FROM TRASH TO TABLE

OPPORTUNITIES FOR REPURPOSING WASTE PRODUCTS INTO NUTRITIOUS FOODS

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SUMMARY

Reducing food waste represents an important opportunity for shrinking the environmental footprint of food systems and supporting planetary health – and if this waste can be repurposed into nutritious foods, then it could also be a benefit for nutrition and human health. To understand the opportunities for repurposing waste products or byproducts into foods, this paper presents a rapid analysis based on desk research and key informant interviews. The analysis considers byproducts across four categories: fruit and vegetable residues, seeds and seed residues, other plant byproducts, and animal byproducts. The assessment considered availability, potential uses, consumer acceptability, food safety, nutritional quality, and feasibility.

Most byproducts examined were found to be readily available and potentially underutilised in LMICs. Among peels, orange, mango, and pineapple peels were found to be feasible for inclusion in various foods due to their rich nutritional profile and moderate consumer acceptance, though feasibility for repurposing at the industrial scale may be restricted to the outputs of large processing facilities (e.g., oranges at juice factories). In the seeds and legumes category, press cakes (the residues from making seed- or legume-based milks and oils) and pumpkin seeds are notable for their global availability, high nutritional content, and consumer acceptability, with minimal food safety risks when properly processed. Fish byproducts and whey emerged as a potential animal-source food byproducts that could provide valuable nutrients if repurposed into consumer-acceptable products.

While more detailed locally specific analyses will be needed to identify specific target products in specific places, this analysis makes clear that repurposing agri-food byproducts into nutritious foods may be a viable strategy to develop affordable, nutritious food products and help address malnutrition in LMICs.

KEY MESSAGES

- Repurposing food waste and byproducts into nutritious food has high potential to simultaneously address environmental and nutrition challenges.
- However, for this to work in practice, the waste / byproducts must be readily available and feasible to repurpose with relatively low cost, and the resulting products must be affordable, acceptable to consumers, safe to consume, and highly nutritious.
- This paper analyses the potential of 21 different waste or byproducts, including fruit and vegetable peels, seed and legume residues, other plant byproducts, and animal byproducts, to be repurposed into nutritious foods in LMICs.
- Taking into consideration multiple different criteria, we identify several high-potential waste/byproduct options, including fruit peels, press cakes, brewers' spent grain, fish offal, and whey.
- A key next step in operationalising these options would be locally specific feasibility studies in high-potential areas.

BACKGROUND AND OBJECTIVE

The global food system has a major impact on the environment. It is estimated to be responsible for about 21-37% of greenhouse gas emissions (1), to use 12.6 million square kilometres of cropland, use 1,810 km^3 of freshwater resources from surface and groundwater, and be a main contributor to water and land pollution, such as through runoff of nitrogen and phosphorous in fertilisers (1,2). Amid growing populations and increasing incomes, the pressures the food system exerts on the environment are expected to increase by 50–92% by 2050, threatening the achievement of global environmental goals (2).

These environmental challenges co-exist alongside persistent malnutrition. While there have been major advances in recent years, stunting (being too short for one's age) affects about 22% of children under age 5, or 148 million children (3). Micronutrient deficiencies are even more widespread, affecting over 1.6 billion pre-school-aged children and women of reproductive age (4). Both these burdens weigh heaviest in low- and middle-income countries (LMICs) and are associated with myriad poor health and nutrition outcomes (such as increased risk of infection, mortality, and blindness) as well as decreased work productivity in adults and cognitive development and educational achievement in children. Overweight/ obesity and related non-communicable diseases, such as diabetes and heart disease, are also widespread and growing problems, including in LMICs.

A major driver of these poor nutrition and health outcomes is unhealthy diets, including too much unhealthy food (such as sugar-sweetened beverages, fast food, and sugary snacks) as well as not enough, and not diverse enough, healthy food (such as fruits, vegetables, legumes, nuts, and fish). Poor diets are common throughout the world, with dietary risks responsible for an estimated 22% of global deaths (5). Dietary inadequacy is particularly common in LMICs. For example, about 70% of young children in Africa and South Asia do not consume a diet of minimally adequate diversity, and about 30% of adolescents in these regions do not eat vegetables even once a day (6). While diet quality has improved globally in recent years, these improvements have been much slower in South Asia and Sub-Saharan Africa (7). To improve diet quality, consumers must have access to safe, nutritious foods in desirable forms and at affordable prices. This is currently a challenge across many areas: it is estimated that 3 billion people worldwide are unable to afford a healthy diet (8).

It is thus increasingly important to identify ways to tackle both these problems – high environmental impacts of food systems and poor diet quality – simultaneously. One option for doing so lies in the large amounts of waste generated by the food system. At present, an estimated one-third of food produced is lost or wasted before being consumed (9), including about one billion tons of food wasted annually at the retail and consumer stages of the food system. Levels of waste and loss are highest for some of the most perishable – and most nutritious – foods, like fruit and vegetables (10). Loss and waste occur along the supply chain, from primary production through storage and distribution to sales outlets and consumers' homes. This can include unplanned, undesired loss due to poor infrastructure and practices as well as disposal of products that could have been eaten but do not meet exacting quality standards, are past their expiration date, or are oversupplied relative to demand.

Food loss can increase food prices and reduce food availability. The amount of food estimated as lost in 2017 would be enough to feed 940 million people (11), and reducing food loss and waste in LMICs by 10% is estimated to be able to reduce fruit and vegetable prices by 14% (12). The importance of addressing food loss and waste has been recognised in Sustainable Development Goal (SDG) 12, which aims to ensure sustainable consumption and production patterns—including by halving the level of food waste (13). In addition to representing the use of resources and environmental impact without a clear benefit, food loss and waste have other negative effects on the environment: as food waste decomposes in landfills, it releases methane and carbon dioxide into the atmosphere. Altogether, food waste generates 8-10% of global greenhouse gas emissions and costs the global economy nearly a trillion US dollars annually (14).

While definitions vary, the Food Waste Index (the official indicator for food waste under SDG 12) includes both ‘edible’ and ‘inedible’ parts of food as contributors to food waste. This is done in explicit recognition that what is ‘edible’ is not clear-cut: not only can it vary across cultures (e.g., whether pigs’ or chicken’s feet are eat or thrown out), but there are also many opportunities for re-using ‘inedible’ parts – either directly as food or as inputs into a food supply chain (15). Converting this ‘inedible’ food into edible food (sometimes called ‘upcycled’ food, (16)) and then into ***eaten*** food thus represents a major opportunity. Better repurposing food waste and byproducts could be an effective way to make nutritious food more accessible to lower-income consumers, helping improve diet quality, and would also help improve the environmental sustainability of the food system (13).

Repurposing waste and byproducts into nutritious foods was identified as one of 13 potential business model innovations that could be used to reach lower-income consumers with nutritious foods through GAIN’s Business Model Research (BMR) project (17). This paper seeks to build on that work by exploring which waste products that could be repurposed into nutritious foods that are affordable for low-income consumers, either as substitutes or entirely new food products. We focus on food waste products, byproducts, or residues that are often not used or not regarded as useful but can be consumed by humans or used as food ingredients, limiting the analysis to products relevant for LMICs.

METHODOLOGY

We used a mixed-methods approach that included desk research and in-depth interviews. Through the desk research, we reviewed 100 reports, papers, briefs, presentations, and articles, including information from websites and databases such as FAO, USDA, FAOSTAT, and USDA Food Central Database. These resources were identified through keyword searches, using words such as byproducts, waste, nutrition, repurpose, LMIC, food safety, availability, affordability, and potential uses. Through this, we narrowed in on 21 potential waste/byproducts to examine (Table 1).[1] These byproducts were selected based on

[1] Press cakes were added later in the process than the others, based on emerging evidence from key informant interviews and feedback on an early draft of the paper.

availability of information, production volume, percentage wasted globally, and expected ease of replicating processing approaches in LMICs. Of note, due to the focus on LMICs, various products with high potential for reuse, but primarily in high-income countries (e.g., olive pomace from olive oil pressing; wine industry byproducts) are excluded. We complemented the information from the literature search with in-depth interviews with six key informants, such as food and nutrition experts and food processors, including in Africa and South and Southeast Asia.

We synthesised these data to provide an analysis of each of the 21 products listed in Table 1. Where possible, we consider availability, feasibility of repurposing, potential uses, consumer acceptability, food safety, and nutritional quality. When considering availability and feasibility, we focus particularly on the level of industrial processing, as waste from industrial facilities is likely easier to capture and valorise than waste from individual consumers or cottage industries. Unless otherwise noted, all production volume data (including in figures) come from FAOSTAT and refer to 2022 estimates. While we sought to also include the environmental impact of processing and post-processing of byproducts, data on this were limited, making it difficult to indicate this for each product. We also feature in textboxes a few case studies of businesses that have successfully repurposed byproducts into nutritious food.

Table 1. Byproducts examined, and estimated share of byproduct per unit original product

Category	Byproduct	Approx. byproduct percentage of original product (by weight)
Fruit and vegetable peels and scraps	Banana peels	35%
	Mango peels	20%
	Orange peels	20%
	Pineapple Peel	15%
	Yam peels	10%
	Cucumber peels	10%
Seeds, legumes, and their residues	Cocoa beans pulp	25%
	Cocoa pod husk	75%
	Coffee bean husk (Cascara)	12%
	Pumpkin seeds	4%
	Aquafaba	Not applicable
	Press cakes (oilcakes)	80%
Other plant byproducts	Cassava leaves	100%
	Brewers spent grain	85%
	Cashew apple	90%
	Corn silk	2%
Animal byproducts	Fish offal	65%
	Whey	90%
	Eggshell	10%
	Bone broth	40%
	Animal skin	6%

RESULTS

The results of the analysis are organised into subsections using four categories of byproducts from Table 1: fruit and vegetable peels and scraps; seeds, legumes, and their residues; other plant byproducts; and animal byproducts.

FRUIT AND VEGETABLE PEELS

Fruit and vegetable scraps consist of leftover parts of fruits and vegetables that are not usually consumed, such as peels, tough ends (e.g., ends of onions or asparagus, leafy tops of celery), cores, seeds, stems, and occasionally overripe, wilted, or bruised portions. They are a primary waste product in food processing industries that use fruits and vegetables as raw material; they are also generated in homes and food service establishments where fruit or vegetables are cooked or served. In 2022, global vegetable production totalled 2.1 billion tonnes, generating an estimated 525 million tonnes of waste, as approximately 25% of a typical vegetable is discarded (18). Fruit and vegetables are often the largest food group contributor to food waste (by mass), making them a key target for reducing waste (15).

Fruit and vegetables are grown and eaten globally, but cultural food preparation styles, such as those in some Mediterranean cuisines, that involve minimal peeling and utilise all vegetable parts, can reduce the availability of scraps. In many small mixed crop-livestock farms, fruit and vegetable scraps may be directly repurposed into animal feed or used for compost that is needed for future cultivation, meaning that few are available for other types of repurposing.

Fruit scraps can be used in jam, infused water, smoothies, vinegar, syrups, chips, sorbet, zest for baking and cooking, salsa, tea, broth, and chutney. Vegetable scraps can be simmered into a stock; used to produce vegetable powders for use in soups, smoothies, and as seasoning; chopped and added to dishes for extra flavour and nutrients; or processed into flours for use in biscuits, bread, and cakes.

Nutritional value varies widely across types of fruits/vegetables and types of scraps, but most are rich in fibre as well as certain micronutrients. As an example, carrot pomace is a byproduct of trimming wet carrots during the extraction of carrot juice. It is rich in carotene and contains high amounts of dietary fibre (19). Cauliflower has a very high waste index, and tons of cauliflower byproducts (stems and leaves) are generated after harvesting every year; these byproducts contain nutrients such as phenolic compounds, vitamin C, glucosinolates, carotenoids and protein (19).

Among fruit/vegetable scraps, fruit peels in particular have various culinary, industrial, and agricultural uses due to their nutritional and chemical properties but are often discarded as waste (20,21). Fruit peels account for 15–60% of fruit waste globally, representing millions of tonnes a year of waste (22). Peels are generally abundant in LMICs. The main challenge associated with repurposing peels is devising effective strategies for collection and aggregation, as the waste often originates from individual consumers who discard it in various locations after direct consumption, unlike larger-scale processors with centralised waste streams. The main exception to this is oranges, a significant share of which are industrially processed into juice.

Given fruit peel's wide availability at low or no cost, cost of byproducts will mostly depend on the costs of this aggregation and of processing, which are affected by the scale of operations. Cleaning, drying, and milling are all relatively simple operations and can be done with a range of levels of complexity, from home production to high-tech and industrial-scale operations. The type of technology used will affect production cost and product quality; for example, products from air- and sun-dried peels are likely more affordable than those from oven- or freeze-dried peels (23,24). Food safety can also pose a challenge in the form of pesticide residues on peels, which can be harmful if ingested in large quantities over time. In most cases, this can likely be addressed with simple washing. In cases where pesticide residues are suspected or known to reach harmful levels, chemical washing (e.g., with a solution of sodium bicarbonate or alkaline electrolysed water) or physical, thermal, and non-thermal plasma treatments may be needed (24,25).

The following subsections provide additional details for four common types of fruit peels in LMICs – orange, mango, pineapple, and banana – as well as two types of vegetable/tuber peels, cucumber and yam. Table 2 summarises production volumes and locations, as well as nutrient content and food safety concerns, for these peels. Figure 1 presents the global distributions of production of the associated fruits (data on cucumber were not available; data on yam are presented separately).

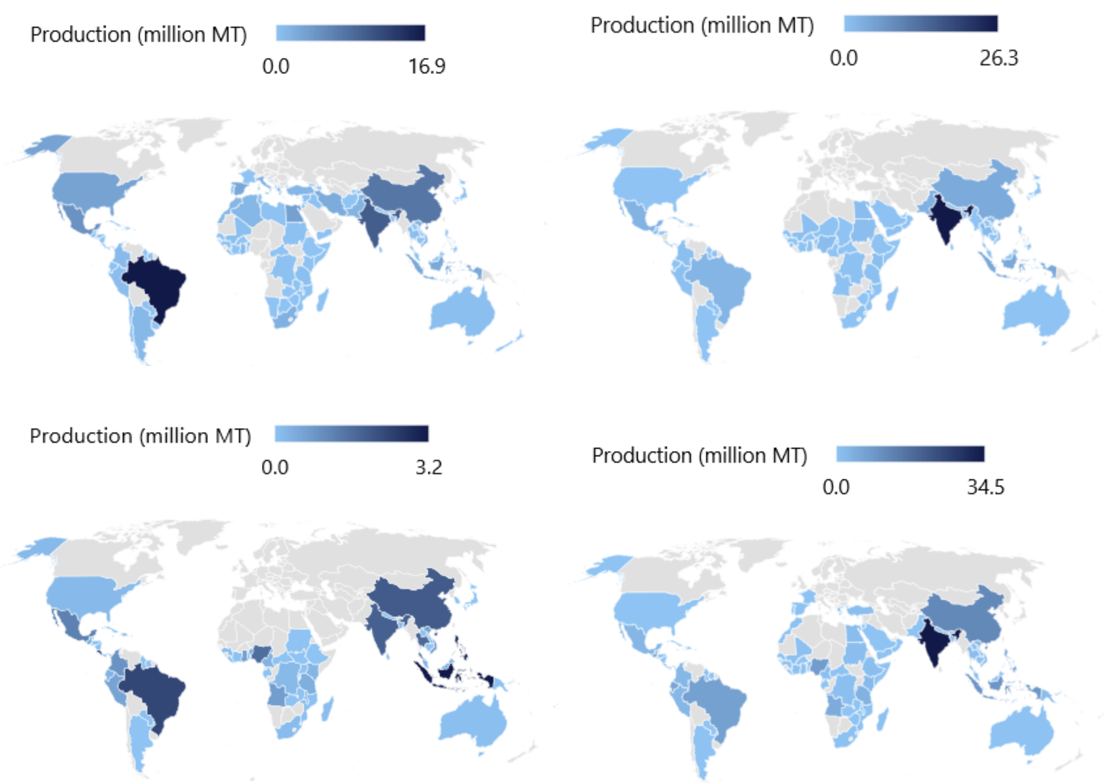

Figure 1. Top producing countries of orange (top left); mango, guava, and mangosteen (top right); pineapple (bottom left); and banana (bottom right).

Table 2. Fruit and vegetable peels

Item	Est. annual global production volume	Major producers	Nutritional content	Food Safety issues
Orange peels	76.4 million MT of oranges; estimated 15.2 million MT of peels, with about 5.1 million MT generated industrially	Brazil, India, China, Mexico	Rich in fibre (14.2 g per 100 g); vitamin C (136 mg per 100 g). Contains phenolic compounds with antioxidant, antimicrobial, and antiviral properties. (26–29)	Generally safe; some concerns with pesticide residues; can harbour harmful bacteria and fungi, making it important to thoroughly wash before processing
Mango peels	60 MT of mangos; about 6 MT of peels	India, Indonesia, China, Pakistan, Mexico	Rich in fibre (36–78 g/100g of dry weight), vitamin C (5.2 – 41.3 mg/100g), vitamin E (20.5 – 52.3 mg/100g) and vitamin A; several minerals (potassium 16.2 – 753.4 mg/100g, Calcium 60.0 – 371.6 mg/100g, magnesium 19.2 – 117.0 mg/100g). (30)	Generally safe; some concerns with pesticide residues
Pineapple peels	29.4 million MT of fruit; about 8 MT of peels	Indonesia, Philippines, Costa Rica, China, India	Rich in fibre (12-14% of volume), and also contain about 4.2% protein and micronutrients such as calcium (280 mg/100g) and iron (2.84 g/100g). (31)	Generally safe; textured surface can trap biological hazards (e.g., dust, mud, microbes), proper handling can help mitigate. Pesticides may be a concern but can be managed.
Banana peels	135.1 million MT; about 36 million MT of peels	India, China, Indonesia, Nigeria, Brazil, Ecuador	Rich in fibre (up to 50% of dry weight); also contain protein (4 – 12% of dry weight) and some minerals (e.g., potassium (71.5 – 84.7 mg/g), manganese (8.7 – 76.2 mg/100 g), and calcium (19.20 – 20.10 mg/100g))	Generally safe, some concerns with pesticide residues; presence of anti-nutrients such as oxalates (harmful for individuals with impaired kidney function when consumed abundantly) (32). Thermal processing significantly lowers the concentration of antinutrients.
Yam peels	About 88 million MT of yams; about 8 million MT of peel	Nigeria, Ghana, Côte d'Ivoire, Benin	Rich in fibre (41%); also contain protein (3.5%) and certain minerals (sodium 99.5 mg/100g, potassium 137.0 mg/100g, iron, 68.5 mg/100g, and calcium 45.5 mg/100 g). However, also contain antinutrients, particularly tannins, which can inhibit absorption of iron and digestibility of proteins. (33)	Risk of contaminants on skin (e.g., soil microbes); low if properly cleaned
Cucumber peels	Estimated about 90 million MT of cucumbers; about 9 million MT of peel	China, India, Turkey, Iran	Good source of vitamin K; also contain fibre, vitamin C, vitamin A, and several B vitamins, as well as minerals such as potassium, magnesium, manganese, copper, phosphorus, zinc, calcium, and iron.	Risk of contaminants on skin, including pesticides; low if properly cleaned

Orange peels

Peels are the main byproduct of oranges, accounting for about 20-40% of the fruit weight (34,35). Orange peels consist of a brightly coloured, waxy outer layer (flavedo) that contains essential oils and pigments and a white spongy and bitter inner layer (albedo) rich in pectin, cellulose, and various other polysaccharides (36). Oranges have high vitamin C content—and the content of peels is even higher than that of the fruit's flesh (26,29).

Traditionally, orange peels have been disposed of through landfilling and incineration, leading to environmental concerns due to their high water content (around 80-90%), organic matter (97%), and low pH (3-4), which can cause eutrophication and acidification if not managed properly (37). Recent advances have focused on valorising orange peels through the production of biofuels and high-value compounds such as bioethanol, lactic acid, pectin, and biomethane by anaerobic digestion (38). However, the direct repurposing of orange peels into human food ingredients is seen as increasingly promising, as it can both reduce waste and help improve the resulting food's fibre and phytochemical content (38).

Orange peels can be processed into various value-added products, including essential oils, flour, and jam (39). Limonene, which is widely used as a flavouring agent in foods and beverages, is the most abundant essential oil in orange peel (40). Orange peels can also be processed into powder through drying and milling (41). The resulting product is stable and, if stored properly, will keep for extended periods without significant degradation and can be used to substitute a portion of wheat flour in biscuits and bread (20,38,42,43). Orange peels also have strong potential as a secondary animal feed (44).

Oranges are widely liked and consumed, with few issues associated with consumer acceptability of orange-based products. For example, one study found orange jam containing 8% peels had the same sensory acceptability, physicochemical, and nutritional characteristics as pure orange jam (45). Yet there is a limit to the amount of orange peel powder that can be used for some products: another study found that biscuits supplemented with 5% and 10% peel were well accepted in terms of sensory evaluation and chemical analysis, but those with a 15% supplementation level were not (46).

Mango peels

Mango peels' use as functional food ingredients has been well-researched, with over 200 papers published on the topic between 2016 and 2020 (30). India has the biggest share of mango, mangosteen, and guava production globally, with about 44% of total global production, implying production of 98,000–280,000 MT of mango peels annually (47). These byproducts are often disposed of in landfills or incinerated, causing environmental issues (47). Non-utilisation of mango waste also reduces profitability of the mango processing industry (48). The peels are nutrient dense, having a higher concentrations of β-carotene (a vitamin A precursor) than the pulp (37). These facts jointly suggest that repurposing mango peels as a food product/ingredient could offer a triple benefit of mitigating waste-related environmental issues, enhancing profitability in the processing industry, and providing added nutrients.

Conversion of mango peels into a powder has been identified as a relatively simple and promising processing strategy, even in resource-constrained settings. The preparation of mango peel powder mainly entails washing the peels, then drying, grinding, and sieving them to obtain a fine powder (49). Adequate drying is essential to stop the enzymatic and microbial activities responsible for the peels' deterioration. This flour can then be used as an ingredient in various food products such as dairy products (e.g., milk, yoghurt, ice cream), pasta, and bakery products (e.g., bread, biscuits) (50).

Pineapple peels

Tough and fibrous pineapple peels are often discarded in landfills or burned and thus associated with considerable economic and environmental burdens. Pineapple is mainly consumed as fresh fruit. There are no recent estimates of the fraction processed industrially in most LMICs, but a recent study in India estimated that approximately 80% of pineapple there is processed into concentrated juice, canned slices, dehydrated slices, or jam (51). In such contexts, there could be large amounts of waste at the industrial level. For example, with an annual processing capacity of about 700,000 MT, Del Monte India alone could generate around 210,000 MT of pineapple peels annually (52).

Pineapple peels have traditionally been used as animal feed and fertiliser and industrially as a substrate for bio-ethanol production (53). Pineapple peel powder or flour is the main food product that can be produced from dry pineapple peels (25,54). The process is straightforward and involves washing, drying, and pulverisation (55). Other uses include in tea, vinegar, and juice. Pineapple peels could also be used as a bioresource for producing value-added products such as bromelain, an enzyme extensively used in the food processing industry for tenderising meat. Pineapple waste can also be processed into functional food ingredients such as organic acids, antioxidants, and fibres (56,57).

When properly used, pineapple peels can have strong consumer acceptability. One study from Nigeria reported that pineapple jam, which included both pulp and peel, had a relatively high acceptability score, indicating positive consumer reception; the addition of peel not only increased dietary fibre but was also generally well-received in terms of sensory attributes (58). A study in India found that replacing 10% of the wheat flour in crackers with pineapple peel powder significantly increased the ash, crude fibre, and phenolic content of the product without altering its sensory attributes.

Banana peels

Banana peels, the main byproduct of bananas, are commonly used as an animal feed ingredient, added to compost, or used directly as a fertiliser (59,60). Unlike seasonal mangoes and pineapples, bananas are generally available year-round in tropical humid areas.

The main value-added food product from banana peels is banana peel flour, which can substitute wheat flour in biscuits and breads. Banana peels can also be incorporated into various food products like pastries, dairy, and meat to boost their content of antioxidants, fibre, and other nutrients (61,62). The main challenge in the process lies at the collection level: since bananas are not widely processed industrially, the peels would mostly need to be collected from consumers or waste facilities. Banana chip producers may be a viable source of banana peels, but their scale is limited (55). Otherwise, collection from dispersed consumers or waste facilities would require logistics, planning, transport, and labour—which may be costly. The final affordability of banana peel-based food products will mainly depend on these costs, plus the cost of processing. There are some encouraging signs, however. A study in India found that instant soup powder from banana peels was a profitable product for micro-industries due to its low production cost (63). Other studies have shown that adding banana peel flour to pastries and other food products can be more affordable than using just wheat flour (64,65) and that pastries made with up to 20% of banana peel flour as a substitute for wheat flour showed good consumer acceptability. Instant soup powder from banana peels in India was also found to be highly acceptable (55). However, the addition of banana peels instead of rice or wheat flour can darken products'

BOX 1. EXAMPLES OF FRUIT WASTE REPURPOSING

GTF Technologies is an American company that uses drying and milling technology to transform byproducts towards other uses. This includes a pineapple powder made from discarded pineapple waste (peels and cores). The resulting high-fibre powder can be used in a range of food and beverage products, and the company claims it captures 7,000 tons of CO_2 equivalent annually by diverting nearly 15 million pounds of pineapple waste.

Diana's Bananas is an American company that uses discarded bananas to create frozen desserts. The bananas in question are diverted from normal retail streams because they are the wrong size or shape, or have been separated from their bunches; they might normally be wasted. Diana's collects these bananas, ripens them, and freezes them at a plant near the banana plantations in Ecuador. They are later dipped in chocolate, packaged, and sold in the dessert aisle of major U.S. retailer Whole Foods, carrying an 'Upcycled Certified' label. The company is also looking into opportunities for converting banana peels into new uses.

Source: (67,68)

colour (66).

Box 1 provides two examples of companies repurposing fruit waste.

Yam peels

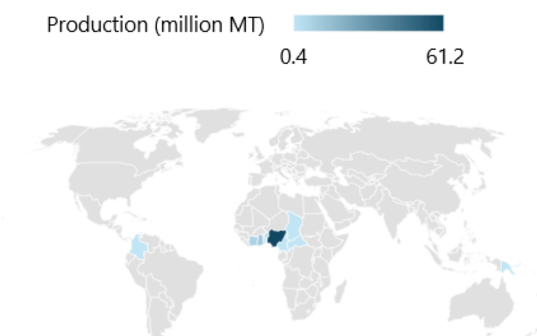

Figure 2. Top producing countries of yam

Yam peels refer to the outer skin and immediately adjacent dried flesh of yams, which are typically discarded during yam processing or preparation for cooking. While yam is not grown widely around the world (Figure 2), it is abundant in West Africa, with Nigeria alone accounting for approximately 70% of global production. During the annual yam harvest season in these countries, there is a steady supply of yam peels, readily accessible.

Yam peels can be repurposed into food products such as flour, dietary fibre supplements, and snack products like chips or crisps. The yam flour ***elubo*** or ***alibo*** in eastern Nigeria is used in making a dough-based dish called Amala; while normally made from yam flesh, yam peels can also be dried and ground into ***elubo*** as a more economical option, for those who cannot afford standard ***elubo***. Yam peel flour could also be used in baking or as a thickening agent.

Repurposing yam peels into food products is relatively easy and cost-effective; it involves drying, milling, and packaging. In traditional processing, which is most of the sector in West Africa, the peels are sun-dried for a few days, after which the dark parts of the dried flesh are peeled off and the white parts are blended until smooth. The resulting powder is then sieved to remove lumps. At a large scale, the drying process may require electric dryers, but this sector is relatively small. While simple, sun-drying exposes peels to dirt and domestic animals such as goats.

In yam-consuming countries, there may be two barriers to acceptability of yam-peel products: households consider them to be a last-resort food option, for times of financial difficulty, and they are not used to purchasing them (consumers instead accumulate the peels over a long period from the yams they consume). Educating consumers about the benefits of yam peels could enhance their appeal, or innovative product development and strategic marketing could position yam peels as a sustainable and health-conscious food choice, thereby increasing consumer acceptance.

Cucumber peels

Cucumber peels are the outer skin removed during the preparation of cucumbers for consumption. Cucumbers are grown globally, but in areas that rely on rainfed agriculture, supply can be inconsistent. Most cucumber peels come from places where cucumbers are processed in large quantities, such as restaurants and eateries. When cucumber is consumed at home, the peel is often eaten with the flesh, thus leaving insignificant byproducts.

Cucumber peels can be added to other vegetable scraps and boiled to create a broth, incorporated into smoothies (increasing fibre content and adding flavour), pickled into a tangy and crunchy snack, blended with spices to produce flavourful chutneys and relishes, or used to infuse water. Converting cucumber peels into these products is relatively simple, as blending, pickling, and infusing do not require expensive equipment or advanced technology. This also suggests low production costs. Consumer acceptability of cucumber peel is generally high due to its mild flavour and crisp texture; indeed, many people normally consume the peels alongside the fruit.

NUTS, SEEDS, LEGUMES, AND THEIR RESIDUES

Legumes, nuts, and seeds tend to be rich in protein, healthy fats, fibre, and minerals, and their processing can involve various byproducts related to their shells, husks, and similar, which may retain some of these nutrients. Some (e.g., pumpkin seeds) may also be seen as byproducts or waste products themselves. This section explores several diverse examples of byproducts within this category: cocoa bean pulp, cocoa pod husk, coffee bean husk, pumpkin seeds, aquafaba, and oilseed cakes. These are summarised in Table 3.

Table 3. Nuts, seeds, legumes, and their residues

	Est. annual global production volume	Major producers	Nutritional content	Food safety issues
Cocoa bean pulp	About 6.5 million MT of cocoa beans, implying about 65 million MT of cocoa pods	Ivory Coast, Ghana, Nigeria, Cameroon, Ecuador, Brazil, Peru	High in sugar and low in protein, but does contain minerals such as calcium (171.5 mg/100g), potassium (950 mg/100g), magnesium (82.5mg/100g), sodium (30.5 mg/100g), phosphorus (62.47 mg/100g). (69)	Limited data, but generally thought to be safe when properly processed
Cocoa pod husk			High in fibre (36-56 g / 100g), mostly insoluble; moderately high in protein (4.21–10.74 g/100 g); some calcium (254 mg / 100g) and potassium (2768 mg/ 100g)	Generally low risk; washing should be used to eliminate bacteria
Coffee bean husks	About 10.8 million MT of coffee beans, suggesting over 1 million MT of husks	Brazil, Vietnam, Indonesia, Colombia, Ethiopia, Uganda, Peru	Mostly carbohydrates; 8-11% protein. Some antioxidant content, particularly of polyphenols.	Generally low risk; washing should be used to eliminate bacteria
Pumpkin seeds	About 28 million MT of pumpkin;	China, Ukraine, Russia, USA	Rich in protein, manganese, copper, magnesium,	Generally safe when properly processed; roasting can lead to

	probably about 300,000-500,000 MT of seeds		potassium, phosphorus, zinc, and iron.	formation of polycyclic aromatic hydrocarbons, which are considered carcinogenic
Aquafaba	About 18 million MT of chickpeas	India, Australia, Turkey, Ethiopia, Russia	Depends on type of pulse, water/pulse ratio, temperature, pH, cooking pressure, and cooking time. An indicative aquafaba is mostly water and contains 2.03–2.59 g/100ml of carbohydrates, 0.08–2.8 g/100 ml of protein, and 0.07–0.1 g/100ml of fat, iron, and magnesium.	Limited data, but generally thought to be safe
Press cakes / oilcakes	No global estimate available, but large (over 220 million MT for vegetable oil)	China, US, Brazil, EU, Ukraine, Russia, Argentina	Typically high in protein and fibre, with micronutrient content varying by type. Some oilcakes contain antinutrients, like phytates and tannins.	Some compounds that form during oil processing may be harmful; improper storage can lead to microbial contamination

Cocoa bean pulp

Cocoa bean pulp is the edible, semi-solid substance that surrounds the cocoa beans inside the cocoa pod, making up about 5-10% of the weight of the cocoa pod. For each kilogram of dry cocoa produced, 0.59 kg of pulp can be obtained (70,71). Cocoa pulp juice is a naturally sweet juice obtained from this pulp; about 100–150 litres of cocoa pulp juice can be produced per metric tonne of wet cocoa beans. As shown in Figure 3, cocoa bean production is concentrated in tropical zones near the Equator, with Ivory Coast and Ghana jointly contributing over 50% of global supply (72).

Cocoa pulp is often used in the fermentation of cocoa beans to enhance the flavour and quality of the beans. During this process, the pulp is digested by bacteria and turns into a liquid that is drained out and discarded on the farm. However, a partial removal of the pulp does not affect bean fermentation, so some of the byproduct can be repurposed into food (73). Cocoa bean pulp is exploited at a small scale in Latin America, where it is used traditionally in the making of homemade drinks and foods. Cocoa pulp-based kefir beverages, cocoa pulp wine, cocoa marmalade, and cocoa vinegar are other foods made from repurposed cocoa pulp (71). The acceptability of cocoa pulp juice among consumers is generally positive, but there is limited data available on other cocoa-pulp-based products.

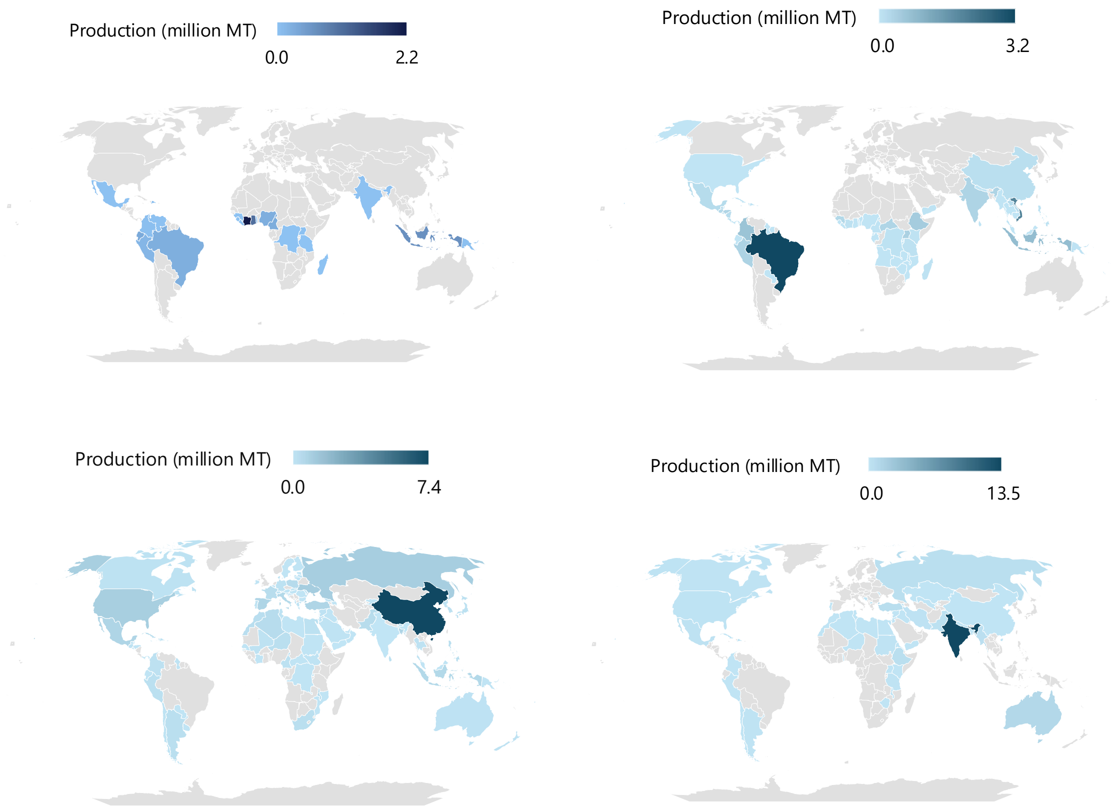

Figure 3. Top producing countries of cocoa (top left); coffee (top right); pumpkin, squash and gourd (bottom left); chickpea (bottom right).

Repurposing cocoa bean pulp into juice is a relatively straightforward process. This typically involves treating the pulp with pectinases to speed up the breakdown of pectin in the pulp and duplicate the fermentation process. Then, the resulting liquid is filtered, centrifuged, pasteurised, and packaged for consumption. Cocoa pulp juice can also be repurposed into a sweetening gel to replace sugar from sugar beets (74). One of the more challenging steps in the process is assembling the pulp, since cocoa is typically grown on a small scale. In Ghana, a startup, KOA, uses a mobile processing unit to collect and process cocoa pulp juice among smallholder farmers.

Cocoa pod husk

Cocoa pod husk, also known as cocoa shell or cacao husk, is the outer protective layer of the cocoa bean. It is removed during processing to extract the inner nibs, which are used to make chocolate and tea (75). Husks constitute approximately 70% of the fresh weight of cocoa fruits.

Cocoa pod husk can be used to make chocolate and tea, fermented into probiotic-rich drinks, or dried and pulverised into a powder or flour as a high-fibre additive in food production. It is high in fibre (mostly insoluble) and moderately high in protein, with some micronutrients, such as calcium and potassium (69). It also contains theobromine, a compound similar to caffeine, but with milder stimulant effects, as well as antioxidants (76).

The theobromine and lignin content, however, can limit the digestibility of cocoa pod husks.

Coffee bean husk (Cascara)

Coffee cascara is the dried outer skin or husk of the coffee cherry (fruit) that remains after the beans have been removed, making up about 12% of the weight of coffee. As with coffee beans, the flavour of coffee cascara varies by production environment; coffee cascara is subtler in taste than coffee beans. Coffee cascara has been traditionally used in some coffee-producing regions, such as Ethiopia and Yemen, for making hot and cold beverages, with the main use being brewing cascara as a tea. It can also be processed into a powder or syrup and used as a natural sweetener or flavouring, or as a source of added fibre. In this form, it can be infused into sauces, baked goods, smoothies, shakes, chocolate bars, jellies, and preserves. It can also be used in producing eco-friendly packaging materials. Cascara has higher antioxidant content and lower caffeine levels than coffee, but there has been limited research on its health impacts.

In high-income countries, particularly in areas with vibrant speciality coffee scenes like New York, San Francisco, and Seattle, cascara is often marketed as a premium product in coffee shops and speciality stores, associated with higher prices. In many LMICs, however, it is underutilised. Box 2 gives an example of high-income country companies repurposing another part of the coffee plant.

BOX 2. REPURPOSING COFFEE CHERRY FRUIT

In addition to the husk, the fruit of the coffee cherry that is not used for coffee beans can also be processed into other uses. The **Coffee Cherry Company** is a Vancouver-based company that takes coffee cherries, processes them to separate the outer fruit from the inner seed (coffee beans), then treats and dries the fruit. The dried pieces are then milled with other grains. The resulting fibre-rich flour can be used to replace wheat flour, cocoa powder, and sugar in certain applications, or can be used as a natural thickener. Acceptability has increased due to growing demand for healthier products, but the taste (resembling coffee) can be a barrier for certain applications. Regulatory standards for the atypical product and strict policies on agricultural imports have also been challenging in certain contexts**. I Am Grounded** is a similar company in Australia that processes coffee cherry into fruit bars and other snacks, which are positioned as premium health foods and sold online and through upscale retailers. The company notes that the use of upcycling and of an unusual ingredient helps add to the product's appeal.

Sources: https://iamgrounded.co/pages/mission, https://coffeecherryco.com/about-us/

Pumpkin seeds

Pumpkin seeds are edible seeds from pumpkins and other varieties of gourd squash; the seed is about 3% of total pumpkin weight. The seeds are cream-coloured, flat, and oval with a nutty, slightly sweet flavour. Pumpkin seeds are generally affordable and accessible in many LMICs, with widespread local cultivation. While some are already processed into snacks, and others are saved for replanting, a large share of the seeds likely goes wasted.

The main use is as snacks (roasted or raw, either whole or with the hull removed), but they can also be used in pumpkin seed spread or turned into flour and incorporated into foods. Raw pumpkin seeds offer slightly higher amounts of water-soluble vitamins compared to their roasted counterparts, but they also contain more antinutrients, which can impair mineral absorption.

Processing of pumpkin seeds into flour is fairly simple and can be accomplished with both manual and mechanised equipment. The manual process requires that the seeds be hydrated, a method called wet dehulling that involves soaking the pumpkin seeds in water to loosen the hull before removing it. Upon removal from the kernel, the seeds are then sun-dried, roasted, and ground into a powder with a mortar or a kitchen blender. Alternatively, the seeds can be dry hulled by roasting them first, which heats the hull and makes it more fragile and easier to remove. In the mechanised process, machines apply friction, pressure, or abrasion to remove the outer shell of the pumpkin seed.

Aquafaba

Aquafaba is the viscous solution from cooking or soaking legumes, especially at boiling temperature. While aquafaba is most commonly associated with chickpeas due to their superior foaming and binding capabilities (77), other pulses such as white beans, kidney beans, and black beans can also provide aquafaba.

Aquafaba is easily produced by boiling or soaking. An industrial product might require pasteurising and packaging. In countries where chickpeas are extensively produced, aquafaba is readily available as a byproduct of cooking chickpeas. However, aquafaba produced by home chefs and food service outlets would be very dispersed in relatively small amounts in small kitchens, making it potentially difficult to valorise. Companies that process chickpeas at larger scale for canning (or hummus, falafel, and similar) might be more viable sources.

Aquafaba can be used as a vegan substitute for egg whites, such as in meringues or as a binding agent in baking. Additionally, aquafaba can be incorporated into sauces, soups, and dressings, adding a creamy texture. It can be included in smoothies and other drinks to boost their nutritional content. Aquafaba is commercialised in powder form as an egg substitute and can be cheaper than eggs.

While aquafaba is not widely known, in regions where legumes are a staple, such as South Asia and the Middle East, there may be high acceptance due to familiarity with chickpeas and their cooking liquid. In cultures unfamiliar with using chickpea water in cooking, acceptance might initially be lower. In addition, vegetarian and vegan may be more likely to accept aquafaba due to its plant-based nature and utility as an egg substitute. Individuals following gluten-free or allergy-friendly diets may also prefer aquafaba for its versatility and non-allergenic properties.

Residues from plant-based oils and milks

Oilseeds such as soybeans, peanuts, flaxseed, rapeseed, cottonseed, coconuts, oil palm, and sunflower seeds are pressed to remove vegetable oil, and the remaining residue is the oilcake or press cake. Usually, a large volume of the oilseed remains as oilcake – for example, about 80% of soybean. The extraction process can vary, leading to different types of oilcakes, such as ghani pressed, expeller pressed, and solvent extracted. Certain extraction methods, like alkali extraction for canola, can result in poor technological properties and solubility, making them unsuitable as food ingredients. A similar pulp exists for the nuts, seeds, and legumes that are pressed for plant-based milks, leaving behind a residue.

Oilcakes are typically high in protein, though the protein quality varies. They also contain other nutrients, such as B vitamins and minerals, though the exact nutrient breakdown also varies widely by type of oilseed. For example, soybean oilcake contains about 40% protein, with small amounts of fat and fibre as well as calcium and phosphorus. Sunflower oilcakes contain about 20% protein and 12-30% fibre and are rich in B vitamins; cottonseed oilcakes are rich in phosphorus and vitamin E.

The primary use of oilcakes is as animal feed, particularly for livestock and poultry. However, there are also options for repurposing them into human food. For example, ***Kulikuli*** is a traditional Nigerian snack that is made from the residue left behind from peanut oil production, which is then spiced, shaped, and fried. Most types of oilcakes can be processed into a powder or flour and added to other foods, or further processed into protein isolates and concentrates. For example, a study using sunflower flour from sunflower oil manufacturing found that adding this to muffins in partial replacement of wheat flour increased the fibre, protein, amino acid, mineral content and antioxidant activity (78).

Some can also be used as meat replacements.[2] Box 3 gives two examples of American companies doing innovative repurposing of oilcakes from soybean and sunflower seed.

[2] Some oilcakes, like those from castor beans, can be toxic; these can usually still be used as fertilisers. Others, such as from oil palm, are not comparatively well suited to food applications.

BOX 3. EXAMPLES OF OILCAKE REPURPOSING

Planetarians is an American company that uses soybean and sunflower oilcake, as well as brewer's spent grain, to produce into plant-based meat replacements described as 'savory strips.' The technology is versatile and uses a wide variety of byproducts, making it adaptable to different raw materials. Their products are cost-competitive with traditional meats like chicken and beef, and cheaper than other alternative proteins like soy concentrate and pea isolate. They sell primarily to institutional buyers, like schools and universities, and are expanding into commercial markets. The product has been well-received for its texture and flavour absorption and due to the growing interest in sustainable and plant-based foods.

Renewal Mill is a Californian company that uses the pulp left over from producing soymilk and dries and mills it to create a gluten-free soy flour, which can then be processed into baking mixes and ready-to-eat snacks like cookies. They use a co-location model, where the production line is situated on-site at the byproduct company, reducing logistics and production costs, ultimately making the product more affordable. This also helps to reduce contamination and spoilage, as the byproducts can be quickly moved from the soymilk production line to the flour production line.

Source: Key informant interviews (2024).

OTHER PLANT BYPRODUCTS

In addition to vegetable and fruit scraps and seed/nut/legume byproducts, discussed above, there are a large number of other secondary products derived from plants during the processing of primary products. Here we discuss four of these that are common in certain LMICs and offer a snapshot of the diversity of the category: cashew apples, cassava leaves, brewers' spent grain, and corn silk. They are summarised in Table 4.

Table 4. Other plant byproducts

	Est. annual global production volume	Major producers	Nutritional content	Food safety issues
Cashew apples	About 6.5-8 million MT of cashew apples (estimated)	Cote d'Ivoire; India, Vietnam, Philippines, Tanzania, Benin, Indonesia, Brazil	Very high in vitamin C (200-269 mg/100ml juice) and fibre; high in sugar.	Adequate processing needed to reduce microbial contamination
Brewers' spent grain	About 36.4 million MT	China, USA, Brazil, Mexico, Germany, but any country with a significant beer industry	High in protein (15-26%) and fibre (35-60%). Most abundant minerals are calcium (360 mg/100g), magnesium (190 mg/100g), phosphorus (600 mg/100g). (79)	While wet, subject to microbial spoilage; generally low risk once dried
Cassava leaves	About 330 million MT of cassava, suggesting over 30 million MT of cassava leaves	Nigeria, DRC, Thailand, Ghana, Cambodia, Brazil	Rich in vitamin C (75 mg/100 g) and vitamin A (as beta-carotene, 950 mg/100g), with some fibre (1.8 g/100g), calcium (56 mg/100g), iron (1.8 mg/100g), and protein (2.3 g/100g).	Must be properly cooked to remove small amounts of cyanide and consumed in moderation
Corn silk	About 1,163 million MT of maize, suggesting a large aggregate volume of corn silk	United States, China, Brazil, Argentina, India, Mexico, Ukraine, Indonesia, South Africa	Corn silk contains about 15.29% protein and 14.82% fibre and is a good source of several minerals, including calcium (133.8 mg/100g), potassium (113.6 mg/100g), magnesium (116.9 mg/100g), and sodium (365.4 mg/100g). Also contains phytochemicals such as flavonoids.	Generally safe; some risk of pesticide contamination

Cashew apple

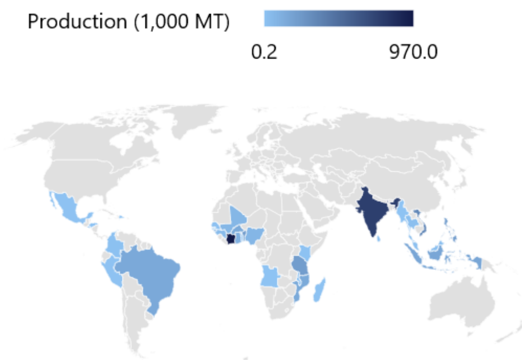

Figure 4. Top ten cashew nut-producing countries

A cashew apple is a fleshy, light red or yellow pear-shaped fruit, about the size of an apple, that develops from the floral part of the cashew flower. It is technically considered a pseudo fruit, or false fruit, since it contains no seed: the cashew nut grows at the bottom of the cashew apple, outside its flesh, covered by a hard shell. For every unit volume of cashew nuts produced, there are about 10 units of cashew apples. Cashew apples are very high in vitamin C (with their juice containing about six times more than orange juice), with large amounts of fibre – but also high in sugars. The top producers of cashews (and thus of cashew apples) are shown in Figure 4.

While the cashew apple itself is not commonly consumed, its juice is consumed directly as juice and used to make wine, and can also be used for vinegars, jelly/jam, chutney/pickles, dried snacks, and in baked goods (80). Its astringency can be reduced by mixing it with other fruit juices. Cashew apple utilisation is greatly hampered by its high perishability: in addition to spoiling quickly, the fruits are soft and easily damaged during transport. As such, processing must take place close to cashew orchards, but there are often inadequate infrastructure, equipment, and skills for processing and preservation in such locations. Instead, cashew apple juice is mostly produced at the very small scale for the local market in cashew-growing regions, and most cashew apples are wasted.

Brewer's spent grain

Brewer's spent grain (BSG) is the major byproduct of beer brewing. It consists of the residual barley malt and other grains after the extraction of fermentable sugars and makes up 85% of brewing waste. While BSG is used as low-value animal feed, the supply often exceeds the feed demands of local farmers near breweries (81). For example, Nigeria (Africa's largest beer producer) produces about 18.2 million hectolitres of beer annually, amounting to roughly 363,600 MT of BSG (82). This excess supply leads to disposal through landfilling, but each tonne of BSG in a landfill releases approximately 513 kg of CO_2 equivalent of greenhouse gases (83).

The product is initially a wet, mostly solid residue, with a short shelf-life, but can be dried and processed in various ways to preserve it. BSG can be ground and then sifted into a powder with higher fibre and protein content, but lower caloric content, then wheat flour; this can then be used in baked goods and snacks. Examples of this from the U.S. and India are given in Box 4. There may be challenges with consumer perception of BSG products among Muslims and other non-alcohol-drinkers.

BOX 4. REPURPOSING BREWERS' SPENT GRAIN IN INDIA AND THE U.S.

Saving Grains is an Indian company that takes BSG from about 60 microbreweries in Bangalore and reprocesses it into flour and related products like chapatis (flatbreads), ladoos (traditional sweets), biscuits, cookies, and granola. They run a 'Back 2 Brewery' model where the finished products are sold back to the breweries that supply the BSG and to restaurants, bulk markets, and stalls. Their products are certified by the national food safety authority, and they undertake lab testing to ensure no contamination. Communicating about this has helped to improve consumer acceptance of the products, as has transparent communication. Due to the high fibre and protein content of the flour, however, it cannot be used in the same way as all-purpose flour and may need to be blended with whole wheat flour for certain products. While the products are more expensive than those made using regular wheat flour, they are cheaper than other high-protein flours, such as Keto flour or almond flour.

ReGrained is division of the American company Upcycled Foods Lab that transforms BSG into flour, which it brands as 'SuperGrain+'. The company claims the flour has 3.5 times the dietary fibre and twice the protein as standard grain flours, with significantly fewer carbohydrates, and that its production emits less CO_2 that other 'alternative' flours, like pea and almond flour – as well as using almost no land or water resources. The flour has been used in breads and rolls, pizza crust, wraps, snack bars, breakfast cereals, and desserts. To date, the company reports diverting 1.3 million pounds of food waste.

Source: Key informant interviews (2024); https://upcycledfoods.com/

Cassava leaves

While the roots of the cassava plant are most commonly eaten, the young leaves are also edible and produced in abundance wherever cassava is grown. These are mainly left to dry and decay on the field after harvest, as the stems are often defoliated and stored for the next planting season. In some cases, cassava stems (still bearing leaves that eventually wither) are replanted immediately after harvesting. Cassava leaf yields can range from around 14.5–22.5 MT per hectare, depending on growth conditions and frequency of harvests (84,85).

Cassava leaves are mostly served as part of a sauce, eaten with starchy dishes or cooked as green vegetables. They can also be blended with flour and used in making fritters, pancakes, wraps, and rolls; dried and crushed into powder to be used as thickener and spice; and as an herbal tea. They are rich in vitamins and contain some minerals and proteins. Given their content of both cyanide and antinutrients such as tannins, however, cassava leaves should be well cooked and consumed in moderation (86).

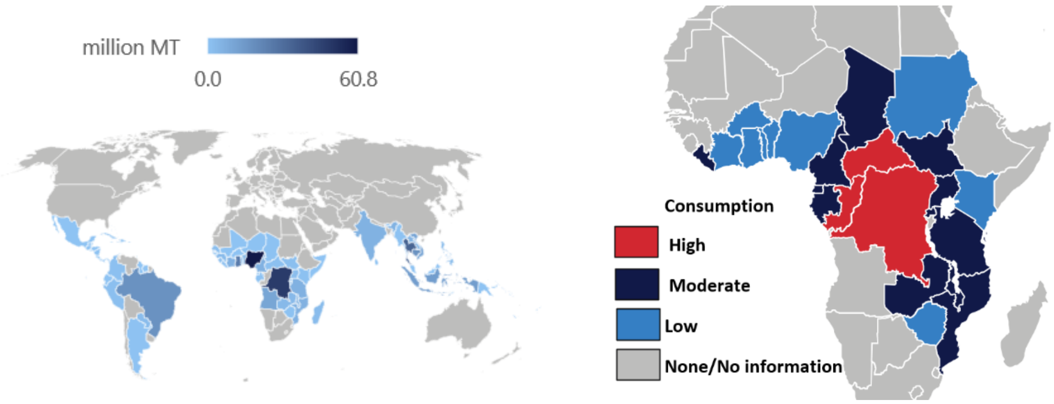

Figure 5. Top ten cassava-producing countries (left); levels of consumption (right), (87)

Cassava leaves are already used in many parts of Central and West Africa (Figure 5). However, even in countries where cassava is acceptable as a leafy green vegetable, other leafy green vegetables (e.g., spinach, amaranth) may be preferred over cassava leaves. Where cassava is produced, there is little difficulty in obtaining and using the leaves. The perishable leaves rarely reach major markets outside of these areas, however. To scale up access, innovative approaches are needed, such as efficient harvesting, drying, and processing techniques, and developing appealing value-added products.

Corn silk

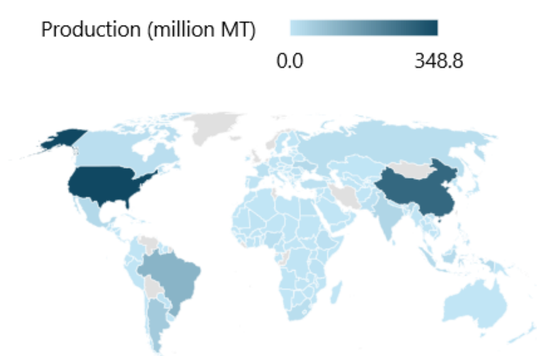

Figure 6. Top producing countries of corn

Corn silk, the stigmas of maize flowers, is a byproduct of corn. Fresh corn silk looks like soft threads of 10-20 cm in length; it can be light green or yellow brown. Corn silk is traditionally considered waste but has also been used for traditional medicine, herbal teas, livestock feed, and nutritional supplements. Corn silk can be used either fresh or dried. Corn silk tea is the most common food/beverage product and is easily created by drying and then boiling corn silk. Corn silk can also be consumed fresh, for example as a topping for salad or soup, or fried to make a crunchy snack, or added to other ingredients to provide a corn-like flavour. While corn silk is not widely used in cooking at present, it's ubiquity (given the large volumes of corn grown every year in every major world region, as shown in Figure 6) suggests there may be potential to use it more widely.

ANIMAL BYPRODUCTS

The production and processing of animal-source foods (i.e., meat, fish and other aquatic animals, eggs, and dairy) also yield numerous byproducts. There are both advantages and disadvantages to these types of foods when it comes to repurposing byproducts. They tend to be highly nutrient-dense, particularly in protein and micronutrients, suggesting potential to enhance diet quality, particularly in low-resource contexts where few animal-source foods are currently consumed. Moreover, since animal-source food production is more resource intensive than that of plant-source foods, there are more lost resources embedded within their unused waste products—implying more potential resource savings from repurposing them. At the same time, animal-source foods and their byproducts also have high food safety risks, requiring careful handling, processing, storage, and packaging. This section explores five diverse types of animal byproducts: pork skin (representative of other livestock skins), whey, bone broth, fish offal, and eggshells. These are summarised in Table 5.

Table 5. Animal byproducts

Product	Est. annual global production	Major producers	Nutritional content	Food Safety issues
Animal skin, particularly pork skin	113 million MT of pork	China, USA, Brazil, Spain, Russia, Germany; all countries that consume animals produce skin as byproducts	High protein (29.3 g/100 g) but also high in fat (40.2 g/100g) and may be high in sodium once processed.	Bacterial contamination during processing (e.g., ***salmonella***, ***E. coli***); thorough cleaning needed to reduce risk
Whey	Over 15 million MT of cheese between the EU and US alone, implying over 100 million MT of liquid whey	India, USA, Pakistan, China, Brazil, Europe	Once dried, high protein (12 g/100g), calcium (500 mg/100g), phosphorus (300 mg/100g), and potassium (400 mg/100g), as well as B vitamins	Pasteurisation may be needed to ensure safety of liquid whey
Bone broth	An estimated 26 million MT of poultry bones alone	US, Brazil, China, Europe; all countries that consume animals produce bones as byproducts	Depends on bones used and cooking length, but can provide calcium, magnesium, phosphorus, protein	Proper handling and storage essential; some concerns around heavy metal accumulation in bones
Fish offal	178 million MT of fish; about 71 million MT of offal	China, Indonesia, India, Vietnam, Bangladesh, Norway, Chile	Depends on type of fish and type of offal, but can provide omega-3 fatty acids, proteins, B vitamins, and minerals (e.g., calcium, phosphorus)	Proper processing and storage needed to mitigate microbial contamination, and controls needed for heavy metals and toxins
Eggshell	82 million MT of eggs, implying about 8 million MT of eggshell	China, India, USA, Indonesia, Brazil, Mexico	Rich source of calcium (about 400 mg/gram); small amounts of other minerals such as magnesium, phosphorus, and potassium	Low to moderate; cleaning and sterilisation (or boiling) required to remove potential bacterial contamination

Animal skin

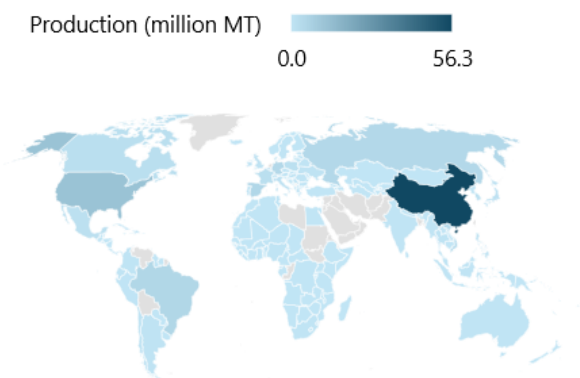

Figure 7. Top ten pork-producing countries

Livestock animals' skin is the outermost layer of the body, which is often removed during processing. This skin is often used for non-food uses (e.g., leather) but can also be repurposed into various food products such as gelatine for use in confectionery and desserts, snack foods, edible films and coatings for food preservation, and protein-rich food additives.

One of the animals for which the skin is used to make food products is pigs. Pork is produced globally, and the significant rise in pork production in recent years—from 87.4 million metric tons in 2010 to 112.8 million metric tons in 2020—suggests a corresponding increase in the availability of all pork byproducts, including skin. Pork production is mostly concentrated in middle- and upper-income countries, with China producing about half the world's total (see Figure 7).

In Latin American countries, ***chicharrón*** is a snack made by seasoning and deep-frying pork skin, though it can also be made with chicken, mutton, or beef skin. Pork rinds, or 'pork scratching', are dried pork skins that are rendered (i.e., slowly cooked until the fat is melted). However, both these foods are high in fat and often sodium and considered processed meat products, which should be avoided for optimal health. Another potential use of pork skin is its application as an alternative ingredient to enhance the nutritional value, texture, and yield of low-fat meat products like burgers (88). Edible films and coatings made from pork skin can also help to preserve different types of food, such as fruits and vegetables, by providing barriers to moisture, oxygen, bacteria, and fungi, while also preventing dehydration and contamination, thereby extending the shelf life and maintaining the quality of various food items (89).

Consumer acceptability of repurposed pork skin products varies across cultures and regions. In Muslim and Jewish communities, many people consider pork meat and its skin to be not able to be consumed, based on religious views. In most major pork-producing regions, however, this would not be expected to a major barrier.

Whey

When milk is coagulated to form cheese, the high-protein liquid that separates from the solid curds is called whey. By volume, approximately 80-90% of milk becomes whey during cheese production. Whey is thus produced in abundance anywhere that cheese is produced; in 2021, Europe produced roughly 2.5 million MT of whey, while Asia produced 96,000 MT.

Globally, about half of whey is disposed in wastewater (90). Whey contains considerable organic matter, with a high biochemical oxygen demand, which makes it a significant environmental threat when disposed of improperly (91). Safe disposal in water requires expensive and complex sewage treatments. Sustainable reprocessing of whey can thus help minimise this environmental impact and be cost-effective. Moreover, whey is fairly easy to aggregate because it can be collected in large quantities during cheese production, which is mostly done on an industrial scale.

Liquid whey contains over 90% water; the remainder is mostly carbohydrates from lactose and protein (0.8 g/100g). Once dried, whey powder is approximately 12% protein by weight, with little fat and high content of calcium, phosphorus, and potassium as well as B vitamins, mainly thiamine and riboflavin (92). Whey's rich protein content and low-fat profile make it a strong candidate for use as a dietary supplement. Processed products include whey protein concentrates and isolates and sweet whey powder (90). These ingredients can then be used to enrich many different types of food products, such as drinks and dairy products; whey water can also be directly used to create dairy drinks. Processing entails filtration, drying if needed, and quality control, and the costs of this processing will impact affordability of end products. However, whey protein generally tends to be competitively priced and affordable compared to other protein sources, and whey-based dairy products have been successfully commercialised in LMICs, such as Ecuador, Kenya, and Pakistan, in some cases at prices cheaper than conventional dairy products (93,94). Whey is also commonly used in products targeting athletes and those trying to build muscle, due to the high protein content.

Bone broth

Bone broth is created by simmering animal bones and connective tissue, often adding seasoning, resulting in a nutrient-rich liquid. The longer the bones are simmered, the greater the concentration of nutrients in the broth. Bone broth can be consumed directly as a beverage or used as a base for soups, stews, and sauces. It can also be dried and powdered or concentrated to create bone broth-based food ingredients and supplements. Though the exact nutrient profile of bone broth varies based on the type of bone, cooking method, and other ingredients used, it contains proteins and small amounts of minerals (calcium, magnesium, phosphorus); the protein content is usually higher than a meat-based broth.

In high-income countries, a large volume of bones is removed from animals during processing, in industrial-scale facilities. In many low-income countries, however, most processing is done by small-scale abattoirs, butchers, restaurants, and home cooks; while these also generate bones as a byproduct, collection for central processing may be limited. Bone broth is widely used in traditional cuisines in many parts of the world and has recently gained popularity as a health food in high-income countries, where it is usually sold at a relatively high price point (e.g., 10 EUR / 100g of dried broth).

Fish offal

Fish processing generates significant amounts of waste, accounting for up to 65% of the total fish weight; this includes muscle trims (approximately 15 – 20%), skin and fins (1 – 3%), bones (9 – 15%), heads (9 – 12%), viscera (12 – 18%), and scales (5%) (95). These are often underutilised. Some can be consumed directly (e.g., in soups and stews), while others can be used to make powders, flours, or extracts that are used as ingredients in foods like soups, sauces, baked goods, and snacks. Fish oils extracted from waste can also be used in supplements or fortified foods. As most fish byproducts retain a fish-like taste and odour, they usually need to be used in contexts where this is suitable to consumers (e.g., savoury snacks and meals) and will likely be most accepted in cultures where fish is commonly eaten.

Repurposing is most feasible in settings where fish is processed centrally (e.g., into filets that are then sold onwards); otherwise, collecting and aggregating fish waste from various sources would require investment in infrastructure and logistics, including cold chain facilities, which could significantly increase costs. The high processing costs for converting fish waste into products like fishmeal and fish oil can also impact their affordability, and infrastructure for this type of processing may be inadequate at present (96).

Eggshell

Eggshell, the outer covering of eggs of various bird species, is primarily composed of calcium carbonate, along with minor amounts of other minerals and organic materials. An eggshell constitutes about 10% of the total weight of an egg (97). Eggshells have very high calcium content: half a chicken eggshell can provide enough calcium to meet the daily requirements for an adult, and this calcium is highly bioavailable, with absorption rates similar to pure calcium carbonate supplements. As such, powdered eggshells can be used as a cheap and effective calcium supplement (98). Additionally, eggshell powder can used to add calcium to various foods, such as bakery items, pasta, cereals, and dairy products. Since the powder is usually not detectable in the finished product, consumer acceptance is likely to be high.

While eggs are produced globally, eggshells are usually disposed of by the consumer or food service provider, meaning wastes are dispersed and would be hard to aggregate. Exceptions to this would be large-scale industrial bakeries, confectioneries, or similar food processors using eggs as an ingredient in large-scale production (and who could potentially reuse the eggshells to add calcium to their products). Repurposing eggshells into food involves basic processes such as washing, boiling or otherwise sterilising, drying, and grinding into a fine powder. These processes are relatively simple and could be implemented in both small- and large-scale operations with minimal new technology required. However, advances in dedicated processing technology could help to improve efficiency (99).

DISCUSSION AND CONCLUSION

This paper sought to expand on prior work that highlighted the potential of repurposing waste products as a way to reduce the prices of nutritious foods and thus better reach lower-income consumers (17). Through a non-systematic review of the literature, complemented by key informant interviews, we examined the potential of 21 waste products, byproducts, and residues from food production and processing to be repurposed into nutritious foods, with a focus on LMICs. A synthesis of this exploration is shown in Table 6.

As the table makes clear, the potential of the 21 byproducts varies widely across both the byproducts and the criterion considered. Due to being waste products, all byproducts examined have moderate to high affordability as raw ingredients—but ultimately the price of the final product will likely depend more on the costs of processing, transportation, handling, and marketing. Food safety risks tend to be highest for animal byproducts, though these also tend to have high nutritional quality. Many byproducts have low feasibility for industrial repurposing due to being widely disbursed at homes and food service locations; exceptions are those with high levels of industrial processing of the primary product, such as orange juice (yielding orange peels), legume- and seed-based oils and milks (yielding press cakes), and cheese (yielding whey). However, feasibility of household-level repurposing is higher for most products, with the exception of those which are rarely available at the household level (e.g., cocoa pods, coffee bean husks, press cakes, brewers' spent grain). Some products that stand out for having moderate or high potential across all criteria are most of the fruit peels for home processing; press cakes, whey, and brewers' spent grain for industrial processing; and pumpkin seeds and orange peels for both home and industrial processing. In cocoa processing areas, cocoa pod husk may also have high potential.

For many of the products discussed here, repurposing processes can be diverse, from washing, drying, and grinding in cottage industries using minimal technology to industrial processes demanding considerable energy, technology, and trained staff. The process chosen will affect the quality and safety of the end product – but also its cost and environmental impact. Some of the products can be produced at home, suggesting they could be the focus of future consumer-focused interventions (e.g., through nutrition behaviour change communication). Others may be promising options for projects and initiatives that work with small companies and start-ups, to try to see whether they could be viably commercialised and marketed.

The lack of information on finished products' prices is a crucial gap when it comes to understanding the potential of waste repurposing to help improve low-income consumers' access to nutritious foods. While research in high-income countries has shown general consumer acceptance towards such foods (100), it has also indicated that most consumers would expect them to be cheaper than 'conventional' alternatives (101). It is indicative that most of the examples identified and profiled in the textboxes in this paper are from high-income countries, and usually feature products directed at upper-income markets and particularly health- and/or environmentally conscious consumers. While 'upcycled' foods will still be able to help reduce food waste if sold at higher prices than 'conventional' alternatives and appealing only to these demographics, their potential for improving diet quality among lower-income consumers in LMICs would be limited. Importantly, many of the byproducts discussed here have alternative uses, such as in animal feed or biofuels; for them to be viable for use in food products, repurposing them as such would need to be equally profitable (or cost-reducing) to these uses for the waste-generating company or individual. Investment in research and development and technology may be needed to bend the cost curve in this direction. In rural areas of LMICs, repurposing via animal feed and composting may be more feasible. Indeed, food waste levels per capita tend to be significantly higher in urban as opposed to rural areas (15).

If bringing such products to market, particular attention would need to be paid to marketing and consumer education. Marketing the products as 'repurposed waste' is unlikely to be the most appealing positioning, aside from for highly environmentally conscious consumers (who are generally a minority). Indeed, some of the products may already face a stigma associated with their consumption (as for yam peels in Nigeria); marketing them as 'waste' could deepen this. Instead, marketing should likely focus on the benefits of the products in terms of sensory aspects, costs, and/or nutritional value (e.g., high protein and fibre content in many cases). As mentioned above, there is cultural specificity in terms of what is considered 'waste' or 'inedible' (15). Some of the uses showcased here are already commonplace in certain countries, while they may be rare in others. Leveraging these differences to normalise 'waste' product consumption in cultures where it is not common could help increase consumer acceptance. Where ingredients are clearly repurposed, consumers may need reassurance on food safety – having clear processes, standards, and certifications from relevant local food safety authorities could help with this. This may require developing new standards. At the same time, where ingredients are integrated into existing products with no change in sensory properties (e.g., eggshell powder in baked goods), consumer uptake should be relatively easy.

A few caveats to the analysis should be noted. First, it was non-exhaustive and undoubtedly excluded many other possible byproducts that could be repurposed. Second, while the analysis estimates the overall volume of byproduct produced, this does not consider alternative uses that might already be occurring, such as in feed, compost, biofuels, or other products (e.g., clothing, cosmetics). The actual volume of byproducts available for repurposing could thus be much lower. The review also encountered several data gaps and topics on which information was hard to find, including the nutrient content / composition of some of the byproducts and information on food safety and affordability of most finished products.

There was also a widespread lack of information on the environmental impacts of most of the byproducts, including the impact of their current disposal practices and the potential impact of the additional processing, packaging, and other actions needed to repurpose them. This is important to understand, since if processing and post-processing of byproducts are relatively low-emissions processes, and decomposition is relatively high-emissions, the net impact of the end product could actually be negative—making it a priority for future investment.

Importantly, this analysis had a global focus, but attempts to actually commercialise any of these products would need to be based on locally specific analysis, considering local availability of ingredients, feasibility of aggregation, technology for processing, consumer acceptability, potential market size, and likely costs. To be viable, the end cost (including aggregation, processing, packaging, distribution, and marketing costs) would likely need to be comparable to substitute products already on the market. While some efforts could be made to market more costly products based on their nutritional or environmental attributes, those features are often not strong motivators for consumer purchases, particularly among lower-income consumers. Entrepreneurs and programme designers would also need to consider whether regulatory approval would be needed.

These caveats aside, this initial analysis has suggested that there are numerous byproducts with strong potential for repurposing into nutritious foods. To unlock their potential, three things are needed. First, technological advancements in aggregation and processing, appropriate for LMIC settings, could help make the products cheaper and more efficient to produce, or higher quality and thus more appealing to consumers. Second, there is a need to develop locally specific business cases that can show such products to be both profitable for companies and affordable to consumers. Third, policies that penalise waste or incentivise its reuse, such as higher taxes on dumping in landfills or tax breaks for companies that repurpose waste, could help to create an enabling environment for more, and more innovative, use of byproducts for nutritious foods.

Table 6. Multi-criteria consideration of byproducts

Category	Byproduct	Est. available volume of byproduct	Affordability	Potential uses	Consumer acceptability	Food safety risk level	Nutritional quality	Feasibility of repurposing – household	Feasibility of repurposing – industrial
Fruit and vegetable peels	Mango peels	High	Moderate	Some	Moderate	Moderate	High	Moderate	Low
	Orange peels	High	Moderate	Many	Moderate	Moderate	Moderate	High	High
	Banana peels	High	Moderate	Some	Moderate	Moderate	Moderate	Moderate	Low
	Pineapple peels	Moderate	Moderate	Some	Moderate	Moderate	Moderate	Moderate	Low
	Cucumber peels	Low	Moderate	Some	High	Moderate	Moderate	High	Low
	Yam peels	Low	High	Few	Low-Moderate	Moderate	Low	Moderate	Low
Seeds, legumes, and their residues	Cocoa bean pulp	Moderate	No Data	Few	High	Low	Low	N/A	Moderate
	Cocoa pod husk	Moderate	No Data	Some	Moderate	Low	Moderate	N/A	Moderate
	Coffee bean husks	Low	No Data	Some	Moderate	Low	Low	N/A	Moderate
	Pumpkin seeds	Moderate	Moderate	Some	High	Low	High	High	Moderate
	Aquafaba	Moderate	No Data	Few	Low	Low	Low	High	Low
	Press cakes	High	Moderate	Some	Moderate	Low	High	N/A	High
Other plant byproducts	Cassava leaves	Moderate	High	Few	High	Moderate	High	High	Low
	Brewers spent grain	High	High	Some	Moderate	Moderate	Moderate	N/A	Moderate
	Cashew apple	Low	High	Few	High	Low	Moderate	High	Low
	Corn silk	Moderate	High	Few	Moderate	Low	Low	High	Moderate
Animal byproducts	Fish offal	High	High	Some	Moderate	High	High	High	Moderate
	Whey	High	Moderate	Many	High	Moderate	High	N/A	High
	Eggshell	High	High	Few	High	Moderate	High	Moderate	Low
	Bone broth	Moderate	No Data	Few	High	High	Moderate	High	Low
	Animal skin	Moderate	Moderate	Few	Moderate	High	Low	Low	Moderate

LEGEND	N/A or No Data	**Least desirable** categorisation for criterion	**Intermediate** categorisation	**Most desirable** categorisation for criterion

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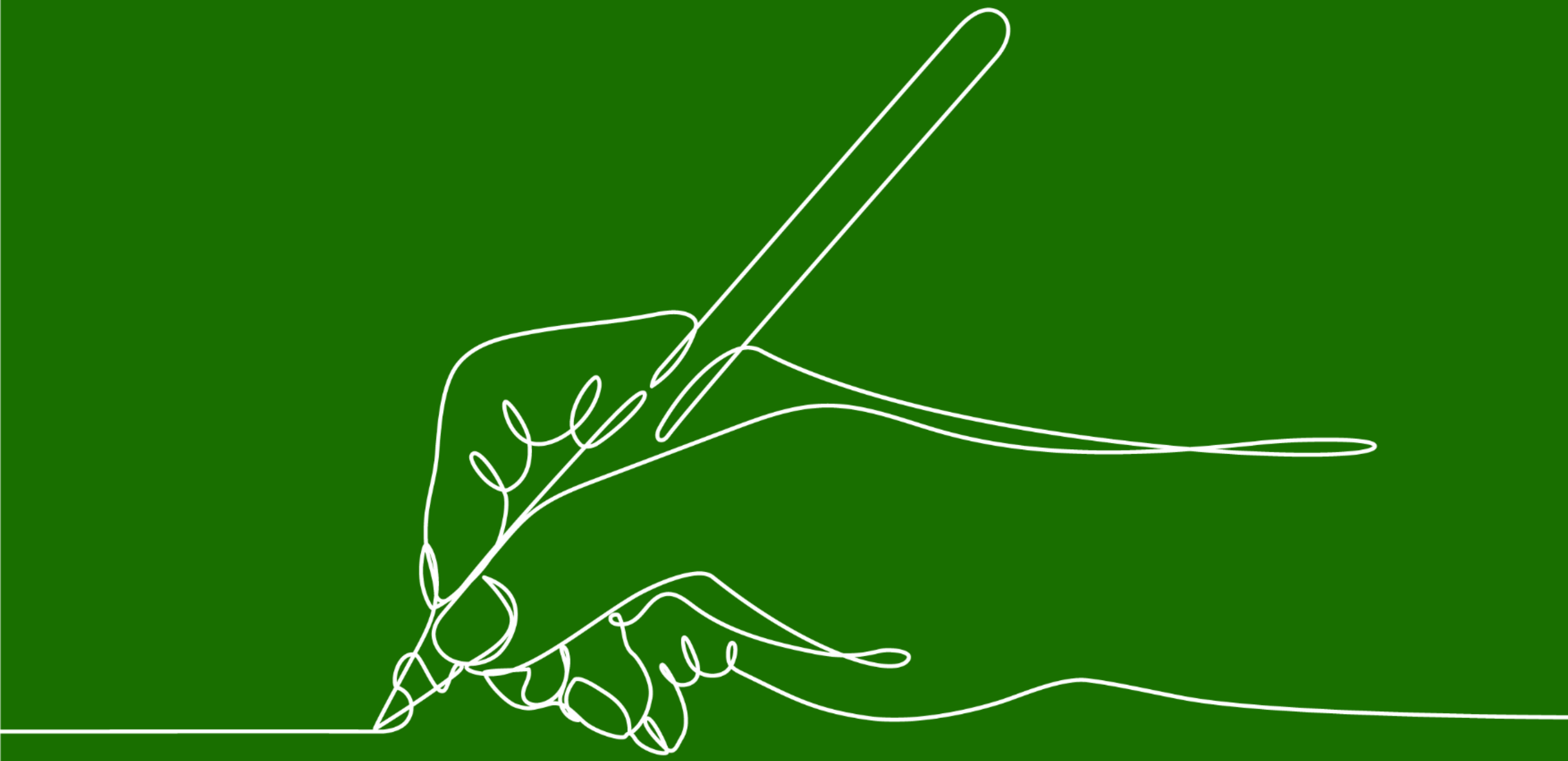

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The Global Alliance for Improved Nutrition (GAIN) is a Swiss-based foundation launched at the UN in 2002 to tackle the human suffering caused by malnutrition. Working with governments, businesses and civil society, we aim to transform food systems so that they deliver more nutritious food for all people, especially the most vulnerable.

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