Underutilized Plants as Sources of Functional Food Ingredients: Evidence from Bioactive Discovery to Food Application and Commercialization

Abstract

Neglected and underutilized species (NUS) have the potential to increase food-system diversity and provide valuable nutrients and bioactive compounds, but there is varying evidence for their development as functional food ingredients along the pathway from composition to commercialization. This narrative review examines compound characterization, evidence for health-relevant function, bioaccessibility and bioavailability, food formulation, market translation, and regulatory and ethical constraints. Selected cereals, legumes, fruits and leafy vegetables are well described for their content of phenolics, flavonoids, carotenoids, fiber, minerals and other classes of compounds. Evidence that these compounds work in people, at realistic doses, in real foods, is much weaker. Chemical antioxidant assays are poor predictors of function, and what reaches the body is strongly shaped by processing and food-matrix effects. Barriers that keep recurring include sensory acceptance, supply consistency, cost, safety, and regulation. Baobab represents a documented regulatory pathway, while quinoa, chia, and sea buckthorn are market comparators. Priorities for progress include standardized reporting, small human studies with clear biomarkers, and shared datasets.

Keywords: *underutilized crops; neglected and underutilized species; functional food ingredients; bioactive compounds; bioaccessibility; bioavailability; value chain; novel foods*

Introduction

Thousands of plant species are edible, yet a very small number supply most of what people eat. Rice, maize, and wheat alone account for more than half of the calories consumed (Hunter et al., 2019), and national food supplies have grown more alike over the past five decades (Khoury et al., 2014). There was good reason for such concentration: these crops are high-yielding, store well, and are amenable to mechanized farming and world trade. It has its costs too. The first is nutritional. Diets based largely on refined cereals are often deficient in micronutrients, protein quality, and fiber. It has been estimated that globally around 56% of preschool-aged children and 69% of non-pregnant women of reproductive age were deficient in at least one of iron, zinc,

vitamin A, or folate (Stevens et al., 2022). The second is climate risk, since a system that depends on a few crops is exposed when heat, drought, or a new pest hits them. Many neglected species are adapted to poor soils, low rainfall, or short growing seasons, and are still cultivated by smallholders where major crops struggle (Dawson et al., 2019). Well-known examples are finger millet, fonio, bambara groundnut, and grass pea (Mayes et al., 2019; Lambein et al., 2019). The third is the loss of biodiversity in fields and in people's knowledge of local plants (Kahane et al., 2013). These arguments have put NUS on the agenda of FAO, CGIAR centers and national programs (Padulosi et al., 2013). The pitch is that such plants could boost nutrition, fortify farming systems and provide rural communities with a new income. To work, it needs evidence that links the plant in the field to a product in the shop, and a benefit in the body. The review considers how much evidence there is.

The term "functional food" has no one legal definition. A food is considered functional within the European tradition when it has been proven to positively affect one or more specific body functions, other than the provision of nutrition, through improving health or decreasing the likelihood of disease, and when it is consumed as part of a regular diet (Diplock et al., 1999). A functional food ingredient is an ingredient added to or isolated from a food to give that effect. Here the term covers whole flours, fiber fractions, protein concentrates, extracts, oils and purified compounds intended for ordinary foods and drinks. This is not the same as a nutraceutical or dietary supplement, which is marketed as a pill, capsule, or concentrated liquid and is governed in many nations as a medicine or supplement. The distinction is significant: a concentrated millet polyphenol pill is subject to separate regulations and a different consumer, while finger millet flour used in bread is subject to food laws, taste standards, and a price per kilogram.

Underutilized plant papers typically adhere to a single format. The abstract concludes that the plant is a promising source of natural antioxidants after a portion of the plant is dried, crushed, and extracted, total phenolic content is determined, and antioxidant activity is evaluated using one or two chemical assays (Huang et al., 2005). Although too thin to support a functional ingredient, this is a helpful initial screen. The compounds might not be able to withstand cooking, might not be released or absorbed during digestion, and might need a dosage that is beyond the reach of regular eating. Taste, availability, and the absence of human data could all prevent the ingredient from being used later on. Few reviews follow a species to commercialization; the majority focus on

chemistry and bioactivity. This review is organized around these stages rather than individual species, so the bottleneck at each step is easy to see (Figure 1). It asks five questions:

1. What species and classes of compounds have been investigated, and how well-characterized are they?
2. What evidence is there for health-relevant function, at doses reachable through food?
3. What is known about bioavailability and bioaccessibility, and how are they altered by processing?
4. In actual food products, which formulation and processing techniques have proven effective?
5. What factors have determined whether a species or ingredient made it to market, and what safety, ethical, and legal requirements are in place?

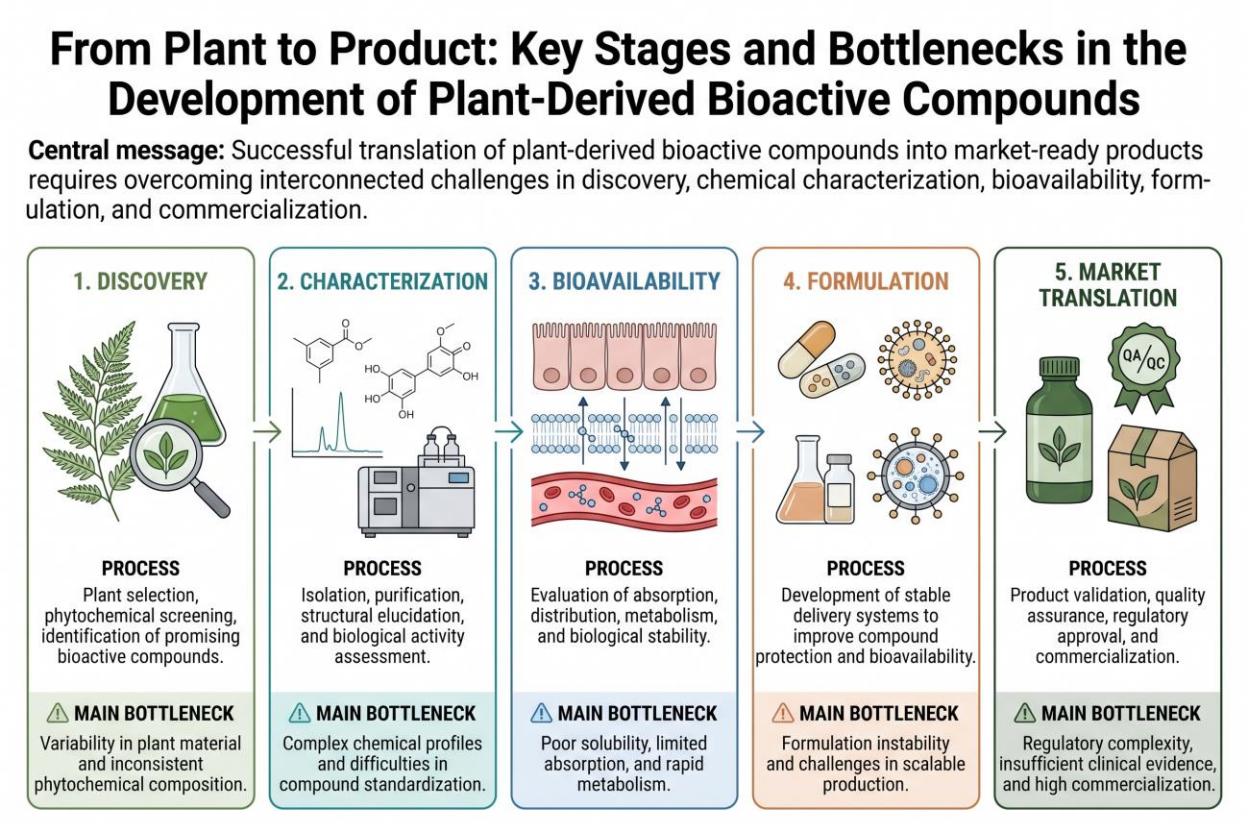


Figure 1. There are five steps involved in turning bioactive chemicals generated from plants into products, and each step has a major bottleneck.

Species and Bioactive Compounds

Cereals and pseudocereals. Fonio (*Digitaria exilis* and *D. iburua*) is a West African grain that cooks quickly and is notable for the sulfur-containing amino acids methionine and cysteine, which are low in many cereals. Finger millet (*Eleusine coracana*) is high in calcium and rich in phenolic compounds, mostly in the seed coat (Devi et al., 2014; Chandrasekara & Shahidi, 2010). Teff (*Eragrostis tef*), from Ethiopia and Eritrea, is gluten-free and a good source of minerals and fibre (Gebremariam et al., 2014). Amaranth (Amaranthus spp.) leaves are consumed as a vegetable in many areas, while the grain is high in lysine and comparatively rich in squalene and phenolics, including rutin (Caselato-Sousa & Amaya-Farfán, 2012).

Legumes. The drought-tolerant African legume known as bambara groundnut (Vigna subterranea) has a well-balanced protein, carbohydrate, and fat content (Mayes et al., 2019). Although the causation of lathyrism, a type of paralysis, is more complicated than neurotoxic β-ODAP alone, the extraordinarily resilient grass pea (Lathyrus sativus) has been connected to significant reliance on it during famines (Lambein et al., 2019). In Africa and Asia, Lablab (Lablab purpureus) is consumed as pods, beans, and leaves. Its raw beans contain cyanogenic chemicals and trypsin inhibitors that must be eliminated during processing.

Fruits. The dry fruit pulp of baobab (Adansonia digitata), which is rich in vitamin C, pectin, and fiber, is now approved for use in the EU and the US for certain purposes (Kamatou et al., 2011; European Commission, 2008; US Food and Drug Administration, 2009). Cactus pears (Opuntia ficus-indica) have betalain pigments, fiber, and mucilage (Feugang et al., 2006), whereas jujube (Ziziphus jujuba) is a long-cultivated Asian fruit with polysaccharides, triterpenic acids, and phenolics (Gao et al., 2013). Vitamin C, carotenoids, flavonoids, and unique oils, such as those containing palmitoleic acid, are abundant in sea buckthorn (Hippophae rhamnoides) berries (Ciesarová et al., 2020).

Leafy vegetables. African nightshade (Solanum scabrum), cowpea leaves, amaranth leaves, spider plant (Cleome gynandra), and other native green vegetables are commonly consumed in Africa and are rich in calcium, iron, folate, and carotenoids. Compared to grains and fruits, their evidence base is far less, with only a few publications containing composition data and minimal functional or bioavailability research.

Every compound class below has been reported in several plant groups. **Phenolic compounds** are the most common class in the literature. They include phenolic acids such as ferulic, caffeic, and

p-coumaric acids, which are common in cereal bran and often bound to cell wall polymers, and flavonoids such as rutin, quercetin, and catechins. Millets carry large amounts of bound phenolics, so the fraction extracted depends heavily on whether the method includes hydrolysis (Chandrasekara & Shahidi, 2010). Tannins occur in some legumes and millets and are both bioactive and antinutritional. **Carotenoids** colour many fruits and leafy vegetables, and being fat-soluble, they depend on dietary fat for absorption (Schweiggert & Carle, 2017). **Saponins** occur in quinoa, many legumes and some leafy vegetables, with reported cholesterol-lowering and immune effects, but they are bitter and can disrupt cell membranes at high doses (Güçlü-Üstündağ & Mazza, 2007). **Dietary fibre and resistant starch** are well-supported contributors to health through effects on gut transit, glucose response, and the microbiota, and the type matters (soluble versus insoluble, fermentable versus not) (Slavin, 2013). The oldest and best-understood contributions are vitamins and minerals, such as calcium in finger millet, folate and carotenoids in leafy vegetables, and vitamin C in baobab and sea buckthorn. However, mineral content must be read in conjunction with phytate and polyphenol content, which decrease absorption (Figure 2).

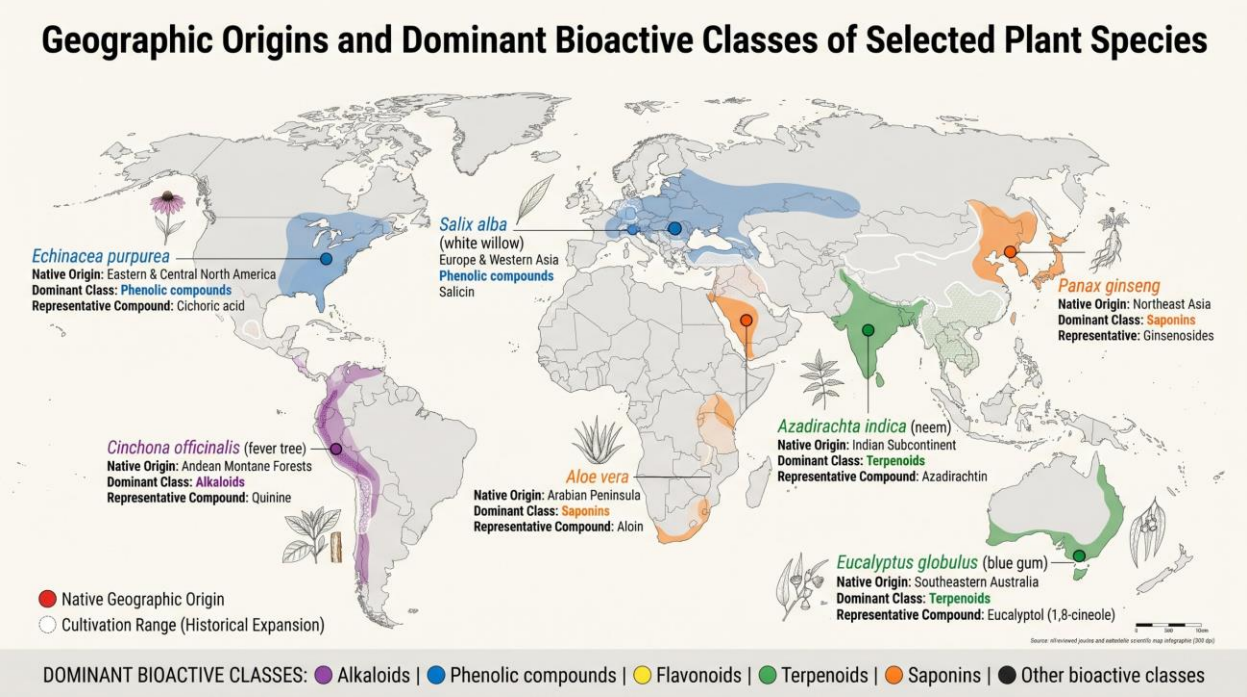


Figure 2. Native origins and dominant bioactive classes of the selected plant species.

Sourcing, Extraction and Analysis

A large share of the variation in reported results comes from the plant material rather than the chemistry. The same species can differ several-fold in phenolic content between varieties, growing locations, seasons, and harvest stages, and drying temperature, storage time, and light exposure change carotenoid and vitamin levels. Yet many papers do not name a cultivar, state the harvest date, or deposit a voucher specimen, and misidentification is a real risk, especially for wild-collected material and local names that refer to more than one species. A voucher specimen in an accredited herbarium (Culley, 2013), DNA barcoding in cases of doubtful identity (CBOL Plant Working Group, 2009), and documentation of genotype, origin, growth circumstances, harvest stage, drying, and storage are all considered best practices. Studies cannot be compared, and findings cannot be replicated without them.

Methanol, ethanol, or acetone are used in conventional extraction together with water for several hours. Methanol and acetone perform well in the lab; however, they are not suitable for use in food extracts. Green techniques have expanded rapidly: natural deep eutectic solvents made from food-grade components have attracted attention despite being viscous and difficult to separate from the target compound (Dai et al., 2013); supercritical CO2 is suitable for lipophilic compounds like carotenoids and oils; and ultrasound-assisted extraction shortens extraction to minutes (Chemat et al., 2017). There is a trade-off between yield, selectivity, and scalability: the approach with the largest phenolic yield is frequently the least selective, and the method that is easiest to scale may result in a lower yield. While most articles mention yield and solvent but not selectivity, scalability, or cost, the practical question for an ingredient is which approach yields a consistent, food-grade product at an acceptable cost.

Although it only detects what it is designed to detect, targeted LC-MS, which compares known substances to standards, is still the gold standard for quantification. With open spectrum libraries and molecular networking (Wang et al., 2016), untargeted metabolomics with high-resolution mass spectrometry can identify undiscovered substances and group similar ones while simultaneously measuring hundreds of characteristics (Wolfender et al., 2015). Studies should specify the identification level employed because identification confidence varies greatly and is frequently blurred. For example, a molecule matched to a standard by retention time and fragmentation is significantly more certain than one tentatively annotated by correct mass alone (Schymanski et al., 2014).

The traditional method of finding the chemical responsible for a certain activity is bioassay-guided fractionation (Atanasov et al., 2021). However, this method is slow, may miss combination effects, and may follow the incorrect target if the assay is a poor proxy for physiology. Metabolomics is used to identify uncommon or prevalent substances for testing, which is the first step in omics-led prioritization. The best research incorporates both.

The question for a food maker is what distinguishes one batch from another. The response often consists of a fingerprint, like an HPLC or LC-MS profile, and a standardization marker, like the total content of a compound class or a named component. Since the active ingredient in many NUS is unknown, a marker should be stable, measurable using a validated method, and ideally connected to the effect. Only a small percentage of papers disclose method validation (linearity, recovery, precision, limits of detection), which restricts cross-study comparison and is a barrier to commercialization.

Evidence for Health-Relevant Function

The most popular tests in this area are ORAC (oxygen radical absorbance capacity), FRAP (ferric reducing power), and DPPH and ABTS radical scavenging. They are inexpensive, fast, and simple to use on a variety of samples (Huang et al., 2005), but they only detect one specific thing: how easily a compound in a test tube gives up an electron or hydrogen atom to a metal ion or synthetic radical. That is far from what happens in the body. Polyphenols are poorly absorbed, extensively metabolized, and usually present in blood at concentrations below 1 µM after normal intakes, far below the levels used in many assays (Manach et al., 2005), and many antioxidant effects in cells and animals appear to run through signalling pathways such as Nrf2 activation rather than direct radical scavenging. The US Department of Agriculture withdrew its ORAC database in 2012 for this reason, stating that the values had no relevance to the effects of bioactive compounds on human health (Cosgrove, 2012). The assays also disagree with each other, because they respond to different chemistry, solvents, and pH. Chemical antioxidant assays should therefore be treated as screening only, since they cannot stand in for in vivo evidence (Granato et al., 2018).

Cell and enzyme assays sit closer to physiology and can be matched to a health target. Anti-inflammatory endpoints are usually tested in macrophage lines stimulated with lipopolysaccharide, and cellular antioxidant activity assays are more realistic than chemical tests because they include uptake and metabolism (Wolfe & Liu, 2007). Glycemic control is mostly tested through inhibition

of α-amylase and α-glucosidase, and extracts from finger millet, jujube, cactus pear, and several legumes inhibit these enzymes in vitro, often through polyphenol and tannin binding (Devi et al., 2014; Gao et al., 2013). These assays remain limited. Enzyme inhibition by crude extracts is often non-specific because tannins bind and precipitate proteins, including the test enzyme, so a positive result needs a proper dose range and comparison against a reference inhibitor such as acarbose. Many cell studies also use extract concentrations in the hundreds of micrograms per millilitre, which would be hard to approach through food.

Rodent models are common for diabetes, obesity, dyslipidemia, inflammation and oxidative stress, and studies on underutilized plants often report significant improvements in blood glucose, lipids or oxidative markers after several weeks of feeding. Sample sizes are often small, randomization and blinding are rarely described (Hooijmans et al., 2014; Percie du Sert et al., 2020), and doses are frequently given by gavage at levels far above what a person would eat. Converting a rodent dose to a human equivalent should use body surface area rather than simple weight scaling (Nair & Jacob, 2016), which papers seldom do. Many studies also test an extract, which is not the same as the food. A rodent study shows that an effect is biologically possible, not that it appears in people eating a normal portion.

In the literature reviewed here, human evidence seems to be scarce. For instance, a study by Coe et al. (2013) found that a baobab fruit preparation reduced the glycemic response to white bread at two dosages without altering satiety or energy expenditure; however, this short-term result should not be interpreted as proof of a long-term health effect. For the reasons mentioned above, plasma antioxidant capacity is a weak endpoint; blinding whole foods is challenging, and washout

durations and control foods are frequently poorly characterized (Figure 3).

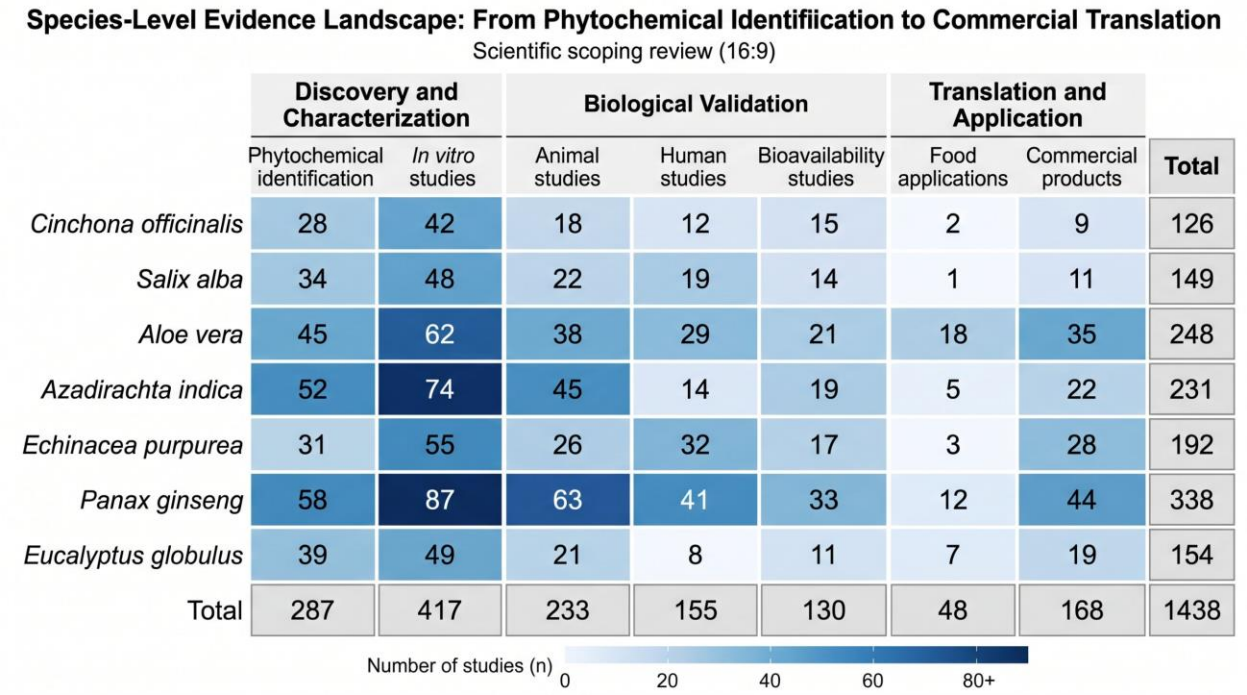


Figure 3. Studies per species, ranging from commercial items to phytochemical identification (n = 1,438).

The question that is frequently ignored is dose relevance. Although polyphenol concentrations following a meal are often in the low micromolar or nanomolar range, primarily as metabolites, a cell study demonstrating an effect at 100 µg/mL only pertains to humans if plasma concentrations are of that order (Manach et al., 2005). Calculating the component content in a typical serving, applying a reasonable absorption percentage, and comparing the outcome with the concentration used in the assay is a straightforward check; in animal work, the equivalent is a daily dose that is comparable to that of humans and may be consumed as food. This should be reported by authors.

Antinutritional Factors and Processing

A compound can be a benefit or a problem depending on dose, matrix, and the person eating it, and many compounds that give underutilized plants their reported activity also interfere with nutrition. Phytate binds iron, zinc, and calcium and reduces their absorption (Gibson et al., 2010). Tannins and other polyphenols reduce protein digestibility and iron absorption (Hurrell & Egli, 2010). Oxalate, abundant in amaranth leaves and some tubers, binds calcium and contributes to kidney stones in susceptible people (Noonan & Savage, 1999). Lectins and protease inhibitors in raw legumes damage the gut lining and reduce protein digestion, and are destroyed by adequate

heat. Cyanogenic glycosides in lablab, lima bean and cassava release hydrogen cyanide on tissue damage and are reduced by soaking, boiling and fermentation (Gemede & Ratta, 2014).

Processing shifts the balance, and sometimes reverses it. Soaking leaches water-soluble antinutrients (Gupta et al., 2015; Samtiya et al., 2020); germination activates endogenous phytase and amylase and raises vitamin and free phenolic content (Gan et al., 2017); fermentation lowers phytate, tannins and oligosaccharides and can release bound phenolics (Hur et al., 2014); and cooking destroys lectins and protease inhibitors but can also degrade heat-sensitive vitamins and polyphenols. Research that analyzes raw flour and indicates a benefit may describe something that no one would consume because many "functional" legumes and grains only function as foods after one or more of these stages.

Bioaccessibility and Bioavailability

In the literature, the terms are used loosely, and misunderstanding arises when they are mixed up. The percentage of a substance that is released from the food matrix into the digestive fluids and is accessible for absorption is known as bioaccessibility (Fernández-García et al., 2009). The portion absorbed by the intestinal cells is known as absorption. Bioefficacy is the biological effect that follows first-pass metabolism, while bioavailability is the portion that enters the systemic circulation and can act on tissues. A chemical may be abundant yet nearly completely unavailable due to its binding to cell walls, trapping in a matrix, or degradation in the gut; therefore, a high measured level in a food indicates nothing about any of these.

The physical and chemical framework that contains a substance is called the food matrix. Only colonic bacteria or processing may release the significant portion of phenolic acids in cereals and millets that are bound to arabinoxylan and lignin in the bran cell wall (Acosta-Estrada et al., 2014; Chandrasekara & Shahidi, 2010). Polyphenols attach to proteins and fiber in legumes, and the degree of tissue disruption and the presence of fat determine the release of carotenoids from leafy vegetables (Schweiggert & Carle, 2017). Changes are released in both directions during processing. Extrusion can change the structure of starch and proteins and create resistant starch (Brennan et al., 2011); fermentation and germination can free bound phenolics (Gan et al., 2017; Hur et al., 2014); heat can release carotenoids but degrade vitamin C and some polyphenols; and fine grinding can increase bioaccessibility by breaking cell walls but exposes compounds to oxygen. As a result, studies must record the matrix and processing, which is one of the most frequent omissions.

With specified enzymes, pH levels, salts, and timings for the mouth, stomach, and small intestine phases, the INFOGEST protocol is a standardized static in vitro digestion technique. Revised in 2019 as INFOGEST 2.0, it was designed to lessen the variation that made previous digestion studies difficult to compare (Minekus et al., 2014; Brodkorb et al., 2019). Gastric emptying and slow changes in pH and enzyme concentration are not captured by static models (Carbonell-Capella et al., 2014). Caco-2 cell monolayers are the norm for absorption (Sambuy et al., 2005). They are more useful for ranking chemicals than for predicting absolute absorption in humans since they are straightforward and repeatable but lack mucus and cell variety. Colonic fermentation models are required for chemicals that reach the colon, where the majority of polyphenols and fiber end up. These models range from batch fecal incubations to continuous systems like SHIME (Molly et al., 1993).

The gut microbiota is the primary metabolic pathway for many plant chemicals. The small intestine absorbs very little of the dietary polyphenols (Selma et al., 2009; Cardona et al., 2013). The rest reaches the colon, where bacteria break down flavonoid glycosides, hydrolyze bound phenolic acids, and produce smaller products such as phenylpropionic acids, urolithins from ellagitannins (Espín et al., 2013), equol from isoflavones, and valerolactones from flavan-3-ols (Selma et al., 2009). These products are often more absorbable than the parent compound and may be responsible for much of the observed effect, so known metabolites should be tested too. Fibre and resistant starch are fermented to short-chain fatty acids, which feed colon cells and affect glucose and lipid metabolism (Koh et al., 2016), but there are few data on the fermentation of fibres from underutilized plants in humans (Figure 4).

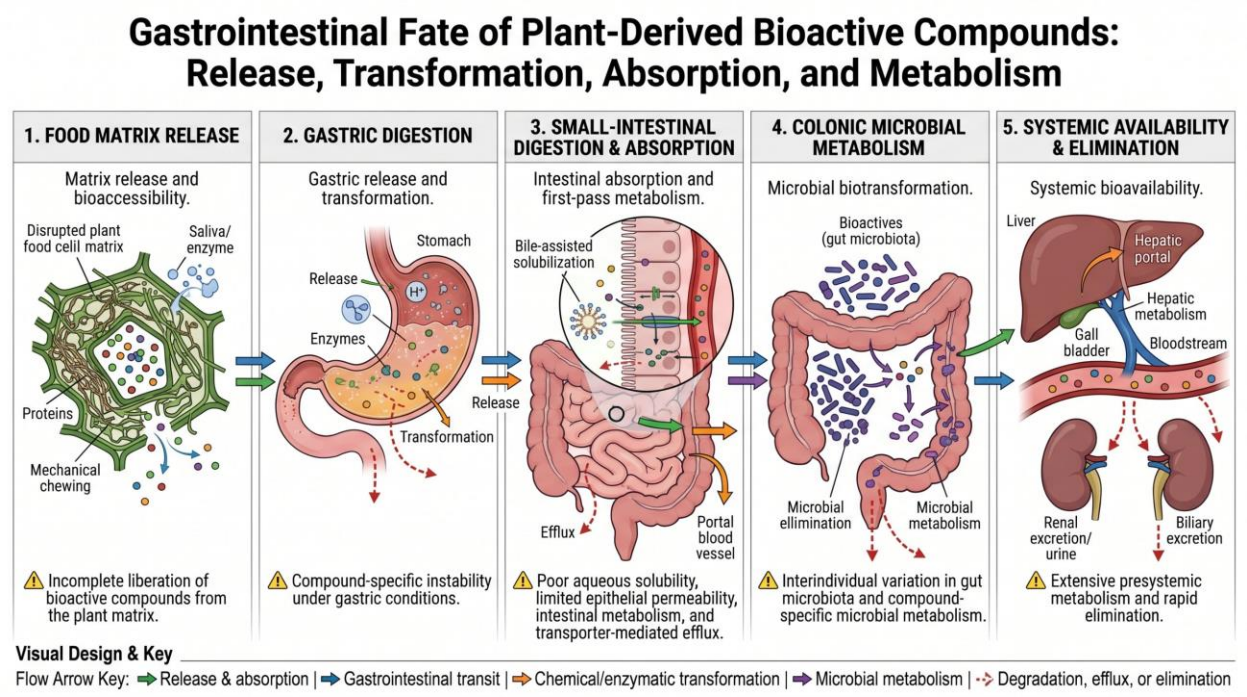


Figure 4. Gastrointestinal fate of plant bioactive compounds: release, transformation, absorption, microbial metabolism and elimination.

Human bioavailability studies measure plasma and urinary metabolites after a defined dose. They need a clear biomarker, enough time points to capture the delayed colonic phase (often 24 hours or more), and control of background diet, and such data appear to be scarce for the species covered here. People also respond differently to the same food: differences in gut microbiota produce "metabotypes" that do or do not make certain metabolites, as seen with urolithins and equol (Tomás-Barberán et al., 2016), and genetics, age, sex, health status, and diet add further variation. Studies should record individual responses because a diet may benefit a subgroup and have minimal average effect in a heterogeneous population. This contributes to the inconsistent findings of meta-analyses of polyphenol trials.

For these plants, the most practical approaches to increasing availability are typically the most straightforward. As with vitamin C and non-heme iron, co-ingestion can increase absorption; fermenting a millet porridge or germinating a legume can enhance mineral and phenolic

availability simultaneously and is inexpensive and consistent with traditional practices (Hurrell & Egli, 2010). For high-value, pure chemicals, advanced delivery techniques make more sense.

Food Formulation and Processing

Using a plant as a flour or entire ingredient is the most direct way to turn it into food because it preserves the natural matrix, saves money on extraction, and works with current eating patterns. In baked goods, pasta, extruded snacks, porridges, and drinks, finger millet, teff, amaranth, fonio, and bambara groundnut are frequently combined with wheat flour. These flours don't act like wheat. Bread with high inclusion levels is dense and small because gluten-free grains like teff, fonio, and amaranth lack the network that gives bread its structure; blending with wheat flour at moderate levels maintains an acceptable texture while increasing the amount of fiber, mineral, or phenolic content (Gebremariam et al., 2014). Heat treatment or germination is typically required before using legume flours since they contribute protein but also antinutrients and beany flavors. By eliminating inhibitors, extrusion can increase the digestion of proteins in bean and millet products. Additionally, the fruit flavor of beverages derived from baobab pulp, sea buckthorn juice, or cactus pear makes them simpler to handle.

Extracts and fractions, such as fruit powders, seed and pulp oils, fiber fractions, protein concentrates, and polyphenol-rich millet bran extracts, are employed when a particular component class is the aim. These substances can be dosed more precisely and have a higher value per kilogram, but a concentrated extract is not the same as the food from which it originated, and the food's history of safe usage does not always apply to it.

During processing and storage, bioactive substances change. Vitamin C, anthocyanins, and betalains are rapidly broken down by heat, although many phenolic acids are more stable and may even become more extractable as the matrix disintegrates; carotenoids oxidize and isomerize when exposed to heat, light, and oxygen. For juice and extract powders, spray drying is the typical industrial approach; sun or hot-air drying is inexpensive but loses more; and freeze-drying is the most cost-effective way to preserve chemicals. Depending on the circumstances, extrusion provides varying retention (Brennan et al., 2011). Therefore, investigations should assess the chemical content in the final food and after storage because the content in the raw plant is not the same as the content in the product.

Encapsulation can regulate release, conceal taste, and shield delicate substances. The most popular and least expensive method at scale is spray drying using maltodextrin, gum arabic, or protein carriers (Gharsallaoui et al., 2007), and emulsions work well with lipophilic substances like carotenoids (McClements, 2015). Although liposomes and nanoparticles provide more control, they are more expensive, more difficult to scale (Assadpour & Jafari, 2019), and may be subject to additional regulatory scrutiny; in the EU, engineered nanomaterials added to food are subject to novel food regulations (European Parliament and Council, 2015; EFSA Scientific Committee, 2018). For a low-value staple, the cost rarely makes sense, but for a high-value, unstable compound it can be the difference between a product and no product (Figure 5).

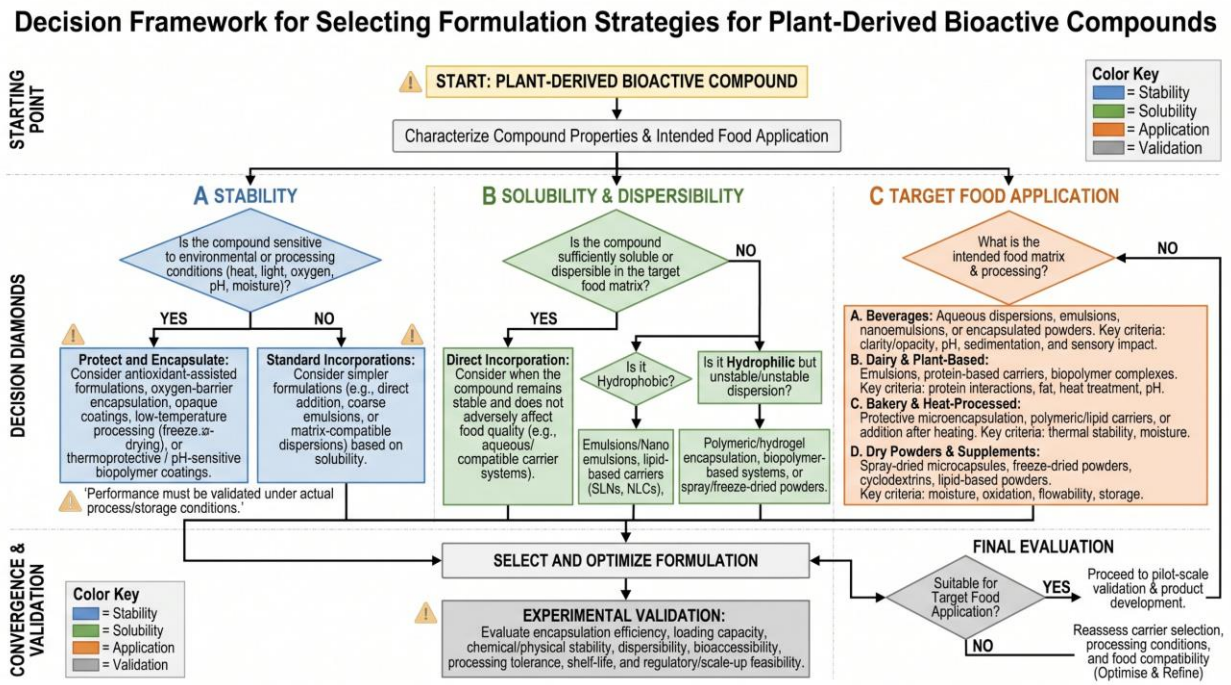


Figure 5. Decision framework for selecting a formulation strategy by stability, solubility, and target food.

Many bioactive compounds taste bad. Polyphenols and tannins are astringent, saponins and some peptides are bitter (Drewnowski & Gomez-Carneros, 2000), and legume flours carry beany notes from lipid oxidation. A highly bioactive ingredient that makes a food unpleasant has no market, so sensory work should come early. Strategies include lowering the inclusion level, choosing foods that tolerate the flavour, heat treatment, fermentation, and encapsulation. A tiny, untrained panel employing a hedonic scale is reported in many food-application publications; this is a start, but it cannot forecast a market. Amaranth, fonio bran, and bambara groundnut are examples of lipid-

containing flours that can develop rancidity in a matter of weeks to months. Therefore, stability should be evaluated in the actual product under real and accelerated storage conditions, assessing both the bioactive and standard quality markers.

Products made from fermented or germinated millet and legumes exhibit the most pronounced increases in mineral availability. Baobab pulp provides fiber and vitamin C to drinks and bars in moderation while maintaining a palatable flavor. Amaranth and teff have functional formulations in gluten-free bakeries, and sea buckthorn juice and oil are well-known in a number of industries. Three characteristics were present in every successful case: a product that consumers enjoyed, a specific component or nutritional value, and a mechanism that maintained it.

Commercialization and Market Translation

According to the NASA scale, technology readiness levels (TRL) range from 1 (basic concepts seen) to 9 (proved in operation) (Mankins, 1995). For plant-derived ingredients, TRLs 1 through 3 deal with lab discovery and proof of concept; TRLs 4 through 5 deal with process and ingredient validation in a relevant setting; TRLs 6 through 7 deal with pilot-scale production and prototype products; and TRLs 8 through 9 deal with a qualified, regulated ingredient in commercial sale. Most papers on underutilized plants sit at TRL 2 to 3, a small number reach TRL 5 to 6, and a few species, including baobab and sea buckthorn, have products at TRL 9. The useful question for each case is what blocked the move to the next level, and the blocker is usually supply, cost, regulation, or buyers (Figure 6).

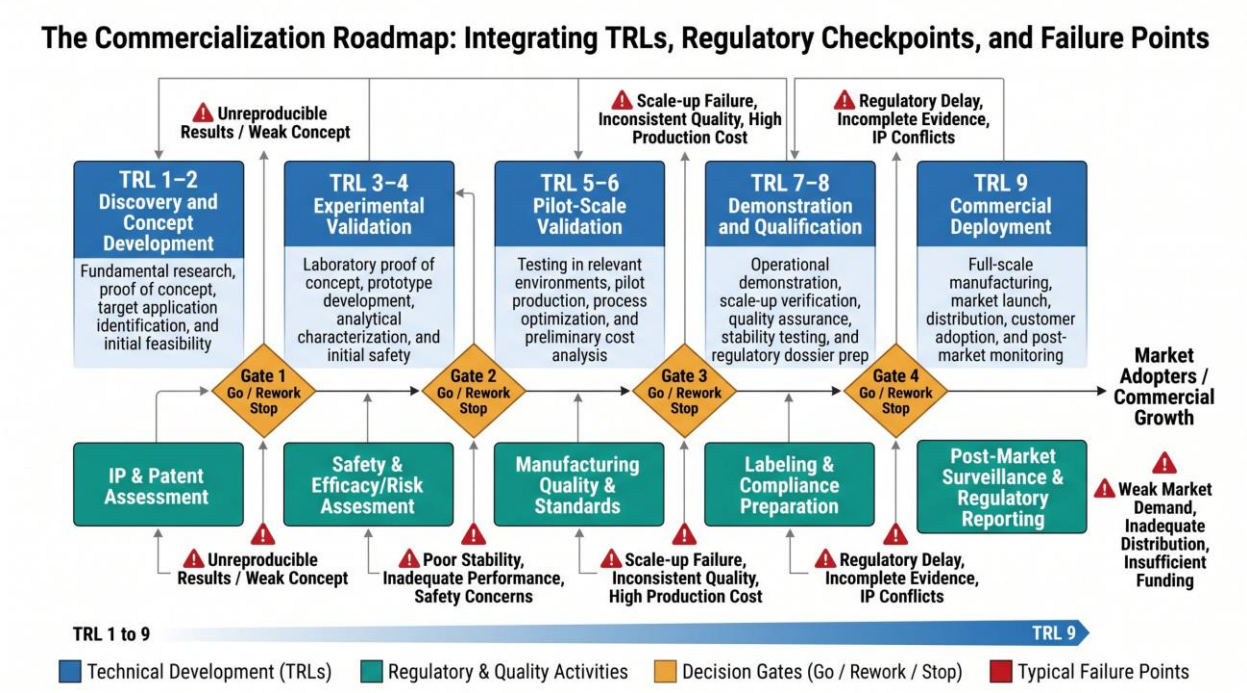


Figure 6. Commercialization roadmap linking TRL 1–9 with regulatory checkpoints, decision gates and typical failure points.

A food firm needs a steady source of consistent material, year after year, which underdeveloped crops generally cannot give. Seed systems are poor or missing, yields are low and erratic because there has been little breeding, and the crop is generally farmed by scattered smallholders, thus aggregation, drying, cleaning, and storage are substantial costs. Wild-harvested items such as baobab depend on tree populations and collectors, and quantity and quality fluctuate with weather and access. Price instability is a further risk, since farmers are left with a harvest nobody wants if customers vanish. Plant breeding is one answer (Dawson et al., 2019), and cooperatives, contract farming and reliable processing hubs are the organizational counterpart.

A procedure that functions well on a lab bench frequently doesn't scale. At industrial volumes, an extraction involving a few milliliters of ethanol is costly and dangerous. Given that it competes with less expensive current ingredients, the first question to address is whether the ingredient can be produced at a price a producer will pay. Techno-economic analysis is generally absent from the literature on underutilized plants, and few articles provide any cost figures.

Customers purchase foods that they are familiar with, trust, and enjoy; novel foods encounter a greater barrier due to their unusual flavor or cooking requirements. The majority of products rely on nutrition claims and origin stories because there is a limited willingness to pay for "superfood"

products in particular markets and because health claims require clearance. Even when export demand increases, local demand may be difficult to establish since consumers in the nations where the crops originate may view them as food for the poor.

Smallholder value chains connected to processors via contracts or cooperatives, suppliers of ingredients offering standardized powders, oils, or extracts, and branded consumer goods that are more valuable but require marketing expenditures are examples of business models. Many crops have benefited from public-private collaborations in their early stages of research, but long-term success typically necessitates shifting from donor money to commercial demand. In many export cases, the majority of the margin went to importers and brand owners, with very little going to the farmers. Therefore, who captures the value is just as important as if it exists.

Success. Among the species in this survey, the baobab is the most obvious example. In 2008, the European Union approved dried fruit pulp as a new food (European Commission, 2008). The US Food and Drug Administration responded in 2009 that it had no concerns regarding a GRAS notice from the trade group Phyto Trade Africa regarding use in fruit cereal bars and blended fruit drinks (US Food and Drug Administration, 2009). Although quality control, supply consistency, and equitable benefit sharing are still issues, the pulp has a recognizable nutritional profile, requires little processing, and generates cash for rural communities throughout Africa. The most talked-about case is Quinoa. Between 2006 and 2013, demand in wealthy nations nearly quadrupled prices, raising concerns among observers that Peruvian consumers would suffer. However, an examination of national household survey data revealed no indication of a decline in household welfare (Bellemare et al., 2018). Concerns about soil deterioration from mechanical quinoa production in southern Bolivia have been reported by others (Jacobsen, 2011). With the aid of oil and juice products with obvious value, chia and sea buckthorn also transitioned from local use to established ingredient markets (Ciesarová et al., 2020; Ullah et al., 2016).

Mixed and stalled. The difficulty of this is demonstrated by Fonio export initiatives in West Africa. Although the grain has good gastronomic and nutritional properties and the labor-intensive processing stage has been resolved by investing in decorticating machines, export volumes have remained low due to supply constraints, pricing, consumer unfamiliarity, and the expense of standardized manufacturing. The safety aspect of grass peas is demonstrated by the fact that, despite low-ODAP variants, its neurotoxicity has restricted their usage as food in many nations. Numerous bioactive-rich extracts and nutraceutical products have faced difficulties due to

intermittent supply or the inability to support their health claims. Products that were successful had a straightforward, inexpensive processing approach, a clearly defined selling point, a real regulatory procedure, and a supply that could be steadily increased. The most common reasons why products stalled were supply and pricing, followed by regulation, consumer desire, and chemistry.

Regulatory, Ethical and Safety Considerations

According to Regulation (EU) 2015/2283 (European Parliament and Council, 2015), a product or ingredient that was not widely consumed in the EU prior to May 1997 must be authorized as a novel food. If a substantial portion of a third country's population has a documented history of safe use for at least 25 years, traditional foods from that country may use a notification procedure; if no safety objections are raised, the food may be authorized more quickly than through the full procedure (European Parliament and Council, 2015; EFSA NDA Panel, 2016). Extracts and concentrates are typically regarded as innovative, and this method necessitates documentation of use, which is often oral or informal for many indigenous foods. While dietary supplements are subject to different regulations, such as new dietary ingredient notice for compounds not commercialized before to 1994 (US Congress, 1994), ingredients can enter the market in the US as GRAS (generally regarded as safe) by self-determination or reporting to the FDA. National authorities and Codex Alimentarius criteria are used by other markets (Codex Alimentarius Commission, 1997). In Pakistan, the relevant bodies include provincial food authorities such as the Punjab Food Authority, the Pakistan Standards and Quality Control Authority, and the Drug Regulatory Authority of Pakistan for products classed as health or alternative medicine.

Claims on health effects require substantiation in most regions. According to Regulation (EC) No 1924/2006 in the EU, claims must be approved following an assessment by EFSA (European Parliament and Council, 2006). As a result of numerous applications failing on the quality of the evidence, the list of approved claims for botanicals has remained small. Disease-risk statements require FDA approval, while structure-function claims on supplements are permitted in the US with notification and a disclaimer. A significant hurdle is that the majority of underutilized plants lack the human data required for any of this. Claims on nutrient content, like "source of fiber" or "high in vitamin C," are frequently a more practical place to start than bioactive claims.

The Nagoya Protocol, which was adopted in 2010 and has been in effect since 2014 (Secretariat of the Convention on Biological Diversity, 2011), mandates prior informed consent and mutually

agreed terms for access to genetic resources and related traditional knowledge, with fair and equitable sharing of benefits. The Convention on Biological Diversity, 1992, establishes that states have sovereign rights over their genetic resources. For NUS, this includes gathering plant material, studying its composition, and using the findings commercially. Before sampling and documenting consent, researchers should review national access rules, as many studies fail to do so. Traditional use-based patents have sparked worries about biopiracy, and benefit-sharing arrangements and defensive publication are useful strategies.

An ingredient's composition, toxicity, allergenicity, contaminants, and interactions are all included in a safety assessment; traditional use is proof of safety only under conventional preparation. In wild-collected material, toxic lookalike species can cause poisoning, while pollutants including heavy metals, mycotoxins, pesticide residues, and microbial loads are especially dangerous for wild or unprocessed material. Underutilized legumes may cross-react with soy or peanut allergies, and medication interactions and effects on children and pregnant women should be taken into consideration, especially for concentrated productsBecause a concentrated extract can deliver a dose that is several times greater than that of the food, safety standards based on conventional food intake do not apply to such products. Plans for sustainable harvesting, domestication, and certification are important since wild harvesting can reduce populations if demand increases. As demonstrated by the quinoa case, commercialization can also cause smallholder land to be converted from food crops to export crops or raise the cost of a local staple beyond the means of those who depended on it. Benefits should be distributed to the source communities through equitable pricing, processing ownership, and revenue sharing.

Research Gaps and Future Directions

There are three obvious gaps, each of which has a workable solution. uniform reporting. The voucher specimen, cultivar, growing conditions, extraction details, identification level, dose in a comparable form, and food matrix are all too frequently omitted from articles. Results would be similar and reusable if a minimum reporting criteria and data template were established through a community approach. Bioavailability data and human investigations. For almost all species, the transition from in vitro research to humans is absent. A standardized INFOGEST digestion combined with a small human pharmacokinetic study of the same food would link in vitro results to a human measurement, and small crossover studies with defined foods, a clear biomarker, a

proper washout, and measured metabolites would tell us more than another round of in vitro screening.

precompetitive datasets and market connections. Data on composition, bioaccessibility, and processing are dispersed throughout articles in various formats. A species could be evaluated based not only on chemistry but also on supply and pricing thanks to open, structured databases that link species, variety, processing, composition, and bioavailability along with agronomic and market data. NUS has not received much attention from breeding for ingredient quality (better yield, uniformity, fewer antinutrients, defined bioactive content), and orphan crops are currently being treated with genomics and gene editing (Dawson et al., 2019). Whether or if scientific advancements generate revenue depends on connecting farmers to markets through cooperatives, processing centers, fair contracts, and consumer education.

Conclusions

Underutilized plants have significant agronomic and nutritional benefits, and there is compelling evidence that many of them contain bioactive chemicals. There is far less proof that such substances work in humans at reasonable dosages and in actual diets, and there is currently no proof for the majority of species. The same bottlenecks—weak authentication and standardization, reliance on chemical assays, limited bioavailability data, few human trials, issues with taste and stability, and most importantly, supply, cost, and regulation—occur between discovery and market. Baobab demonstrates that when a straightforward procedure, a clear advantage, and a practical regulatory method are combined, the door is open. Standardized reporting, modest human trials with distinct biomarkers, and shared datasets that link composition and bioavailability to market and agronomic data will all contribute to progress.

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