients [9].

8. From Waste Valorisation to Precision Nutrition

Precision nutrition aims to move beyond general dietary recommendations by developing strategies tailored to an individual's genetic makeup, metabolic profile, gut microbiome, and overall health status [9,19]. Growing evidence shows that differences in the gut microbiome are a major reason people respond differently to the same foods, particularly to blood glucose, blood lipid, and post-meal inflammatory responses. Dietary components such as fibre, polyphenols, and other fermentable compounds play a key role in shaping the composition and activity of the gut microbiota, making them important targets for personalised nutrition interventions [21].

Fermented foods are especially relevant to precision nutrition because they combine several characteristics that support gut health. They contain diverse communities of beneficial microorganisms embedded within the food matrix, are naturally enriched with organic acids, bioactive peptides, and biotransformed phytochemicals produced during fermentation, and, in the case of plant-based fermented foods, retain dietary fibre and phenolic compounds that can promote microbial survival and beneficial interactions within the gut. These features may offer advantages over some fermented dairy products, where

fibre is naturally absent [34]. A recent scoping review further demonstrated that the health effects of fermented foods vary considerably among individuals and are influenced by factors such as age, sex, geographical location, hormonal status, existing health conditions, and genetic background. These findings support the need for a precision nutrition approach to fermented-food research rather than relying on universal dietary recommendations [21].

Fermented ingredients produced from tuber and legume by-products have considerable potential within this emerging field. Fermentation increases the levels of soluble fibre and oligosaccharides, providing fermentable substrates that support the growth and activity of beneficial gut microorganisms. It also enhances the availability of bioactive compounds, including isoflavone aglycones and phenolic compounds, whose metabolism and health benefits are closely linked to the gut microbiome. When these ingredients are consumed in minimally processed fermented forms, they may also introduce beneficial microorganisms that can temporarily influence the gut microbial ecosystem [6].

Advances in precision fermentation further strengthen this potential. By carefully selecting specific microbial strains and optimising fermentation conditions, it is possible to produce fermented by-products with targeted nutritional and functional properties. This approach enables the development of functional ingredients designed to support specific health outcomes or meet the dietary needs of particular population groups, while allowing fermented agri-food by-products to be engineered for defined functional properties, such as increased isoflavone aglycone content or enhanced production of short-chain fatty acid precursors, rather than relying on the inherent variability of different substrates [34].

Realising this potential in practice, however, requires integrating by-product characterisation and fermentation process data with individual-level physiological and microbiome data, an interdisciplinary step that has, to date, been explored mainly in conceptual or small-scale intervention studies rather than in large, by-product-specific human trials [20]. The conceptual links between fermented by-product ingredients, host and microbiome variability, and precision-nutrition outcomes are depicted in Figure 4.

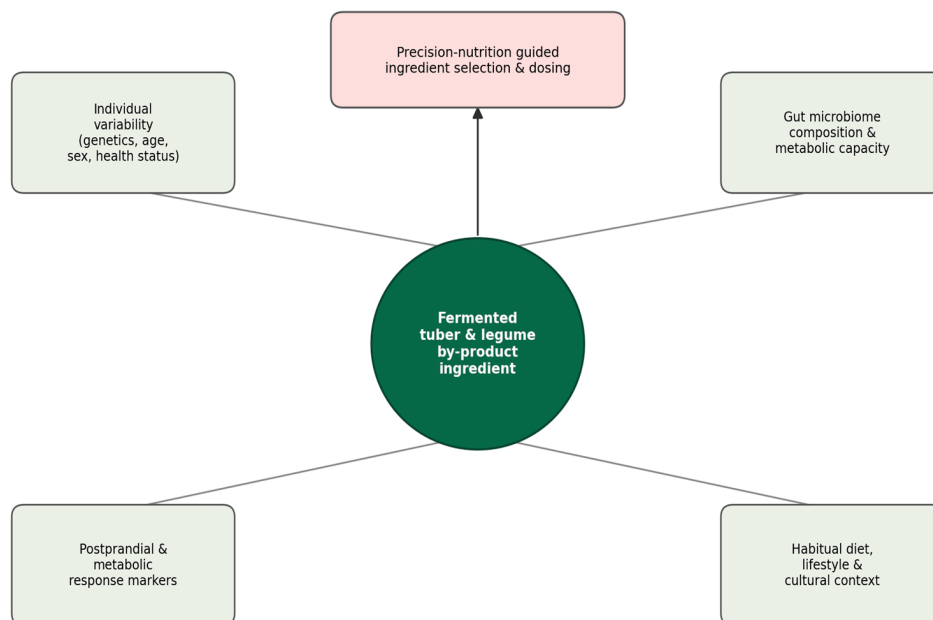


Figure 4. Conceptual framework linking fermented by-product ingredients with precision nutrition.

9. Challenges, Safety, and Regulatory Considerations

Despite the technological maturity of many fermentation processes at laboratory scale, several barriers constrain their translation into mainstream functional ingredients. First,

compositional variability, caused by cultivar, harvest season, processing method and by-product fraction, can produce inconsistent fermentation kinetics and final composition, making reproducible product specifications difficult. Second, inadequate control of glycoalkaloids, cyanogenic glucosides, mycotoxins or pathogens can result in unsafe batches, regulatory non-compliance and product recalls. These compounds must be reduced to safe levels and their concentrations verified analytically at the batch level, as the effectiveness of fermentation in reducing toxicants can vary according to process conditions, substrate characteristics, and starter-culture activity. Inadequate monitoring and verification may increase the risk of consumer exposure to potentially toxic concentrations and create regulatory and commercial consequences, including product recalls, non-compliance with food-safety requirements, and reputational damage to producers [17]. Mycotoxin and pathogen contamination risk in solid-state fermentation of moist, nutrient-rich residues also requires robust hygienic and process controls, particularly when spontaneous or non-sterile fermentation is used for cost reasons, and undetected lapses in these controls can lead to spoilage losses, mycotoxin accumulation, and, in the worst case, foodborne illness outbreaks [26].

Third, scale-up of solid-state fermentation from laboratory trays to industrial bioreactors introduces heat and mass-transfer constraints, such as oxygen diffusion, temperature, and moisture gradients, that can compromise the yield and consistency achieved at small scale, a recurring theme in reviews of SSF for bioactive-compound recovery from agri-food residues. If not adequately addressed through appropriate reactor design and process control, scale-up limitations may result in batch failures, inconsistent bioactive yields, reduced process efficiency, and increased production costs, thereby undermining the economic feasibility of commercial-scale production [51,52]. Fourth, regulatory uncertainty concerning novel-food status, permitted strains, and health claims can delay market entry and increase compliance costs. Finally, limited human evidence for precision-nutrition claims can weaken scientific substantiation and make health-related marketing claims difficult to defend [21].

Scale-up also requires a systematic distinction between SSF and SmF. SSF can reduce water use and downstream processing, but heat removal, moisture control, oxygen transfer, mixing, and pH monitoring become increasingly difficult as bed depth and reactor volume increase. SmF provides better mixing and online control of pH, dissolved oxygen, and temperature, but generally requires more water, energy, and sophisticated equipment. These trade-offs mean that the industrially preferred process depends on the product, organism and substrate rather than on a universal superiority of either system [52]. The main barriers to industrial-scale deployment, together with proposed mitigation strategies, are summarised in Table 4.

Table 4. Principal challenges to industrial-scale deployment of fermented by-product ingredients and proposed mitigation strategies.

Challenge	Underlying Cause	Mitigation Strategy	References
Compositional variability	Cultivar, season, processing method, by-product fraction	Systematic raw-material characterisation; standardised sampling and reporting	[2,8]
Residual toxicants (glycoalkaloids, cyanogenic glucosides)	Incomplete or inconsistent microbial detoxification	Validated starter cultures; batch-level analytical verification; process optimisation	[4,17]
Microbial safety in non-sterile SSF	Moist, nutrient-rich substrate favouring contaminants	Defined starter inoculation; hygienic design; hurdle technologies (pH, aw control)	[11,26]

Table 4. *Cont.*

Challenge	Underlying Cause	Mitigation Strategy	References
Scale-up heat or mass transfer limitations	Oxygen and moisture gradients in large-scale SSF bioreactors	Bioreactor engineering; process modelling; hybrid SSF/SmF strategies	[11,53]
Regulatory and novel-food classification	Jurisdictional variability in strain approval and claim substantiation	Early regulatory engagement; harmonised safety dossiers; transparent labelling	[3,21]
Limited human clinical evidence for precision-nutrition claims	Reliance on in vitro/ animal/substrate-level studies	Stratified human trials linking ingredient intake to microbiome/metabolic phenotype	[20,21]

10. Future Perspectives

Several research directions are likely to shape the next phase of this field. Multi-omics characterisation, integrating metabolomics, proteomics and microbial community sequencing of fermenting by-product substrates, can clarify the mechanistic links between specific starter cultures, process parameters and the resulting bioactive-compound profile, moving the field from largely empirical optimisation toward rational, precision-fermentation design. Coupling this with computer-based and machine-learning-assisted process modelling may help address the scale-up and heat or mass-transfer challenges that currently limit industrial SSF deployment.

Second, stratified human intervention studies that pair defined fermented by-product ingredients with individual microbiome and metabolic phenotyping are needed to substantiate precision-nutrition claims that currently rest largely on mechanistic plausibility.

Third, integrated biorefinery approaches that recover multiple value streams (functional food ingredients, enzymes, single-cell protein, bioenergy) from the same by-product feedstock could improve the overall economic and environmental case for fermentation-based valorisation relative to single-product extraction routes.

Finally, harmonisation of safety and regulatory frameworks across regions, alongside consumer communication that clearly differentiates by-product-derived fermented ingredients from conventional recycled or lower-grade inputs, will be important for building market and regulatory confidence in these ingredients as legitimate, safety-verified components of next-generation functional foods.

11. Conclusions

Fermentation offers a technically robust, comparatively low-cost, and environmentally safe method for transforming tuber and legume agri-food by-products from a disposal liability into functional food ingredients with enhanced bioactive compound content, improved digestibility, and reduced antinutrient load. The evidence reviewed across potato, sweet potato, cassava, soybean, and other pulse by-products consistently shows that fermentation enhances their nutritional and functional value. These improvements include greater antioxidant capacity, improved protein quality, increased levels of prebiotic dietary fibre, and, in some cases, enhanced bioavailability of phytochemicals, such as the conversion of okara isoflavones into more readily absorbed forms. Collectively, these findings demonstrate the potential of fermentation to transform agri-food by-products into high-value functional ingredients. An emerging area of interest is the role of these fermented ingredients in precision nutrition, particularly through their interactions with the gut microbiome. Although current evidence suggests that fermented tuber and legume by-products may help support personalised dietary strategies by influencing gut microbial composition and function, most of the available research is based on mechanistic studies

and laboratory investigations. Therefore, well-designed human intervention studies involving diverse population groups are needed to validate these promising findings and establish their effectiveness in precision nutrition. Addressing compositional variability, safety verification, scale-up engineering and regulatory harmonisation will be essential prerequisites for translating laboratory-validated fermentation processes into commercially viable, safety-assured functional ingredients that connect waste valorisation with the personalised nutrition needs of future food systems.

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