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Underutilized Legumes, Oilseeds and Tubers as Sustainable Protein Sources: Processing, Fermentation, Nutritional Quality and Food Safety of Plant-Based Foods

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ABSTRACT
Global demand for protein is rising at a time when the environmental costs of animal production and the climate vulnerability of major crops are becoming more apparent. Most plant-based protein ingredients are drawn from a very small number of crops, principally soybean, pea and wheat, which leaves food systems exposed to supply shocks and neglects a large reservoir of nutritious, climate-resilient species that are grown and eaten locally, particularly in Africa and Asia, but have received little research or commercial attention. This review examines underutilized legumes (including bambara groundnut, African yam bean, pigeon pea, cowpea landraces, winged bean, lupin, grass pea and mung bean), oilseeds (including melon seed, sunflower, cottonseed and moringa) and tubers and roots (including tiger nut, cassava leaves, yam and potato) as sources of protein for plant-based foods. For each group it considers composition, protein functionality and agronomic value, and it then reviews the processing technologies, including dehulling, soaking, germination, cooking, protein extraction and hydrolysis, that improve their nutritional and functional properties. Particular attention is given to fermentation, both the indigenous alkaline and lactic fermentations that have long been used to transform these crops in West Africa and Southeast Asia and the controlled, starter-culture-driven fermentations that can bring those traditions into modern food manufacture. The review then evaluates nutritional quality, including amino acid adequacy, digestibility and bioactive peptides, and food safety hazards, including natural toxicants such as cyanogenic glycosides, β-ODAP and gossypol, allergens, mycotoxins and microbial pathogens. It concludes that underutilized crops can make a significant contribution to sustainable protein supply, but that realising this potential requires investment in breeding, processing infrastructure, controlled fermentation, food safety assurance and the regulatory recognition of traditional foods.

Keywords: underutilized crops; neglected and underutilized species; bambara groundnut; African yam bean; tiger nut; melon seed; plant protein; fermentation; antinutritional factors; food safety

I. INTRODUCTION

Securing an adequate supply of protein for a growing world population is among the central challenges facing food systems. Animal-source foods are efficient sources of high-quality protein, but their production uses a disproportionate share of agricultural land and contributes substantially to greenhouse gas emissions, water use and biodiversity loss (Poore and Nemecek, 2018; Willett et al., 2019). Plant proteins offer a more resource-efficient alternative, and the market for plant-based foods has grown substantially over the past decade. Yet this growth has been built on a strikingly narrow crop base. Soybean, pea and wheat supply the great majority of plant protein ingredients in international trade, and much of the scientific literature on plant-based foods concerns only these crops.

That narrowness carries risks. Dependence on a small number of crops exposes supply chains to disease, climate extremes and trade disruption, and it concentrates the benefits of the protein transition in a small number of producing regions. It also neglects a large number of species that are nutritious, adapted to marginal environments and culturally embedded in local diets, but that have received little investment in breeding, processing or marketing. These species are variously described as neglected and underutilized species, orphan crops or "future smart foods" (Mayes et al., 2012; Tadele, 2019; Li and Siddique, 2020). They include legumes such as bambara groundnut, African yam bean, pigeon pea, winged bean, lablab and grass pea; oilseeds such as melon seed (egusi), moringa and sunflower; and tubers and roots such as tiger nut, yam and cassava, whose leaves and processing side streams can also supply protein.

Many of these crops are particularly important in sub-Saharan Africa, where protein-energy malnutrition remains a public health concern and where climate change is expected to reduce the yields of many staple crops. Bambara groundnut, for example, can produce a harvest on poor soils and under drought conditions in which groundnut and maize fail, and it has been proposed as an exemplar underutilized legume for resilience under climate change (Mayes et al., 2019). Cheng et al. (2019) argued that underutilized tropical legumes represent one of the most promising and least exploited sources of alternative protein, provided that constraints related to antinutrients, processing and supply chains can be overcome.

The same crops have long been transformed into palatable, safe and nutritious foods through traditional processing, and above all through fermentation. In West Africa, the alkaline fermentation of African locust bean, African oil bean and melon seeds yields protein-rich condiments such as iru (dawadawa), ugba and ogiri; lactic fermentation produces cereal and legume gruels and beverages; and in Southeast Asia, fungal fermentation produces tempeh from soybean and other legumes (Nout and Kiers, 2005; Olasupo and Okorie, 2019). These traditional processes reduce antinutritional factors, improve digestibility, generate flavour and, when properly controlled, suppress pathogens. They also provide a foundation for modern, controlled fermentations that can bring underutilized crops into mainstream plant-based foods.

This review brings together the literature on underutilized legumes, oilseeds and tubers as sustainable protein sources, with a focus on the processing, fermentation, nutritional quality and food safety issues that determine whether they can be converted into safe, acceptable plant-based foods. Its objectives are to: (i) characterise the protein potential of the principal underutilized legumes, oilseeds and tubers; (ii) review processing technologies that improve their nutritional and functional properties; (iii) examine traditional and controlled fermentation as a tool for improving quality and safety; (iv) evaluate their nutritional quality; and (v) assess the food safety hazards associated with them and the controls available. It closes by identifying research and policy priorities.

2. REVIEW APPROACH

The review is a narrative synthesis of peer-reviewed literature and authoritative technical reports. Searches were conducted in Scopus, Web of Science, PubMed, AJOL and Google Scholar using the common and scientific names of the crops considered, combined with terms including "protein", "protein isolate", "functional properties", "antinutritional factors", "germination", "fermentation", "starter culture", "lactic acid bacteria", "Bacillus", "mycotoxin", "aflatoxin", "cyanogenic glycosides" and "food safety". Priority was given to studies published between 2005 and 2024, although earlier work was retained where it remains the principal source on a crop or process. Reference lists of key reviews were searched for additional studies.

The review deliberately gives weight to research from Africa and Asia, where most underutilized crops are grown and consumed and where much of the primary research on their composition, processing and fermentation has been conducted. Studies from Nigeria, South Africa, Ghana, Côte d'Ivoire, Burkina Faso, Ethiopia, India, Malaysia and elsewhere are therefore discussed alongside work from Europe and North America. "Underutilized" is used here in a relative sense: several of the crops discussed, such as cowpea and yam, are staples in their regions of origin, but they remain underused as sources of protein ingredients and are rarely considered in the international plant-based food literature.

3. UNDERUTILIZED LEGUMES

3.1 Bambara Groundnut

Bambara groundnut (Vigna subterranea) is an indigenous African legume that is grown mainly by smallholder farmers, many of them women, across sub-Saharan Africa. Its seeds are often described as a "complete food" because they contain substantial quantities of carbohydrate, protein and fat, with protein typically around 18–24% (Azman Halimi et al., 2019). Azman Halimi et al. (2019) reviewed its nutritional composition and concluded that it has considerable potential to contribute to nutritional food security, noting its relatively favourable amino acid profile compared with other pulses and its content of minerals such as iron and potassium. Nutritional evaluation of a landrace from Côte d'Ivoire confirmed its value as a source of protein, dietary fibre and minerals (Yao et al., 2015).

Agronomically, bambara groundnut tolerates drought, high temperatures and poor soils and, like other legumes, fixes atmospheric nitrogen. Mayes et al. (2019) described it as an exemplar underutilized legume for resilience under climate change and summarised progress in genomics and breeding that could overcome constraints such as low and variable yields, long cooking times and the lack of improved varieties.

The protein of bambara groundnut can be recovered as concentrates and isolates with useful functional properties.

Arise, Amonsou and Ijabadeniyi (2015) prepared protein concentrates from South African bambara groundnut landraces by different extraction methods and found that the method strongly influenced protein content, solubility and emulsifying and foaming properties, indicating that extraction conditions can be chosen to suit particular applications. Arise et al. (2016) showed that enzymatic hydrolysates of bambara protein and their low-molecular-weight ultrafiltration fractions have antioxidant activity, suggesting potential uses in functional foods. These studies, conducted by African researchers in collaboration with Canadian groups, illustrate the growing capacity to convert this traditional crop into modern food ingredients.

3.2 African Yam Bean

African yam bean (Sphenostylis stenocarpa) is a tuberous legume grown in West and Central Africa, particularly in southern Nigeria, for its seeds and, in some areas, its edible tubers. Its seeds contain around 20–25% protein and are a traditional food in Nigeria, but consumption is limited by very long cooking times (the "hard-to-cook" defect), by antinutritional factors, and by the flatulence associated with oligosaccharides (George, Obilana and Oyeyinka, 2020). George, Obilana and Oyeyinka (2020) reviewed the past and future importance of the crop and argued that improved processing and product development could reverse its decline in cultivation.

Research on its protein fractions supports that view. Ajibola et al. (2016) characterised the albumin, globulin and protein concentrate of African yam bean seed and found that the albumin fraction, composed of polypeptides of 26 kDa or less, had higher solubility and better foaming properties than the globulin fraction or the concentrate. This fractional variation, similar to that observed in pea and other legumes, suggests that targeted fractionation could yield ingredients with specific functions. Because its tubers are also edible and relatively protein-rich for a root crop, African yam bean is an unusual example of a crop that can supply protein from both seeds and underground organs.

3.3 Pigeon Pea and Cowpea

Pigeon pea (Cajanus cajan) is a drought-tolerant perennial legume grown widely in South Asia, eastern and southern Africa and the Caribbean. Its seeds contain around 20–22% protein and are consumed as dhal and in many other forms. Saxena, Kumar and Sultana (2010) reviewed its nutritional quality and emphasised its contribution to protein intake in vegetarian diets in India, as well as the need to reduce antinutrients such as protease inhibitors and polyphenols through processing.

Cowpea (Vigna unguiculata) is a staple in West Africa, where Nigeria is the largest producer, and it is widely eaten in bean porridge, akara (fried bean cakes) and moin-moin (steamed bean pudding). Although it is not underutilized as a food in its regions of production, it remains underused as a protein ingredient in the international plant-based food industry. Gonçalves et al. (2016) described cowpea as a "renewed multipurpose crop" with a protein content of around 20–25%, drought tolerance and the capacity to improve soil fertility, while noting constraints such as antinutrients and flatulence-causing oligosaccharides. Jayathilake et al. (2018) summarised evidence for its health benefits, including its content of dietary fibre and phenolic compounds with antioxidant activity.

3.4 Winged Bean, Lupin and Mung Bean

Winged bean (Psophocarpus tetragonolobus) is a tropical legume in which almost all parts, including seeds, pods, leaves, flowers and tuberous roots, are edible. Its mature seeds have a protein and oil content comparable to soybean, which has led to its description as a potential "soybean of the tropics". Tanzi et al. (2019) synthesised past research on winged bean and concluded that it has considerable potential for food and nutritional security in the humid tropics, but that its development has been held back by a lack of improved varieties and by limited processing research.

Lupins (Lupinus spp.) have high protein contents, often 30–40%, low starch and relatively high fibre. Sweet lupin varieties with low alkaloid content are grown in Australia and Europe and used in bakery products, pasta and meat alternatives. Lucas et al. (2015) reviewed the prospects of lupin as a protein crop in Europe and emphasised its adaptation to poor, acid soils and its potential to reduce reliance on imported soybean. Lupin is, however, a recognised allergen in the European Union, and cross-reactivity with peanut has been reported (Jappe and Vieths, 2010).

Mung bean (Vigna radiata) is widely grown in Asia and is consumed as whole seeds, sprouts and starch noodles. Its seeds contain around 21–31% protein, which is limited mainly in the sulphur amino acids (Zhu, Sun and FitzGerald, 2018). This protein, dominated by an 8S globulin, has good emulsifying and gelling properties and has been used as the basis of commercial egg substitutes. Zhu, Sun and FitzGerald (2018) reviewed the nutritional, functional and bioactive properties of mung bean proteins and peptides and highlighted their antihypertensive and antioxidant activities.

3.5 Grass Pea

Grass pea (Lathyrus sativus) is an extremely hardy legume that survives both drought and flooding and is often the only crop that yields in years of severe drought in Ethiopia, Bangladesh and India. Its seeds are high in protein, but they contain the neurotoxin β-N-oxalyl-L-α,β-diaminopropionic acid (β-ODAP), which can cause neurolathyrism, an irreversible paralysis of the lower limbs, when grass pea is consumed as the main food for extended periods. Lambein et al. (2019) reviewed the paradoxical status of grass pea as an "orphan crop, nutraceutical or just plain food", noting that the toxicity of β-ODAP is modulated by diet and that grass pea is safe when consumed as part of a balanced diet, while low-ODAP varieties and processing can further reduce the risk. Grass pea illustrates both the resilience of many underutilized crops and the importance of food safety research in their promotion.

3.6 Agronomic and Environmental Value of Underutilized Legumes

The case for underutilized legumes rests not only on their nutritional value but also on their contribution to sustainable farming systems. Like other legumes, they form symbioses with nitrogen-fixing rhizobia, which reduces or removes the need for synthetic nitrogen fertiliser and benefits subsequent crops in rotation. Stagnari et al. (2017) reviewed the multiple benefits of legumes for agricultural sustainability, including improvements in soil organic matter, soil structure and microbial activity, the breaking of pest and disease cycles in cereal-based systems, and lower greenhouse gas emissions per unit of protein produced. Many underutilized legumes add a further benefit: tolerance of drought, heat and poor soils that allows them to produce yields where major crops fail (Mayes et al., 2019; Cheng et al., 2019).

These properties are especially valuable in the smallholder systems of sub-Saharan Africa, where fertiliser is expensive, soils are often degraded and rainfall is increasingly variable. Intercropping bambara groundnut, cowpea or pigeon pea with cereals such as maize, sorghum and millet is already common in the region and provides both food security and soil fertility benefits. Increasing demand for these legumes as protein ingredients could therefore reinforce sustainable farming practices, provided that value chains return an adequate share of the value to farmers. At the same time, the environmental benefits of legumes can be undermined if expansion leads to land clearing or if post-harvest losses are high, so improvements in storage and processing are an integral part of their sustainable development (Augustin et al., 2016).

4. UNDERUTILIZED OILSEEDS

4.1 Melon Seed (Egusi)

The seeds of several cucurbits, including Citrullus lanatus and Cucumeropsis mannii, are widely consumed in West Africa as egusi, which is ground and used to thicken soups and stews. The seeds are rich in oil, often around 45–50%, and in protein, which can exceed 30% on a whole-seed basis and is concentrated further in the defatted meal. Ogunbusola et al. (2022) compared methods for extracting protein concentrates from white melon (Cucumeropsis mannii) seed and found that salt solubilisation produced concentrates with the highest protein content (74.9%), yield (42%), solubility across pH 3–9 and whiteness, making them promising for food applications. Melon seed protein is also a traditional substrate for fermentation, and the fermented condiment ogiri is made from melon seeds in parts of Nigeria.

A major constraint on melon seed as a protein source is its susceptibility to fungal contamination. Bankole, Ogunsanwo and Mabekoje (2004) found high levels of fungal contamination and aflatoxin B1 in melon seeds sold in Nigerian markets, and Adedeji et al. (2017) detected potentially hazardous bacteria and multiple mycotoxins in locust bean, melon seeds and their fermented products in south-western Nigeria. These findings point to the need for good agricultural, drying and storage practices before melon seed protein can be developed as an internationally traded ingredient.

4.2 Sunflower and Cottonseed

Sunflower is a major oilseed globally, but its protein is largely used as animal feed. Sunflower meal contains the 11S globulin helianthinin and 2S albumins, which have useful emulsifying and foaming properties, and it is low in antinutritional factors compared with many legumes (González-Pérez and Vereijken, 2007). Its main limitation is its high content of chlorogenic acid, which oxidises at alkaline pH to produce green discolouration and can bind to proteins, reducing their digestibility. Processing strategies to remove phenolic compounds before protein extraction are therefore important for food use.

Cottonseed is produced in large quantities as a by-product of cotton fibre in Africa, Asia and the Americas, and it contains around 20–25% protein. Its use as food is prevented by gossypol, a polyphenolic toxin. Rathore et al. (2020)

described the development of ultra-low gossypol cottonseed by selective gene silencing, which eliminates gossypol from the seed while retaining it elsewhere in the plant, and argued that the technology could open a vast resource of plant-based protein for human nutrition. For cotton-growing regions of West Africa, including northern Nigeria, such varieties could convert a by-product into a food protein.

4.3 Moringa

Moringa oleifera is a fast-growing, drought-tolerant tree grown throughout the tropics. Its leaves are rich in protein, vitamins, minerals and polyphenols, and dried leaf powder has been widely promoted as a nutritional supplement in Africa and Asia. Leone et al. (2015) reviewed its cultivation, phytochemistry and pharmacology and reported that the leaves contain a substantial proportion of protein on a dry basis, together with antioxidant and anti-inflammatory compounds. Moringa seeds are also rich in oil and protein, and their proteins have coagulating properties used in water treatment. The use of moringa leaf protein in plant-based foods is limited by its strong flavour and green colour, but it has potential in fortified foods and blended products.

5. UNDERUTILIZED TUBERS AND ROOTS

5.1 Tiger Nut

Tiger nut (Cyperus esculentus) is not a nut but the small tuber of a sedge. It is eaten raw, roasted or as a beverage in West Africa, where the drink is known in Nigeria as kunnu aya, and in Spain, where it is the basis of horchata de chufa. Tiger nuts are rich in starch, fat with a fatty acid profile similar to olive oil, and dietary fibre, and they contain a modest quantity of protein, typically below 10% (Sánchez-Zapata, Fernández-López and Pérez-Alvarez, 2012). Maduka and Ire (2018), reviewing the tiger nut plant and its applications, emphasised its value as a source of energy, fibre and minerals and its potential in beverages, flours and dairy alternatives.

Although tiger nut is not a high-protein crop, it is an important base for plant-based foods because it provides the fat, sweetness and body that consumers expect from dairy alternatives, and it can be combined with protein-rich legumes or oilseeds. Its natural sugar content supports fermentation. Yeboah et al. (2023) developed fermented tiger nut-based probiotic beverages in Ghana, using a tiger nut and millet base fermented with Lacticaseibacillus casei, and reported improved nutritional content and microbiological safety over a short shelf life at both refrigerated and ambient temperatures.

5.2 Cassava Leaves

Cassava (Manihot esculenta) is grown principally for its starchy roots, which are low in protein, but its leaves are rich in protein, often reported at around one-fifth to one-third of dry weight, and in vitamins and minerals. Cassava leaves are eaten as a vegetable in many parts of Africa, including as saka-saka in Central Africa and as a soup ingredient in parts of Nigeria. Latif and Müller (2015) reviewed their potential in human nutrition and concluded that they are a valuable and underused protein source, provided that their cyanogenic glycosides and other antinutrients are reduced by processing. Because cassava is grown on a very large scale, particularly in Nigeria, the world's largest producer, the leaves represent a substantial protein resource that is often left in the field.

5.3 Yam and Potato

Yams (Dioscorea spp.) are staple tubers in West Africa, and Nigeria accounts for the majority of global production. Their protein content is modest, typically below 10% of dry matter, but their storage protein, dioscorin, has been reported to have antioxidant and other bioactivities. Obidiegwu, Lyons and Chilaka (2020) reviewed the nutritional and therapeutic potential of the Dioscorea genus and highlighted bioactive compounds including dioscorin, diosgenin and mucilage polysaccharides.

Potato is not underutilized as a food, but its protein is a largely unexploited by-product. During potato starch manufacture, a protein-rich juice is released, which contains the storage glycoprotein patatin and a range of protease inhibitors. Waglay, Karboune and Alli (2014) examined methods for recovering potato protein isolates from this stream and characterised their properties, which include good solubility, emulsifying and foaming capacity and a well-balanced amino acid profile. Potato protein is now used commercially in some plant-based foods, and itsrecovery illustrates how processing side streams fromroot crops can be converted into high-value protein ingredients.Table 1 summarises the principal underutilized crops discussed, their typical protein content, their main

Table 1. Selected underutilized legumes, oilseeds and tubers as protein sources

Crop	Type	Typical protein (dry basis)	Principal advantages	Key constraints
Bambara groundnut	Legume	18–24%	Drought tolerance; balanced composition; indigenous to Africa	Hard-to-cook; low yields; limited improved varieties
African yam bean	Legume	20–25% (seed)	Edible seeds and tubers; soluble albumin fraction	Long cooking time; antinutrients; declining cultivation
Pigeon pea	Legume	20–22%	Perennial; drought tolerance	Protease inhibitors; polyphenols
Cowpea	Legume	20–25%	Staple in West Africa; soil improvement	Oligosaccharides; antinutrients
Winged bean	Legume	30–40% (seed)	All parts edible; soybean-like seed composition	Limited varieties and processing research
Lupin (sweet)	Legume	30–40%	High protein; low starch; acid-soil adaptation	Alkaloids; allergenicity
Mung bean	Legume	~21–31%	Emulsifying and gelling 8S globulin; used in egg substitutes	Low sulphur amino acids; trypsin inhibitors
Grass pea	Legume	25–30%	Extreme drought and flood tolerance	β-ODAP neurotoxin
Melon seed (egusi)	Oilseed	>30% (seed); higher in defatted meal	High protein and oil; established food use	Aflatoxin susceptibility
Sunflower	Oilseed	30–50% (meal)	Low antinutrients; large supply	Chlorogenic acid; discolouration
Cottonseed	Oilseed	20–25%	Large by-product supply; ultra-low gossypol varieties	Gossypol toxicity
Moringa	Leaf/oilseed	High in dried leaf	Drought-tolerant tree; micronutrient-rich	Strong flavour; colour
Tiger nut	Tuber	<10%	Fat, fibre and sweetness for dairy alternatives	Low protein; aflatoxin risk in storage
Cassava leaves	Leaf	~20–35%	Very large biomass; widely grown	Cyanogenic glycosides
Yam	Tuber	<10%	West African staple; bioactive storage protein (dioscorin)	Low protein content
Potato (juice protein)	Tuber side stream	Isolate >80%	Balanced amino acids; side-stream valorisation	Glycoalkaloids must be removed

Note: Values are indicative and vary with genotype, environment and analytical basis; compiled from Azman Halimi et al. (2019), George, Obilana and Oyeyinka (2020), Saxena, Kumar and Sultana (2010), Gonçalves et al. (2016), Tanzi et al. (2019), Lucas et al. (2015), Zhu, Sun and FitzGerald (2018), Lambein et al. (2019), Ogunbusola et al. (2022), González-Pérez and Vereijken (2007), Rathore et al. (2020), Leone et al. (2015), Sánchez-Zapata, Fernández-López and Pérez-Alvarez (2012), Latif and Müller (2015), Obidiegwu, Lyons and Chilaka (2020) and Waglay, Karboune and Alli (2014).

advantages and the key constraints that must be addressed through processing or breeding, and Figure 1 compares their reported protein ranges.

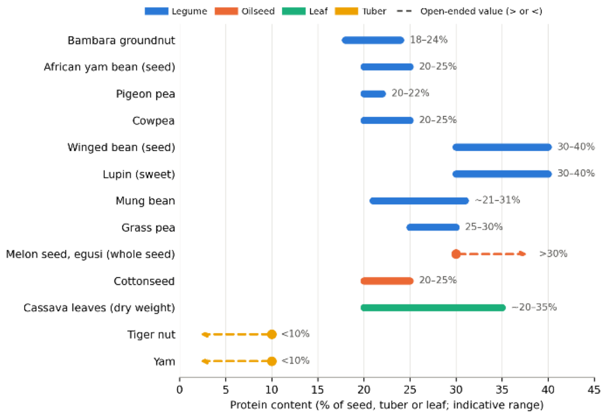

Figure 1. Indicative protein content of selected underutilized legumes, oilseeds, leaves and tubers. Bars show reported ranges; dashed arrows show values reported only as an upper or lower bound. Sunflower (meal), moringa (dried leaf) and potato (juice-protein isolate) are omitted because their values refer to processed fractions rather than whole seeds, tubers or leaves. Values vary with genotype, environment and analytical basis; sources as in Table 1.

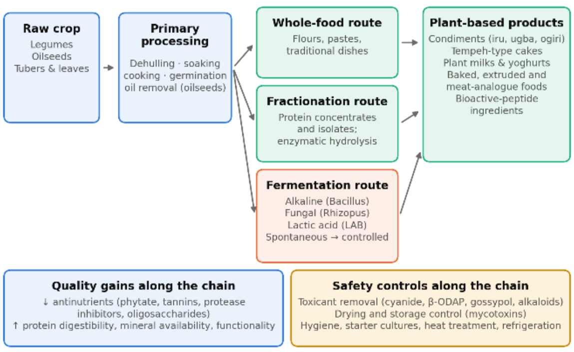

Figure 2. Processing and fermentation routes for converting underutilized legumes, oilseeds and tubers into plant-based foods, with the principal quality gains and safety controls along the chain. Compiled from the studies reviewed in Sections 6 to 9.

6. PROCESSING TECHNOLOGIES

Converting underutilized crops into safe, acceptable plant-based foods involves a chain of operations, from primary processing through whole-food, fractionation or fermentation routes to finished products. Figure 2 summarises these routes and the quality gains and safety controls associated with them; each stage is discussed in this section and in Sections 7 to 9.

6.1 Primary Processing: Dehulling, Soaking, Cooking and Germination

The first stage in converting underutilized legumes and oilseeds into foods is primary processing. Dehulling removes the seed coat, which is often rich in tannins and fibre, and improves digestibility and appearance. Soaking hydrates the seed, leaches water-soluble antinutrients and oligosaccharides, and shortens cooking time. Cooking inactivates heat-labile antinutrients such as protease inhibitors and lectins and gelatinises starch. Egounley and Aworh (2003) examined the effects of soaking, dehulling, cooking and fermentation with Rhizopus oligosporus on soybean, cowpea and groundbean (Macrotyloma geocarpum) and found that each step reduced oligosaccharides, trypsin inhibitors, phytic acid and tannins, with the combination of steps producing the largest reductions.

Germination is a particularly promising low-cost process. During germination, endogenous enzymes are activated that hydrolyse storage proteins, degrade phytate and oligosaccharides, and synthesise vitamins. Ohanenye et al. (2020) reviewed the effects of germination on legume proteins and concluded that it improves protein digestibility, amino acid availability and the generation of bioactive peptides, while reducing antinutrients. Germinated legume flours can be used directly in foods or as a substrate for further processing. For crops such as African yam bean and bambara groundnut, which suffer from hard-to-cook defects and high antinutrient content, germination offers a simple means of improving quality that is accessible to small-scale processors.

6.2 Protein Extraction and Fractionation

Protein concentrates and isolates can be prepared from underutilized legumes and oilseeds by the same wet extraction methods used for soy and pea: alkaline or salt solubilisation, removal of insoluble components, and recovery by isoelectric precipitation or ultrafiltration. Kumar et al. (2021) reviewed the mechanisms of plant protein extraction and noted that emerging methods such as ultrasound-, microwave- and enzyme-assisted extraction can improve yields and preserve functionality while reducing the use of chemicals and energy. The choice of method matters:

studies on bambara groundnut and melon seed show that extraction conditions strongly influence the protein content, yield and functional properties of the resulting ingredients (Arise, Amonsou and Ijabadeniyi, 2015; Ogunbusola et al., 2022).

Dry fractionation, which separates protein-rich and starch-rich fractions by milling and air classification, is an attractive option for starch-rich legumes such as bambara groundnut, cowpea and African yam bean, because it avoids water use and preserves native protein functionality. However, its application to underutilized legumes has been little studied, and research is needed to determine how their seed structure and composition affect separation efficiency.

For oilseeds, oil removal is the key step. Cold pressing, aqueous extraction and enzyme-assisted aqueous extraction can recover oil while leaving protein in a less denatured state than solvent extraction, which is important for food use. For sunflower, removal of phenolic compounds before or during protein extraction is essential to prevent discolouration (González-Pérez and Vereijken, 2007). For cottonseed, the use of ultra-low gossypol varieties removes the need for extensive detoxification (Rathore et al., 2020).

6.3 Enzymatic Hydrolysis and Bioactive Peptides

Enzymatic hydrolysis converts proteins into peptides and amino acids, improving solubility and, in some cases, generating peptides with biological activity. Udenigwe and Aluko (2012) reviewed the production, processing and health potential of food protein-derived bioactive peptides, and Aluko (2015) reviewed peptides with antihypertensive activity derived from food proteins, including legume proteins. Bioactive peptides with antioxidant and antihypertensive activities have been obtained from bambara groundnut (Arise et al., 2016) and mung bean (Zhu, Sun and FitzGerald, 2018), among others. These findings suggest that underutilized crops could be sources of functional food ingredients as well as bulk protein, although the evidence of physiological effects in humans remains limited.

6.4 Product Formation

Underutilized crops can be incorporated into a wide range of plant-based foods. Legume and oilseed flours can be used in baked goods, pasta, snacks and extruded products to raise protein content and complement cereal proteins. Protein concentrates and isolates can be used in meat analogues and in beverages. Tiger nut, melon seed, bambara groundnut and other crops can be processed into plant-based milks, which Sethi, Tyagi and Anurag (2016) described as an emerging segment of functional beverages. These beverages can in turn be fermented into yoghurt-like products, combining the fat and sweetness of tiger nut or coconut with the protein of legumes. Traditional products such as moin-moin, akara, kunnu and bean-based porridges also offer models for convenient, protein-rich foods that could be adapted for wider markets.

6.5 Blending and Protein Complementation in Product Design

Because no single underutilized crop supplies a complete package of protein quality, functionality and sensory appeal, product design usually depends on blending. The principle of complementation, in which legumes supply lysine and cereals or oilseeds supply the sulphur amino acids, is well established in traditional diets and can be applied deliberately in formulated products (FAO, 2013; Mariotti and Gardner, 2019). A beverage or yoghurt base might combine tiger nut, which provides fat, fibre and natural sweetness, with bambara groundnut or cowpea protein, which raises protein content and lysine, and a small proportion of melon seed or sunflower protein, which contributes sulphur amino acids and emulsifying capacity. Similarly, extruded snacks and breakfast products can combine sorghum, millet or maize with legume flours to improve protein quality without sacrificing expansion or crispness.

Blending also improves functionality. Different protein fractions and sources vary in solubility, gelation, emulsification and foaming, as the studies of African yam bean fractions (Ajibola et al., 2016) and melon seed concentrates (Ogunbusola et al., 2022) illustrate. Combining proteins with complementary properties can produce more robust ingredients than any one source, and it spreads supply risk across several crops. Blends must, however, be assessed as a whole for allergenicity, antinutrient content and microbial load, because each component brings its own hazards.

7. FERMENTATION

Fermentation is one of the oldest and most effective methods of improving the nutritional quality, flavour, digestibility and safety of legumes and oilseeds. It is especially important for underutilized crops because many of them are already consumed mainly in fermented forms, and because fermentation can overcome some of their principal limitations.

7.1 Indigenous Alkaline Fermentations in West Africa

Alkaline fermentation, dominated by Bacillus species, is characteristic of the protein-rich condiments of West Africa. These products are made by boiling, dehulling and fermenting seeds for several days, during which Bacillus subtilis and related species hydrolyse proteins to peptides and amino acids, releasing ammonia and raising the pH. The resulting products are strongly flavoured and are used in small quantities to season soups and stews, where they contribute protein, umami flavour and, in some cases, vitamins.

The best known is iru or dawadawa, made from the seeds of the African locust bean (Parkia biglobosa), known as soumbala in Burkina Faso. Ouoba et al. (2004) characterised Bacillus subtilis and Bacillus pumilus strains isolated from soumbala fermentation and assessed them as potential starter cultures, demonstrating that controlled fermentation with selected strains is feasible. Ugba, made from the seeds of the African oil bean tree (Pentaclethra macrophylla), is a traditional food in south-eastern Nigeria. Olasupo, Okorie and Oguntoyinbo (2016) reviewed the biotechnology of ugba and found that its fermentation is driven mainly by Bacillus subtilis, that fermentation reduces antinutrients and improves digestibility, and that controlled starter cultures could improve its safety and consistency. Ogiri, made from melon or castor seeds, and okpehe, made from Prosopis africana seeds, are further examples (Olasupo and Okorie, 2019).

These fermentations offer a model for developing new products. Bacillus-fermented legumes are protein-rich, flavourful and shelf-stable once dried, and the Bacillus strains involved produce proteases and other enzymes that could be harnessed in controlled processes. However, traditional production is usually spontaneous and carried out under variable hygienic conditions, which leads to inconsistent quality and safety risks that are discussed in Section 9.

The nutritional contribution of these condiments is often underestimated because they are consumed in small quantities. Yet for many households in West Africa they are a regular source of protein, essential amino acids and B vitamins, and their intense savoury flavour allows smaller quantities of meat or fish to be used in meals. In this respect, alkaline fermented condiments perform a role similar to that of soy sauce, miso and natto in East Asian diets, and they could serve as clean-label, plant-derived flavour ingredients in modern plant-based foods, where umami flavour is often supplied by yeast extracts or added glutamate. Realising that opportunity will require consistent production under controlled conditions, characterisation of their flavour compounds, and demonstration of their safety, including the absence of toxigenic Bacillus strains and excessive biogenic amines (Anyogu et al., 2021; Olasupo and Okorie, 2019).

7.2 Fungal Fermentation: Tempeh and Beyond

Tempeh, the traditional Indonesian product made by fermenting cooked soybeans with Rhizopus species, is a model for fungal fermentation of legumes. The fungal mycelium binds the beans into a firm cake, and fungal enzymes hydrolyse proteins, lipids and antinutrients, improving digestibility and flavour. Nout and Kiers (2005) reviewed tempeh fermentation, innovation and functionality and noted that tempeh-like products can be made from many legumes and cereals other than soybean. Egounlety and Aworh (2003) showed that Rhizopus oligosporus fermentation of cowpea and groundbean, in combination with soaking, dehulling and cooking, substantially reduced antinutrients. Tempeh-type fermentation therefore offers a route to protein-rich, minimally processed whole foods from underutilized legumes such as bambara groundnut, African yam bean and pigeon pea.

7.3 Lactic Acid Fermentation

Lactic acid fermentation is widely used in Africa to produce cereal gruels and beverages, such as ogi and kunnu, and is increasingly used to produce plant-based dairy alternatives. Lactic acid bacteria lower the pH, suppress pathogens and spoilage organisms, reduce antinutrients such as phytate, and produce flavour compounds and, in some cases, exopolysaccharides that improve texture. Emkani, Oliete and Saurel (2022) reviewed the effects of lactic fermentation on legume proteins and found that it can improve their digestibility and modify their functional properties. Adebo et al. (2022) reviewed the impact of fermentation on the nutritional constituents and nutrient bioavailability of cereals and legumes and concluded that fermentation generally reduces antinutrients, increases the availability of minerals and some vitamins, and improves protein digestibility, although effects vary with substrate and microorganism.

Enujiugha and Badejo (2017) reviewed the probiotic potential of cereal-based beverages and argued that traditional African fermented beverages could be developed as vehicles for probiotic cultures. The same logic applies to legume- and tuber-based beverages. The fermented tiger nut and millet beverage developed by Yeboah et al. (2023) illustrates how traditional ingredients can be combined with defined probiotic cultures. Adebo et al. (2017) reviewed fermented pulse-based foods in developing countries and emphasised their potential as functional foods and ingredients.

7.4 From Spontaneous to Controlled Fermentation

The transition from spontaneous to controlled fermentation is central to the modernisation of fermented foods from underutilized crops. Spontaneous fermentation relies on the microorganisms present in the raw materials, equipment and environment, which leads to variable quality and allows pathogens and toxin producers to grow in some batches. Controlled fermentation uses defined starter cultures, selected for their performance and safety, and controlled conditions of time, temperature and hygiene.

Several steps are needed to make this transition. First, the microorganisms responsible for desirable fermentation must be isolated and characterised, as Ouoba et al. (2004) did for soumbala and as Olasupo, Okorie and Oguntoyinbo (2016) described for ugba. Second, strains must be selected for rapid fermentation, desirable flavour, antinutrient degradation and the absence of virulence factors, toxin genes and transferable antibiotic resistance. Third, fermentation conditions must be optimised and validated. Fourth, starter cultures must be produced and distributed in forms that small-scale processors can use. Marco et al. (2021) noted that the health benefits of fermented foods depend on the microorganisms and processes involved, which further supports the use of well-characterised cultures.

Controlled fermentation also offers a food safety benefit. A starter culture that rapidly lowers the pH and produces antimicrobial compounds can suppress pathogens that would otherwise grow during spontaneous fermentation. For lactic fermentations of legume and tuber bases, the time taken to reach a safe pH is a key parameter; for alkaline Bacillus fermentations, where pH rises rather than falls, safety depends instead on hygiene, raw material quality, competitive exclusion by the starter culture and post-fermentation drying.

7.5 Fermented Plant-Based Yoghurts from Underutilized Crops

Plant-based yoghurt is one of the most promising product categories for underutilized crops because it combines several of the advantages discussed above. Tiger nut, coconut and legume bases can be blended to supply fat, fermentable sugar and protein; lactic fermentation lowers the pH, generates a clean acid taste, reduces off-flavours and antinutrients and suppresses pathogens; and the product can carry live cultures with potential probiotic function (Marco et al., 2021; Enujiugha and Badejo, 2017). Dates and other naturally sweet fruits can provide fermentable sugars without the addition of refined sugar, and hydrocolloid-free formulations can rely on the acid-induced gelation of legume globulins (Emkani, Oliete and Saurel, 2022).

The technical challenges are also clear. Plant bases differ in buffering capacity, sugar content and protein structure, so fermentation kinetics, final texture and syneresis vary with formulation. Starter cultures developed for dairy milk may acidify slowly in plant bases, prolonging the period in which pathogens and spore-formers could grow. Statistical design of experiments, such as response surface methodology, is well suited to optimising formulation variables, including the proportions of base ingredients, the inoculum level and the fermentation time, against multiple responses such as pH, titratable acidity, viscosity, viable count and sensory acceptability. Validation of the safety of the optimised formulation, including challenge testing against relevant pathogens, is a necessary final step before commercial production.

Such products have particular relevance for consumers who avoid dairy because of lactose intolerance, milk allergy, cultural or religious practice or personal preference, and for regions where dairy is expensive or cold chains are unreliable. They also create demand for underutilized crops and value-added processing opportunities close to where those crops are grown. The fermented tiger nut and millet beverage developed by Yeboah et al. (2023) and the wider literature on African fermented beverages (Enujiugha and Badejo, 2017; Adebo et al., 2017) suggest that the knowledge base for such products is well developed, although standardised formulations and safety data remain limited.

8. NUTRITIONAL QUALITY

8.1 Amino Acid Composition and Digestibility

The nutritional value of a protein depends on its content of indispensable amino acids and on its digestibility. The FAO (2013) recommended the Digestible Indispensable Amino Acid Score (DIAAS) as the preferred measure of protein quality. Like most legumes, underutilized legumes are generally rich in lysine but limited in the sulphur amino acids methionine and cysteine, whereas cereals are limited in lysine. Combining legumes with cereals, as in many traditional African and Asian meals, therefore improvesprotein quality. Oilseeds such as melon seed and sunflower tend to be richer in sulphur amino acids than legumes and can serve as complements to them. Tubers such as tiger nut and yam contribute modest amounts of protein, but potato protein has a well-balanced amino acid profile (Waglay, Karboune and Alli, 2014).

Table 2 summarises the principal types of fermentation applied to underutilized crops and their main effects.

Protein digestibility in underutilized crops is often reduced by antinutritional factors and by the structure of their proteins and cell walls. Gilani, Xiao and Cockell (2012) showed that protease inhibitors, tannins, phytates and other antinutrients reduce protein digestibility and amino acid bioavailability, sometimes substantially. The processing methods discussed in Section 6, including dehulling, soaking, cooking, germination and fermentation, improve digestibility by reducing these factors and by partially hydrolysing proteins.

Table 2. Fermentation of underutilized legumes, oilseeds and tubers

Fermentation type	Principal microorganisms	Examples	Main effects
Alkaline (Bacillus)	Bacillus subtilis, B. pumilus, B. [illegible]	Iru/dawadawa (African locust bean); ugba (African oil bean); [illegible]	Protein hydrolysis; umami flavour; antinutrient reduction; rise in pH
Fungal (solid state)	Rhizopus spp.	Tempeh and tempeh-type products from soybean, cowpea and groundbean	Mycelial binding; improved digestibility; antinutrient reduction
Lactic acid	Lactobacillaceae, Lactococcus, Streptococcus, Leuconostoc	Plant-based yoghurts and beverages from tiger nut, legumes and cereals	Acidification; pathogen inhibition; flavour; phytate reduction; potential probiotic function
Mixed/spontaneous	Variable yeasts, LAB and Bacillus	Many traditional products	Variable quality and safety; basis for starter culture selection

Note: Compiled from Montagnac, Davis and Tanumihardjo (2009), Lambein et al. (2019), Buta et al. (2020), Rathore et al. (2020), Jappe and Vieths (2010), Bankole, Ogunsanwo and Mabekoje (2004), Adedeji et al. (2017), Anyogu et al. (2021), Okorie et al. (2017) and Bartula et al. (2023).

8.2 Antinutritional Factors

Antinutritional factors in underutilized crops include protease inhibitors, lectins, phytates, tannins, oxalates, saponins and flatulence-causing oligosaccharides. Samtiya, Aluko and Dhewa (2020) reviewed these factors and the strategies available to reduce them, including soaking, germination, cooking, fermentation and enzymatic treatment. It is important to recognise that some of these compounds, such as phytates, tannins and saponins, also have potential health benefits at moderate intakes, including antioxidant and cholesterol-lowering effects, so the goal of processing is to reduce them to levels at which they do not impair nutrition rather than to eliminate them.

8.3 Micronutrients and Bioactive Compounds

Many underutilized crops are rich in micronutrients. Bambara groundnut contains significant amounts of iron and potassium (Azman Halimi et al., 2019), cassava and moringa leaves are rich in vitamins A and C, calcium and iron (Latif and Müller, 2015; Leone et al., 2015), and legumes generally supply folate and B vitamins. However, the bioavailability of iron and zinc from plant foods is limited by phytate, which fermentation and germination reduce. Underutilized crops are also sources of bioactive compounds, including phenolic antioxidants, bioactive peptides and dietary fibre, which may contribute to the prevention of chronic diseases (Jayathilake et al., 2018; Obidiegwu, Lyons and Chilaka, 2020). These properties strengthen the case for their use in plant-based foods designed for health as well as sustainability.

8.4 Nutritional Quality of Processed Products

Assessments of protein quality are often made on raw seeds or on isolated proteins, but consumers eat processed foods. The nutritional quality of a finished product depends on the whole formulation, the processing history and interactions between ingredients. Heat treatment improves digestibility by inactivating protease inhibitors, but severe heating, particularly under alkaline conditions or in the presence of reducing sugars, can reduce the availability of lysine through Maillard reactions (Gilani, Xiao and Cockell, 2012). Fermentation generally improves protein digestibility and mineral availability, but the extent of improvement depends on the microorganism and conditions (Adebo et al., 2022). For this reason, product developers should measure protein quality in finished products, using methods consistent with the DIAAS framework where possible, rather than relying on values for raw ingredients.

Micronutrient fortification is a further consideration. Plant-based alternatives to dairy and meat may not provide vitamin B12, vitamin D, calcium or iodine in amounts comparable to the animal products they replace, and fortification may be needed when these products are intended to substitute for animal foods in the diet. Underutilized crops that are rich in particular micronutrients, such as moringa and cassava leaves, can contribute to fortification strategies, although their bioavailability must be considered.

9. FOOD SAFETY

The promotion of underutilized crops as protein sources must be accompanied by attention to food safety. These crops can contain natural toxicants, allergens and chemical contaminants, and the traditional processes used to prepare them can allow microbial hazards to develop if they are not properly controlled.

9.1 Natural Toxicants

Several underutilized crops contain natural toxicants that must be reduced by processing or breeding. Cassava roots and leaves contain cyanogenic glycosides, principally linamarin, which release hydrogen cyanide when the plant tissue is damaged. Montagnac, Davis and Tanumihardjo (2009) reviewed processing techniques for reducing the toxicity of cassava and found that soaking, fermentation, drying and cooking are effective when properly applied, whereas inadequate processing can lead to acute poisoning and to chronic conditions such as konzo. Cassava leaves require similar treatment before consumption (Latif and Müller, 2015).

Grass pea contains β-ODAP, which causes neurolathyrism when grass pea is consumed as the principal food for extended periods (Lambein et al., 2019). Buta et al. (2020) showed that fermentation supplemented with phytase reduced β-ODAP in grass pea seeds by 13–62% and phytate by 7–91%, depending on conditions, demonstrating that processing can substantially reduce this hazard. Cottonseed contains gossypol, which must be removed or avoided through ultra-low gossypol varieties (Rathore et al., 2020). Lupin contains quinolizidine alkaloids, which are controlled in sweet varieties and by debittering processes. Potato protein must be purified to remove glycoalkaloids such as solanine.

9.2 Allergens

Allergenicity is a concern for all protein-rich foods. Lupin is a recognised food allergen in the European Union and can cross-react with peanut (Jappe and Vieths, 2010). Other legumes, including cowpea, pigeon pea and bambara groundnut, share structurally related storage proteins with peanut, soybean and pea, and cross-reactivity is possible, although data on the allergenicity of most underutilized crops are sparse. As these crops are introduced into new markets and processed into concentrated protein ingredients, systematic assessment of their allergenic potential, including cross-reactivity with established allergens, will be needed.

9.3 Mycotoxins

Mycotoxins are a major food safety concern for underutilized crops, many of which are grown, dried and stored under warm, humid conditions that favour fungal growth. Eskola et al. (2020) estimated that 60–80% of food crops globally contain detectable mycotoxins and that around a quarter exceed regulatory limits. In Nigeria, Bankole, Ogunsanwo and Mabekoje (2004) found aflatoxin B1 in melon seeds sold in markets, and Adedeji et al. (2017) detected multiple mycotoxins in locust bean, melon seed and their fermented condiments. Tiger nuts and groundnuts are also vulnerable to aflatoxin contamination during storage. Good agricultural practices, rapid and thorough drying, proper storage and testing are essential for developing these crops as safe, tradable protein sources.

9.4 Microbial Hazards in Fermented Foods

Traditional fermented foods are generally regarded as safe, and fermentation itself is a food safety tool. However,

Table 3. Principal food safety hazards and controls for underutilized protein crops

Hazard	Crops most affected	Principal controls
Cyanogenic glycosides	Cassava roots and leaves	Grating, soaking, fermentation, drying, cooking
β-ODAP	Grass pea	Low-ODAP varieties; fermentation; balanced diets
Gossypol	Cottonseed	Ultra-low gossypol varieties; detoxification
Alkaloids and glycoalkaloids	Lupin; potato	Sweet lupin varieties; debittering; purification
Aflatoxins and other mycotoxins	Melon seed, groundnut, tiger nut, locust bean, cereals	Good agricultural practice; rapid drying; storage control; testing
Bacillus cereus and other pathogens	Alkaline fermented condiments; plant-based milks	Hygiene; starter cultures; heat treatment; drying; refrigeration
Allergens	Lupin; legumes cross-reactive with peanut and soy	Allergenicity assessment; labelling

Note: Compiled from Montagnac, Davis and Tanumihardjo (2009), Lambein et al. (2019), Buta et al. (2020), Rathore et al. (2020), Jappe and Vieths (2010), Bankole, Ogunsanwo and Mabekoje (2004), Adedeji et al. (2017), Anyogu et al. (2021), Okorie et al. (2017) and Bartula et al. (2023).

spontaneous fermentations conducted under poor hygienic conditions can allow pathogens to survive or grow. Anyogu et al. (2021) reviewed the microorganisms and food safety risks associated with indigenous fermented foods from Africa and identified hazards including Bacillus cereus, Staphylococcus aureus, pathogenic Escherichia coli, Salmonella, mycotoxins and biogenic amines. Alkaline fermentations present a particular challenge because the rise in pH does not inhibit pathogens as lactic fermentation does, and some Bacillus species, notably B. cereus, can produce toxins.

Direct evidence supports these concerns. Okorie et al. (2017) examined ugba samples from Nigeria and detected 14 species of potentially pathogenic bacteria, 67% of which were identified only by a culture-independent method, suggesting that conventional culture methods may underestimate the hazards in these products. Adedeji et al. (2017) found potentially hazardous bacteria and mycotoxins in fermented locust bean and melon seed products and attributed contamination to poor hygiene during production and handling. These findings do not mean that traditional fermented foods are unsafe, but they show that improved hygiene, controlled fermentation with selected starter cultures, and appropriate post-fermentation processing are needed to ensure their safety, particularly if they are to be produced at larger scale or traded internationally.

Plant-based beverages and dairy alternatives made from underutilized crops also present microbial risks. Bartula et al. (2023) found that pathogens including Listeria and Salmonella and spore-forming Bacillus and Paenibacillus species could grow in commercial plant-based milk alternatives, in some cases faster than in bovine milk. Because plant bases such as tiger nut milk are nutrient-rich and near neutral in pH, they require validated heat treatment, hygienic processing and refrigeration, or rapid acidification by a starter culture, to prevent pathogen growth.

9.5 Food Safety Management for Small and Medium-Scale Processors

Most underutilized crops are processed by small and medium-scale enterprises, often household or community businesses, for which formal food safety management systems can seem out of reach. Yet the principles of hazard analysis and preventive control are scalable. A small processor making a fermented legume condiment or a tiger nut beverage can identify the principal hazards (for example, mycotoxins in raw materials, pathogens in water and on equipment, and the risk of slow fermentation), establish simple controls (raw material sorting and drying, potable water, cleaning schedules, starter cultures and pH or time checks) and keep basic records. Anyogu et al. (2021) emphasised that training in hygiene and the adoption of controlled fermentation are the most effective interventions for improving the safety of African fermented foods.

As production scales up, and particularly where products are exported, more formal systems based on Hazard Analysis and Critical Control Point principles are required, supported by laboratory testing and validation studies. For fermented products, critical limits for the rate of acidification or for final pH and water activity, established through challenge testing, provide a scientific basis for safety assurance. The development of shared infrastructure, such as regional laboratories, starter culture banks and pilot processing facilities, can help small processors meet these requirements.

10. CHALLENGES AND FUTURE DIRECTIONS

The evidence reviewed here indicates that underutilized legumes, oilseeds and tubers have substantial potential as sustainable protein sources, but several challenges must be addressed before that potential can be realised.

Breeding and agronomy. Most underutilized crops have received little investment in breeding, and their yields are often low and variable. Genomic tools and participatory breeding programmes, such as those described for bambara groundnut (Mayes et al., 2019) and winged bean (Tanzi et al., 2019), can improve yield, reduce cooking time and antinutrient content, and adapt crops to changing climates. Seed systems that make improved varieties available to smallholder farmers are equally important.

Processing infrastructure. The lack of processing infrastructure, from dehulling and milling to protein extraction and fermentation, is a major barrier. Investment in small- and medium-scale processing near production areas can add value, reduce post-harvest losses and create employment. Low-input technologies such as germination, dry fractionation and controlled fermentation are particularly suitable.

Standardisation of fermented foods. The development of starter cultures for indigenous fermentations, validated for safety and performance, would improve the quality and safety of traditional products and enable their production at larger scale. This requires collaboration between microbiologists, food technologists and traditional producers, and systems for producing and distributing cultures.

Food safety research and assurance. More data are needed on the prevalence of pathogens, mycotoxins and other hazards in underutilized crops and their products, on the effectiveness of processing in controlling them, and on the allergenicity of their proteins. Food safety management systems appropriate to small-scale processors, based on hazard analysis principles, should be developed and supported.

Product development and consumer acceptance. Underutilized crops must be converted into foods that consumers find convenient, affordable and appealing. Traditional products offer a starting point, and blends with familiar ingredients can ease adoption. In international markets, underutilized crops may benefit from the interest in novel, sustainable and "ancient" foods, but they must meet the same standards of quality and safety as established ingredients.

Market linkages. Global demand for plant-based foods creates an opportunity for underutilized crops to reach new markets, but most of the value in plant-based food chains is currently captured in ingredient processing and branded products rather than in primary production. Developing processing capacity in producing regions, building quality assurance systems that meet export requirements, and communicating the sustainability and cultural heritage of these crops could help producers and processors capture more of that value. Diaspora communities in North America and Europe, who are familiar with foods such as egusi, iru, kunnu and moin-moin, represent an established entry market from which wider consumer adoption could grow.

Policy and regulation. Recognition of underutilized crops in agricultural research priorities, nutrition programmes and food regulations would support their development. Li and Siddique (2020) argued that neglected and underutilized species can contribute to the goal of Zero Hunger if they are integrated into policy and investment. Regulatory frameworks for novel foods in export markets should recognise the history of safe use of traditional crops, while requiring appropriate safety assessment for new ingredients and processes.

11. CONCLUSION

Underutilized legumes, oilseeds and tubers offer a diverse and largely untapped resource for sustainable protein supply. Crops such as bambara groundnut, African yam bean, pigeon pea, winged bean and grass pea are nutritious and climate-resilient; oilseeds such as melon seed, sunflower and cottonseed contain substantial protein that is currently underused; and tubers and roots such as tiger nut, cassava and potato can contribute protein, fat and functional properties to plant-based foods. Processing technologies, including dehulling, soaking, germination, protein extraction and enzymatic hydrolysis, can improve their nutritional and functional properties, and fermentation, both traditional and controlled, can reduce antinutrients, improve digestibility, generate flavour and enhance safety.

Realising this potential requires attention to food safety. Natural toxicants, allergens, mycotoxins and microbial pathogens are real hazards, but they can be controlled through breeding, good agricultural practices, appropriate processing, controlled fermentation with selected starter cultures and hygienic manufacturing. With investment in research, processing infrastructure and supportive policy, underutilized crops can diversify the global protein supply, improve nutrition and livelihoods in the regions where they are grown, and provide the basis for a new generation of safe, nutritious and sustainable plant-based foods..

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