Chapter 20

Opportunities for Food Waste Products as Sustainable Synthetic Alternatives

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Food waste is rich in organic molecules with desirable chemical or physical properties, such as poly/oligosaccharides, proteins, lipids, and bioactives or antioxidants, which can be exploited as high-value products. Using extraction or upgrading techniques (such as chemical, physical, or biochemical) to produce the desired product can open opportunities for natural alternatives to many existing synthetically derived products, such as those which rely on fossil fuels. This can include additives to enhance flavor, aroma, color, or texture, supplements or functional foods with nutraceutical benefits and positive effects for human health, as well as new fabrics and materials. These products can be used by many different sectors: food and beverage, wellness, cosmetics, fashion, domestic products, packaging, and construction. Although many such opportunities have been identified, research is still in its infancy, and therefore significant challenges exist for commercialization (scale-up, logistical, regulatory, and evaluation of overall environmental impact). However, achieving valorization through integrated biorefinery concepts could provide tremendous opportunities to move away from our dependence on fossil fuels and step towards a circular economy.

1. Introduction

Synthetic products touch every aspect of our life, from the food we eat to the household products we use and clothes we wear. Still, their production can cause damage to the planet in all stages of the life cycle: raw material extraction, manufacture, use, and disposal. Finding alternative products or production routes that use sustainable starting materials can produce eco-friendly alternatives that can reduce our reliance on petrochemicals and help limit the effects of climate change.

Food waste has enormous potential as a starting material in producing sustainable synthetic alternatives. Food waste encompasses any edible materials which are discarded, lost, or degraded at any point in the food supply chain, including harvest, processing (primary/secondary), packaging, transport, storage, marketing, and consumption. It is rich in nutrients (carbohydrates, proteins, lipids, vitamins etc.) and has many intrinsic properties (antimicrobial, health-promoting or aroma/flavor modifying) that can be exploited and valorized. This can be achieved by using simple processing techniques (drying and macerating) or by more complex integrated methods (extraction, biochemical conversion) depending on the desired properties of the finished products. These can replace synthetic products already on the market (such as dyes, texture modifiers, fragrances, and supplements) and can be considered natural and offer biodegradability. By repurposing this resource, it can be prevented from ending up in landfill, breaking down and releasing greenhouse gases to the atmosphere.

However, the valorization of food waste does face many challenges in upgrading and extraction. Strategies, such as thermal, chemical, or biochemical, are required to convert the waste into value-added chemicals [Sindhu et al., 2019]. Still, processes must use low environmental impact technologies and/or integrated biochemical processing approaches (e.g., fermentation and microbial transformations) to ensure sustainability [Lin et al., 2013]. In addition, products must meet current standards (safety, purity, etc.) and regulatory requirements [Ravindran and Jaiswal, 2016]. Similarly, new processes must compete with the economics of well-established synthetic processes; therefore, a balance between environmental sustainability and economic profitability is needed.

In this chapter we will address the opportunities for food waste products as sustainable synthetic alternatives across several sectors. First, we will assess the production of food additives (to enhance food quality or shelf-life) followed by nutraceuticals and functional foods/supplements (which have health and nutritional benefits). Additional applications will also be briefly discussed, including pigments/colorants, fragrances, bioplastics, enzymes, and textiles. Finally, the technological, economic, and societal challenges associated with valorization of food waste for use as commercial products will be considered.

2. Food Additives

Food additives improve food quality, by enhancing flavor, texture, or shelf-life. Producing food additives from food waste is logical for working towards a circular economy. As global diets move towards sustainable options, the market for clean label and eco-friendly food additives is growing [Campos Vega et al., 2020] and the global market for food additives was valued at US$41.9 billion in 2020 [BCC Research, 2021].

2.1. *Flavorings*

The production of flavor compounds from sustainable feedstocks is of increasing research interest. The global market for flavorings and flavors is projected to reach US$36 billion by 2024 [BCC Research, 2020]. Many fruit, vegetable and cereal residues and even mixed organic wastes have been considered to produce flavor additives [Laufenberg and Schulze, 2009]. The type of waste and intended flavor of the product determines the valorization process.

Although direct extraction of flavor compounds from food waste is possible, it can be difficult due to their volatility and low solubility therefore, solid-state fermentation [Laufenberg and Schulze, 2009] or other microbial production methods [Lee and Trinh, 2020] are more common. For example, 2-pentanone, which gives a banana flavor, and citrus-flavored d-limonene can be produced by fermentation of olive mill wastes [Guneser et al., 2017]. Although the cost of fermentation still struggles to compete with well-established synthetic routes, they offer the ability to produce optically pure forms of the desired compound [Kövilein et al., 2020].

Different wastes can give different flavor profiles. Esters can generate a range of flavors including fruity, buttery, or sweet [Lee and Trinh, 2020] and the production of flavored esters (isoamyl acetate, ethyl dodecanoate,

decanoate, octanoate, and phenyl ethyl acetate) has been reported by fermentation of orange peel [Mantzouridou et al., 2015]. Sour flavors are also common additives to foods; fumaric and malic acids are used as a food and beverage acidulant and are currently produced synthetically from petrochemicals. Their production by fermentation of glucose-rich wastes is presently the subject of investigation, such as malic acid production from soy and sugar cane molasses, sweet potato, or Jerusalem artichoke [Kövilein et al., 2020] or fumaric acid from waste bread [Lin et al., 2013] or apple industry waste [Das et al., 2015].

One of the most well-studied flavor additives from food waste is vanillin. Vanillin is the key flavor component of vanilla and is predominantly produced synthetically from fossil fuel hydrocarbons. Naturally extracted vanilla makes up only 1% of the market due to the potency (100x greater than naturally sourced) and cost (approximately 1%) of synthetic vanilla. Microbial production of vanillin, known as biovanillin, is the focus of much research with cereal waste and agro-industrial wastes and by-products such as sugar beet pulp and coconut husks all considered to be suitable substrates. Although some routes to the microbial production of vanillin are reported to be economically feasible, it is still generally regarded as an expensive alternative and significant growth is required to compete with the synthetic market [Martău et al., 2021].

2.2. *Preservatives/anti-browning*

Browning is a challenge that the meat industry faces, limiting the shelf life of fresh produce. A result of an enzymatic process, browning can change food's appearance, taste, and nutritional value. Traditionally ascorbic acid and its derivatives, nitrates/nitrites, and sulfites are used to reduce this effect as they inhibit the oxidative enzymes that cause the browning process. However, a lack of sustainability and potential risk of the development of carcinogenic compounds (in the case of nitrates and nitrites) have driven interest in natural antimicrobials as alternative preservatives. These include phenolic compounds, essential oils, and antimicrobial peptides [Shwaiki et al., 2021].

Plant-produced compounds are often explored as additives to reduce food spoilage. By their very nature, plants have evolved strategies to protect themselves from harsh conditions and predators and therefore produce potential preserving additives [Shwaiki et al., 2021]. These food stabilizers can be produced by drying and macerating [Ahmed et al., 2014], distillation [Kanatt et al., 2010], or enzyme-assisted valorization [P. Sharma et al., 2021] and can be used to preserve meat or dairy.

Many wastes are a good source of phenols, flavonoids and carotenoids and can enhance product shelf life, including citrus peels, fruit pomace residues [Ravindran and Jaiswal, 2016]. Muíño et al. [2017] demonstrated that antioxidants extracted from olive oil waste delay discoloration and lipid/protein degradation in lamb patties by up to 3 days. Similarly, olive leave extract has been used as a natural preservative when added to beef patties [Hayes et al., 2010] and peeled shrimp by controlling the microbial load [Ahmed et al., 2014]. Pomegranate peel extract has been used to extend the shelf life of chicken products by 2-3 weeks [Kanatt et al., 2010] and Martínez et al. [2020] demonstrated that leafy green vegetables prevented protein thiol oxidation in pork products. Other potential preservatives also include chitin and chitosan, extracted from shellfish waste, which can immobilize enzymes in wine, sugar, and fish [Nazzaro et al., 2018]. Although this area shows significant promise, more studies are required to fully understand the mechanisms of preservation and to ensure compliance with existing food additive regulations.

2.3. *Sugars & sweeteners*

Although the commercial production of sugars (or monosaccharides) is from sugarcane and sugar beet and not synthetic, they are abundant in many plant wastes and are worth discussing briefly. Extracted from biomass rich in polysaccharides, waste must go through several processing stages to release the monosaccharides such as physical or chemical treatment or microbial/enzymatic [Bhaumik and Dhepe, 2015]. Although there are many types of sugar, glucose and fructose are some of the most prevalent in nature and, therefore subject of much research.

Sugar syrups such as high fructose corn have been explored as food and beverage waste products. Bread residues have been converted into a glucose syrup by enzymatic hydrolysis (using α-amylase and glucoamylase). This can be further converted into a fructose syrup through glucose isomerase [Riaukaite et al., 2019]. Sugar-rich hydrolysate has been converted into food standard high-fructose corn syrup by adsorption, ion-exchange chromatography, isomerization, and glucose-fructose separation using a simulated moving bed and evaporation [Kwan et al., 2018b]. Similarly, the assessment of valorization of food and beverage waste to fructose syrup, high fructose syrup, or glucose-rich syrup showed it to be economically and technologically feasible [Kwan et al., 2018a].

In addition to sugars, sweeteners (such as sugar alcohols) can impart a sweet flavor when used as an additive but have a much lower calorific value. Sweeteners are produced synthetically and the increasing demand for more 'natural-based' diets is fueling interest in those derived from plants or their byproducts. For example, sugar alcohols can be produced from cellulosic biomass [Bhaumik and Dhepe, 2015], and xylitol has been produced microbially from many different agricultural wastes using various microorganisms [Espinoza-Acosta, 2020]. Commercial examples include Xilinat, a brand of xylitol produced from sweetcorn husk waste, and Fooditive Sweetener, which is produced from waste pears and apples [Markets and Markets, 2020].

2.4. *Texture modifiers*

Texture modifiers are added to foods to change and control their viscosity. They can take the form of small molecule surfactants, proteins (meat, dairy or plant-based), polysaccharides, or protein-polysaccharide complexes [Chen, 2015], so there are many opportunities to extract or produce their food waste. Emulsifiers are common texture modifiers as their surface-active properties can increase the stability of colloidal systems, and their market value as food additives is predicted to reach US$4.14 billion by 2024 [BCC Research, 2018a]. As with previous additives, there is a growing demand for natural sources.

Simple texture modifiers can be derived from wastes using minimal processing. For example, aquafaba (wastewater from chickpeas), which contains fiber, protein, saponin, and phenolic compounds, has foaming, gelling, thickening, and emulsification properties, allowing it to be used as an egg substitute in vegan cooking [Campos Vega et al., 2020]. Texture modifiers have also been produced from olive processing waste by drying olive pulp and removal of fats and polysaccharides by extraction [Filotheou et al., 2015] or by enzyme-assisted valorization from starch (corn, rice, potato) waste [P. Sharma et al., 2021]. Similarly, oat bran extract is effective for producing stable oil emulsions due to the presence of saponins [Ralla et al., 2018].

Alternatively, food waste can generate specific compounds with texture modifying properties. Lecithins extracted from trout processing waste were shown to perform well, forming oil emulsions compared to those extracted from typical sources, such as soybean and egg yolk [Topuz et al., 2021]. Pectin also has gelling/thickening properties, which make it advantageous in confectionary production, as meat fat replacement and as a stabilizing agent in acidified dairy products [Fermoso et al., 2018]. It can be extracted from plant wastes by acid hydrolysis [Lin et al., 2013] or using ultrasound techniques, as well as microwave-assisted extraction (MAE) [Fermoso et al., 2018].

3. Nutraceuticals & Functional Foods/Supplements

Food wastes contain many bioactive compounds, which have value within the wellness and nutraceutical industries. Nutraceuticals are foods, which play a medicinal role in maintaining or improving health and wellbeing by boosting immunity or preventing disease [Kumar et al., 2017] therefore offering extra benefits above the basic nutritional value of food. This can include antioxidant, anti-cancerous, anti-inflammatory, antimicrobial, cardioprotective and immunomodulatory properties which arise from their ability to modulate metabolic processes and/or boost defense mechanisms (antioxidant effect, receptor activities inhibition, enzyme induction or inhibition, free radical scavenging, and control of gene expression) [P. Sharma et al., 2021]. Research involving the extraction of value-added nutraceuticals or bioactives from food waste is growing significantly and beginning to rival that of biofuels [Ravindran and Jaiswal, 2016].

The potential for nutraceutical products from food waste are extensive. Waste can be valorized with little intervention, such as drying and grinding into a powder rich in fibers and bioactives, or can be targeted, with multiple separation and extraction techniques or additional synthetic or microbial treatments (such as fermentation) [Patel and Shukla, 2017] to produce one chemically pure product. The challenge of separating these compounds means researchers must find a market for the desired product to justify the cost against synthetic alternatives. Methods of extraction can include solid-liquid extraction, liquid extraction, distillation, supercritical fluid extraction, ultrasound-assisted extraction (UAE), or microwave-assisted extraction (MAE), pulsed electric field extraction, and enzyme-assisted extraction [P. Sharma et al., 2021] and depend on the type of food waste.

Nutraceuticals are sourced from a variety of food waste. By-products from fruit and vegetable waste (peels, seeds, pomace, etc.) are rich in antioxidants or phenolic molecules and animal by-products (blood and offal or tripe), have good nutritional value due to their collagen and chitosan content [Patel and Shukla, 2017] amongst other carbohydrates, proteins, or fats. Similarly, cereals produce several different by-products (bran, germ, husk, and fermentation/ milling waste), which offer potential valorization opportunities by recovery of starch, protein, lipids, and dietary fiber [Campos Vega et al., 2020].

Nutraceutical ingredients, such as antioxidants (which prevent oxidation of molecules and formation of free radicals that can attack cells in the body potentially causing cancer [Sindhu et al., 2019]) can be classified by their structure: phenolics, flavonoids carotenoids, dietary fiber, polysaccharides, proteins, lipids, and fatty acids [Campos Vega et al., 2020]. These are discussed in the following sections.

3.1. *Bioactive compounds*

3.1.1. *Phenols/phenolic acids*

Phenolic compounds are crucial to a healthy diet [Melini et al., 2020] as they act as antioxidants by several different mechanisms (free radical scavenging, hydrogen donation, singlet oxygen quenching, chelation, or prevention of superoxide attacks) [Lafka et al., 2007]. Phenolic acids are generally linked by ester bonds in polysaccharides, lignin or protein chains, but they can also be present as free, esterified, and glycosylated forms. Common examples include p-hydroxybenzoic acid, chlorogenic acid, syringic acid, vanillic acid, vanillin, p-coumaric acid, ferulic acid, salicylic acid, and caffeic acids [Campos Vega et al., 2020].

Turning food waste into functional phenolics can be achieved by drying, macerating and/or extraction, although care must be taken to maintain final product quality [Melini et al., 2020]. Fruit waste has been shown to contain gallic, caffeic, ferulic, vanillic, and coumaric acids which can be extracted in methanol and evaporated to dryness [Paulino et al., 2020]. Winery wastes are also rich in phenolics (catechin, epicatechin, hydroxytyrosol, tyrosol etc.), as well as phenolic acids (caffeic, syringic, vanillic, gallic, and coumaric) [Lafka et al., 2007] and these have been valorized by UAE or MAE [Melini et al., 2020]. UAE has also been used to extract phenolic compounds from fruit and vegetable wastes (apple, berry, citrus, tomato, and onion), root and tuber waste (potato peels and carrot pomace), as well as cereals and legumes (wheat bran and mung bean hulls) [Melini et al., 2020]. Similarly, superfluid extraction is effective for phenolic compounds found in grape, apple, and orange pomace and from walnut husks and hazelnut [Melini et al., 2020].

Biological methods, such as fermentation or enzyme-assisted extraction have also been used to increase the phenolic content of food waste. Fermentation of fruit wastes, cereals [Sadh et al., 2018b], and oil cakes [Ancuţa and Sonia, 2020] has been shown to increase their concentration significantly. Enzyme-assisted extraction has also been used to liberate phenolics by breaking down cell structure in grape waste, pistachio green hulls, pomegranate peels [Melini et al., 2020], and rice bran/husk waste [P. Sharma et al., 2021].

Applications for phenolic products have also been explored. Ellagic acid and punicalagin, found in pomegranate rind, are used in skincare due to their anti-inflammatory and anti-fungal effects [Ko et al., 2021]. Phenolics extracted from fruits, vegetables, and seed/oil crops have been used to fortify bakery products such as bread, biscuits, desserts, dairy products, and other snacks [Melini et al., 2020; Ancuţa and Sonia, 2020]. They are reported to increase the phenolic content of the final baked good. However, more work is required to determine if this translates to improved bioaccessibility and bioavailability [Melini et al., 2020].

3.1.2. *Flavonoids*

Flavonoids, commonly found in plants, are of increasing interest as nutraceuticals due to their antioxidant, anti-allergic, anti-inflammatory, antimicrobial, anticancer, and antidiarrheal properties [Jablonský et al., 2018; Torres-León et al., 2018]. Flavonoids are a subclass of phenolic compounds, generally composed of a benzene and a benzopyran ring, and can be further classified as chalcones, flavones, flavonols, anthocyanins, and proanthocyanidins [Falcone Ferreyra et al., 2012].

Flavonoids are abundant in many fruits and vegetable wastes. Onion peel in particular is an excellent source of flavonoids [Kuppusamy et al., 2020], as well as tomato waste which has been shown to contain catechin, quercetin, naringenin, rutin, and kaempferol [Paulino et al., 2020]. Bananas are rich in quercetin, myricetin, kaempferol, and cyanidin and its pulp is rich in catechin, gallocatechin and epicatechin [B. Singh et al., 2016] and mangos have been found to contain 17 different flavonoids [Campos Vega et al., 2020].

Flavonoids such as quercetin, kaempferol, and isorhamnetin have been extracted from food waste using deep eutectic solvents and UAE from grape pomace, olive leaves, wheat bran, spent filter coffee, onion waste, lemon peels, and buckwheat [Jablonský et al., 2018]. Naringin has been extracted from citrus waste and quercetin (and its derivatives) extracted from pistachio lees by supercritical fluids [Kumar et al., 2017].

As with other phenolic molecules, flavonoids have been used to fortify processed food. Flavonoids from black bean seed coats were used to enrich bread, with more than 90% retained after baking [Kumar et al., 2017]. However, this is positive in terms of valorization, as with phenolics more research is needed to determine if this translates to health benefits.

3.1.3. *Tannins*

Tannins are plant secondary metabolites with many reported health benefits. Tannins are large molecules containing multiple phenols and hydroxyl groups and aromatic rings, which allow them to act as excellent antioxidants by electron scavenging, as well as being water-soluble. Tannins can be grouped as gallotannins, ellagitannins, condensed tannins, complex tannins, and phlorotannins. They are present in plants and herbs and have traditionally been used as alternative medicine or in the leather industry. They have potential as additives in food, nutraceutical, and pharmaceutical industries due to their antioxidant, antimicrobial, anti-diabetic, cardioprotective, and anti-inflammatory properties [Fraga-Corral et al., 2021].

Tannins are present in fruit, vegetable, and other food wastes and many opportunities to recover them from the byproducts have been studied. Punicalagin (an ellagitannin) is the phenolic component in pomegranate rind responsible for its antioxidant activity. It has been extracted using ultrasound or heat-assisted extraction [Ko et al., 2021]. Similarly, condensed tannins have been extracted from red grape pomace using heat-assisted extraction [Ping et al., 2012]. Other waste sources rich in tannins include coffee, tea, and nut waste. Coffee pulp has been explored as a source of procyanidins with UAE [Wong-Paz et al., 2021] and tea leaves can also undergo tannin extraction by supercritical fluid [Maran et al., 2015]. Chestnut shells are rich in tannins and can be extracted at low costs, and could be used as antioxidant supplements in food, cosmetic or pharmaceutical formulations [Aires et al., 2016].

3.1.4. *Carotenoids*

Carotenoids are a large class of molecules that, in addition to their pigment properties which will be discussed later, are beneficial to human health. They have a polyene chain structure (containing three or more alternating double and single carbon-carbon bonds), usually consisting of 9-11 double bonds and often terminating in phenolics. They can be further classified as carotenes (α-, β-), xanthophylls, and homologs [Gupta et al., 2014]. Although their extraction from natural sources is possible, it is a low-yielding process. Therefore, microbial production of carotenoids is the subject of research, and as their global market is reported to reach US$2.0 billion by 2022 [BCC Research, 2018b] this is expected to increase.

Agricultural crops in particular, are the focus for the production of carotenoids, with some fruits and vegetables reported to be rich in specific carotenes. Tomato waste has been shown to contain β-Carotene and lycopene [Paulino et al., 2020], and solid-state fermentation has been used to increase its lycopene content [Sadh et al., 2018b]. Bananas are a rich source of several carotenoids, including lutein, α- and β-carotene, violaxanthin, auroxanthin, neoxanthin, isolutein α- and β-cryptoxanthin [B. Singh et al., 2016].

Astaxanthin is a common carotenoid, which is already the subject of much research due to its health benefits, including antioxidant, anti-ageing, and anti-inflammatory properties. It has a significant market value (estimated to reach US$427 million by 2022 [BCC Research, 2018b]), but approximately 95% of this is currently produced synthetically [Stachowiak and Szulc, 2021]. It has been extracted from crustacean waste by chemical processing and produced biologically by microbial fermentation/enzyme extraction [Sindhu et al., 2019], and production from wine lees is a potential sustainable production method as it only requires basic physical extraction methods (solid/liquid separations, distillations, evaporations) [Cortés et al., 2019]. However, existing commercial microbial production has faced challenges, including low productivity and prohibitive cost [Jiang et al., 2017].

3.2. *Dietary fibers*

Dietary fibers are food additives and are considered functional foods due to their health-promoting properties. They are reported to reduce blood cholesterol and sugar levels and improve cardiovascular health. Their consumption has been linked to decreased risk of hypertension, obesity, diabetes, cardiovascular disease, and some gastrointestinal disorders [Hussain et al., 2020]. Dietary fibers can be used as a food additive to boost the nutritional value of dairy products, beverages, flour products [Hussain et al., 2020], meat products [Ko et al., 2021], and bakery products [Campos Vega et al., 2020]. They are considered as a way to reduce malnutrition and hunger in developing countries [Torres-León et al., 2018].

The potential raw materials for dietary fibers are far-ranging. Dietary fibers include polysaccharides (except starch) such as arabinoxylan, β-glucan, arabinogalactan, cellulose [Campos Vega et al., 2020], pectin

[Ravindran and Jaiswal, 2016], and inulin [Fermoso et al., 2018]. They are common in cereal grains [Campos Vega et al., 2020] and fruit and vegetable wastes [Hussain et al., 2020; Torres-León et al., 2018]. Extraction/production methods include dry/wet processing, chemical, enzymatic, and microbial. To ensure the sustainability of these materials, green extraction methods are currently the subject of much research, including water, ethanol, or steam extraction, pulsed electric field or UAE, and high hydrostatic pressure-assisted extraction [Hussain et al., 2020].

One challenge in applying dietary fibers is that when combined into existing food products, they can alter the taste and texture of food as well as rheological characteristics and moisture content [Pop et al., 2021]. Several studies have tried to address this. Fibers added to dairy products (such as milk, yogurt, and ice cream) negatively impacted the smell and taste. Still, they improved the rheological characteristics, and dietary fibers used to fortify bakery products did not negatively affect taste and texture [Pop et al., 2021]. Soluble dietary fibers have also been used to improve the properties of beverages and drinks, such as altering the stability and viscosity [Hussain et al., 2020].

Many examples of dietary fibers from waste materials are already on the market. Regrained produces 'SuperGrain+', a flour made from by-products of the brewing process, Planetarians produce a flour from defatted sunflower seeds and the Coffee Cherry Company produces a flour from coffee bean fruit [Peters, 2019].

3.3. *Other Polysaccharides*

3.3.1. *Starch*

Starch is considered a green alternative material and has many potential applications. A carbohydrate composed of amylose and amylopectin, starch is produced from cereals and tubers (corn, cassava, and rice), but alternative sources are being explored as the market increases. Fruit waste is a significant source of starch, with kiwifruit, pineapple, mango, tropical fruits (litchi, jackfruit), avocado, apple, and banana waste all the research subject. The source of the starch affects its physiochemical properties;

therefore, this must be characterized to align with the intended application [Kringel et al., 2020].

3.3.2. *Chitosan*

Chitosan is a polysaccharide with one reactive amine and two reactive hydroxyl groups. It has many applications as a value-added chemical in food, pharmaceutical, and chemical industries due to its biodegradability, biocompatibility, and low toxicity. In addition, it has been reported to be antimicrobial, anti-cancerous, antioxidant, analgesic and benefit the cardiovascular system, making it suited to biomedical applications [Muthu et al., 2021]. As a derivative of chitin (the second most abundant polymer after cellulose), it is also widely present in food wastes [Ravindran and Jaiswal, 2016], particularly in shellfish waste, and many methods of extraction have been explored. However, acid/alkaline extraction is most common [Muthu et al., 2021].

3.4. *Proteins*

Proteins can be used as functional foods or nutritional supplements. They have reported health benefits ranging from antiviral and antimicrobial, prebiotic activity, and immunomodulation, contributing to cancer prevention, promoting liver health, and increasing satiety response. They have been used as additives for yoghurts, fermented beverages, supplementing bakery and confectionary products, and animal feeds [Torres-León et al., 2018].

Protein extraction from food waste can be achieved via many different substrates and processes. Whey protein is a widely available product made from liquid whey, a by-product of the cheese-making process. It is extracted and dried, forming a protein-rich powder but can also be produced by the enzyme-assisted valorization of cheese [P. Sharma et al., 2021]. Enzyme-assisted extraction of proteins has also been demonstrated from meat sources (poultry, bovine and porcine liver) as well as from cereal (quinoa and rice), oil crops (rapeseed meal), fish waste, and tea leaves using various enzymes (endopeptidases, aminopeptidases, carbohydrases, and dipeptidyl peptidases) [Kamal et al., 2021]. Proteins have also been isolated using UAE from rice, soybean, wheat germ, meat products, seeds, and spent grain [Kamal et al., 2021], as well as from oil cakes by solubilizing in alkali and isoelectric precipitating with acid, washing, and drying [Ancuţa and Sonia, 2020]. Other extraction techniques considered include MAE, hydrodynamic cavitation, supercritical extraction, pulsed electric field, biphasic flotation, and hybrid techniques [Kamal et al., 2021].

One commonly researched waste protein is collagen, as it has applications in the cosmetic, pharmaceutical, medical, and leather industries. As a fibrous protein, it occurs in nature, giving rigidity to connective tissue and, as such, can be extracted from animal and fish waste [Ravindran and Jaiswal, 2016]. However, bovine sources are rarely used due to allergy and disease concerns [Ahmed et al., 2020]. Collagen can be solubilized and extracted in acid and extracted using centrifugation and freeze-drying [Ravindran and Jaiswal, 2016].

4. Pigments/Colorants

Pigments (or colorants) are substances that give color to food and beverage, materials, cosmetics, paints, and pharmaceuticals. Historically many pigments have been extracted from natural sources, including plants (saffron, paprika, turmeric, and various flowers) or microbes (e.g., bacteria, algae, fungi, and yeasts) and insects but synthetic alternatives became popularized due to their high stability, low production costs, and concentrated form [M. Sharma et al., 2021]. As modern lifestyles seek more eco-friendly products, there is growing research interest in natural dyes, and sourcing these from food wastes enables them to compete economically with synthetic alternatives and reduce environmental toxicity [Sharmila et al., 2020].

A range of molecules can be considered as natural colorants. Carotenoids and anthocyanins as well as betalains and chlorophylls [M. Sharma et al., 2021] are potential colorants as they are responsible for the colors of plants (See Table 1). Pigments can be extracted using conventional techniques, such as Soxhlet extraction, organic/inorganic solvents, maceration, or distillation, as well as more environmental methods: green solvents, MAE, UAE, accelerated solvent extraction, pulsed electric field extraction, supercritical fluid extraction, and enzyme-assisted extraction [M. Sharma et al., 2021; Sharmila et al., 2020].

Table 1. Properties of natural colorants [M. Sharma et al., 2021; Sharmila et al., 2020].

Molecule Class	**Subclass**	**Color**	**Solubility**
Anthocyanins		Varies with hydroxyl groups and sugar structure	Hydrophilic
Betalains	Betacyanins and betaxanthin	Red-purple/orange	Hydrophilic
Carotenoids	Carotenes and xanthophylls	Red, yellow, or orange	Lipophilic
Chlorophyll		Green	Amphiphilic
Monascus metabolites	Monascin and ankaflavin	Yellow, orange, or red	
Tripyrrole	Prodigiosin	Red	

In addition to pigments naturally present in food waste, fermentation can increase their concentration. Prodigiosin is a class of tripyrrole antibiotic pigments that has been used in carbonated drinks, textiles, cosmetics, and dairy products. Production has been demonstrated by fermentation using several substrates; peanut powder, bagasse, kitchen waste, and corn cob powder [Sharmila et al., 2020]. Monascus fermented products are a secondary metabolite class with applications as both coloring and preservation agents in food and substrates such as jackfruit seeds, corn cobs, durian fruit seeds, orange processing wastes, and bakery wastes have all been considered [Sharmila et al., 2020].

One particularly interesting pigment derived from waste is astaxanthin. Astaxanthin is a common carotenoid with color properties that range from yellow to red. It is already in high demand as a colorant as it has uses in fish foods such as the coloration of salmon, trout, and shrimp meat. Chemical synthesis of astaxanthin is common in pharmaceutical, cosmetic, and food industries which use only natural astaxanthin. Therefore, a significant market exists for the natural product. Extraction from shellfish waste is possible using supercritical fluids [Stachowiak and

Szulc, 2021] and several microorganisms have been shown to produce astaxanthin and some have been converted into commercial processes.

Several examples of the practical application of these pigments exist. Anthocyanins present in pomegranates can give color to edible films, thereby reducing transparency and inhibiting the oxidation of packaged foods due to light exposure [Ko et al., 2021]. The application of pigments from food waste has also been applied commercially, including the 'Clean Colors' range by sustainable fashion brand Patagonia [Nayak et al., 2020] and Kaiku Living Color, which converts waste food to paint dye [Stjernsward, 2021].

5. Fragrances

Aromatic volatile compounds can improve the fragrance properties of products such as foods and beverages, cosmetics, domestic products, or perfume. Although many natural products are already used to produce fragrances, using waste offers economic advantages. Brands are already experimenting with fragrances produced from waste products, such as 'I Am Trash' from Ogilvy [Embleton, 2021]. Aromatic compounds, such as ketones, acids, alcohols, aldehydes, esters, or lactones (see Table 2), can be formed from food waste using physical, enzymatic or fermentation techniques [Sharmila et al., 2020].

Table 2. Examples of fragrance molecules from food waste

Molecule	Examples	Fragrance	Ref
Esters	Isoamyl acetate, ethyl esters, phenyl ethyl acetate and ethyl hexanoate	Sweet fruity and floral aromas	[Mantzouridou et al., 2015]
Terpenes	Limonene, cymene, pinene, camphor, menthol, carvone, terpineol	Aromas of flowers, fruits, seeds, leaves, woods, and roots	[Sharmila et al., 2020]
Lactones	6-Pentyl-α-pyrone	Fruity, buttery, creamy, sweet, or nutty aroma	[Sharmila et al., 2020]

Aldehydes	Vanillin and cinnamaldehyde	Fruity or floral aromas as well as oily or fatty fragrances	[Ladeira et al., 2010]
Thiols		Roasted coffee or meat aromas	[Sharmila et al., 2020]
Ketones		Fruity or buttery aromas	[Sharmila et al., 2020]

A range of food wastes and production methods have been explored for producing aromatic compounds. Orange peel [Mantzouridou et al., 2015] and rambutan seed fat [Khairy et al., 2018] have been used for the production of esters via solid-state fermentation, and the use of lipolytic enzymes to produce esters is also a promising area of research [Hadj Saadoun et al., 2021]. Lactones are extractable from food waste using microbial, lipid oxidation, or thermal treatments. Fermentation for lactone production has been reported for castor oil, sugarcane, and cassava bagasse [Sharmila et al., 2020]. Similarly, natural vanillin production has been reported by fermentation of coffee pulp, apple marc, maize bran, and maize fiber [Martău et al., 2021]. The production of aldehydes by microorganisms has also been demonstrated using carrot pomace, sugar beet pulp, wheat bran, corn cob, and apple pomace [Sharmila et al., 2020].

Limonene is one of the most common fragrance compounds. Conventionally it is distilled, or solvent extracted from the essential oil extract from citrus peels [Lin et al., 2013; Ozturk et al., 2019], but extraction from orange peel waste using bio-based solvents has been shown to outperform extraction using petrochemical solvents [Ozturk et al., 2019]. Limonene concentration in the waste can also be increased by microbial fermentation of waste such as olive mill wastes [Guneser et al., 2017] and waste cooking oil [Pang et al., 2019].

Future research may focus on aroma compounds not yet considered, such as thiols or ketones. Limited research has explored their presence in waste products, although grape marc has been reported to be rich in thiol precursors [Jelley et al., 2016]. Ketones have been observed to increase after enzyme hydrolysis from fish waste [Peinado et al., 2016] and being reported in various waste streams, but more research is required [Guneser et al., 2017; Khairy et al., 2018].

6. Surfactants

The use of synthesized surfactants has been declining since the 1960's [Lokesh et al., 2017] as consumers search for more environmental solutions. Surfactants are commonly found in home and personal care products [Lin et al., 2013]. They are important due to their emulsification, detergency, lubrication, and solubilization properties [Lokesh et al., 2017]. They can be derived from food waste, specifically, sugars, peptides, amino acids, fatty acids, and hydroxy acids, all of which offer good alternatives to fossil fuel-derived sodium lauryl sulphate [Lin et al., 2013] and sugarcane bagasse, orange peel, cassava waste, oil mill waste, animal wastes, and waste cooking oils have all been considered as substrates. Conversion strategies that appear promising for economization include solid-state fermentation, cell immobilization, yield-enhancing techniques (growth enhancers and nanoparticle use), and production with other value-adding materials (such as enzymes) [Ancuţa and Sonia, 2020; Singh et al., 2019].

Surfactants can also be produced from food waste by-products using chemical processes. For example, surfactants (pentose sugars combined with fatty alcohols) derived from agricultural residues such as wheat bran and straw have already been commercialized [Lin et al., 2013]. Alkyl polyglucosides possess foaming and wetting properties at ambient temperatures making them useful in detergents, cleaners, and personal care products. They are synthesized by Fischer glycosidation using plant-based fatty alcohols and a carbohydrate, such as agricultural residues. As this process has an environmental impact, the substrate must be carefully selected to ensure this offers an advantage over existing synthetics [Lokesh et al., 2017].

Microbial production of surfactants from food waste is also a growing area of research. So-called biosurfactants can be produced from various food wastes and can have diverse structures and functions [Singh et al., 2019]. Rhamnolipids, sophorolipids, trehalolipids are all examples of biosurfactants [Ancuţa and Sonia, 2020] with *Pseudomonas*, *Bacillus*, *Rhodococcus*, and *Candida* amongst the most common producers [Singh et al., 2019]. Biosurfactants are projected to have a market value of

US$5.52 billion by 2022 [Markets and Markets, 2017]. Still, recovery of these biosurfactants remains the critical challenge in developing an economically viable process and the production of biosurfactants is not as competitive as synthetic alternatives [Singh et al., 2019]. Therefore, the use of cheap substrates is essential to their commercialization.

Many companies have already introduced biosurfactants from renewable sources to the market, with the key manufacturers being Ecover, Jeneil Biotech, Evonik, and Biotensidon [Markets and Markets, 2017].

7. Bioplastics

Bioplastics are a growing area of research as a sustainable replacement for non-biodegradable plastics. Bioplastics can be categorized based on their structural polymer; starch or cellulose-based and aliphatic polyesters (polylactic acid (PLA), polyhydroxyalkanoates (PHAs), polybutylene succinate) are the main examples [Korte et al., 2021]. However, protein-based and fat-based (bio-enriched polyurethane, polyethylene monomers) plastics are also being researched [Mekonnen et al., 2016]. The bioplastic market is growing significantly and is expected to reach an estimated US$16.8 billion by 2030 [Ponnappan et al., 2021]. Many manufactures have already introduced bioplastics (specifically biopolymer coatings) to their products, including Cargill, Danimer Scientific, NatureWorks, Novamont, and EcoSynthetix [Ranganathan et al., 2020].

Properties of bioplastics vary with different polymers. Polylactic acid has high mechanical strength and stiffness, but brittle. PHAs exhibit many desirable properties such as strength and low moisture/oxygen permeability [Pérez et al., 2016]. Polyhydroxybutyrate has comparable properties to polyethylene and polypropylene, although it is stiffer and more fragile. It is generally well suited to food packaging or cosmetic product bottles [Rivero et al., 2017].

Many biopolymers can be produced by fermentation of carbon-rich food wastes. Polylactic acid is produced by bacterial fermentation of carbohydrates to first form lactic acid and then polymerized (by condensation, dehydration-condensation, or ring-opening polymerization)

[Rivero et al., 2017]. PHAs are commonly produced by fermentation and can be synthesized by various microorganisms as an energy reserve when carbon is present in excess [Pérez et al., 2016]. The high production costs of these materials can be prohibitive, so using food waste (glucose, sucrose, etc. or bread wastes) is a possible way to reduce these costs [Ravindran and Jaiswal, 2016; Lin et al., 2013].

Production of chitosan blend-based films has also been investigated for fresh food products due to its microbe-resistant, biocompatible, and biodegradable properties. Chitosan can be extracted from crustacean waste [Korte et al., 2021]. Chitosan-based materials have good mechanical properties (comparable to HDPE and LDPE) and selective permeability to carbon dioxide and oxygen.

Producing a bio-based plastic from protein sources requires effective modification as it is stiff and brittle due to extensive intermolecular interactions. Protein-based plastics have, however, been formulated from bone meal using plasticizers and denaturants into plant pots at a cost-competitive with petroleum-based plastics. Meat and chicken feathers have also been reported as being successfully converted to plastics. One major limitation of animal protein-based plastics is its sensitivity to humidity (except for keratin-based sources) [Mekonnen et al., 2016]. Protein isolates extracted from oil cakes (sunflower oil, pumpkin, soybean, cashew nut oil, rapeseed oil, and peanut oil) have also been used to produce biopolymers with varying success [Ancuţa and Sonia, 2020; Lin et al., 2013].

Although significant effort has been made into bio-based plastics, they still do not offer comparable properties and, therefore, level of protection as fossil-based plastics [Korte et al., 2021]. Research is ongoing to improve this, such as adding additives that can help give the films additional or improved properties. For example, the phenolic content of pomegranates improves the antimicrobial properties of bioplastics due to their ability to chelate carbohydrates, vitamins, and minerals, which makes them unavailable to bacteria [Ko et al., 2021].

More research is also required into the life cycle of bioplastics. One recent study highlighted the need to balance the environmental benefits of bioplastics against the increased risk of food spoilage. However, it also indicated that bioplastics diverted food waste from landfill to greener waste management strategies such as anaerobic digestion or composting, contributing to the circular economy [Kakadellis and Harris 2020].

8. Enzymes

The use of enzymes to perform chemical transformations is growing due to their sustainability and non-toxic properties and their selectivity and low energy requirements [R. Singh et al., 2016]. Due to the associated cost with enzyme production, a considerable proportion of which can be attributed to raw material procurement, food waste is increasingly studied as a possible starting material for their production. Generally, this is performed as solid-state fermentation, although yields can be improved by media optimization techniques or use of genetically superior enzymes. One challenge faced in enzyme production is the cost of enzyme isolation and purification [Ravindran and Jaiswal, 2016; Uçkun Kiran et al., 2014].

Lignocellulosic food waste is a popular choice for enzyme production as degrading complex structures into sugars requires oxidative enzymes, such as cellulase, lactase, amylase, xylanase, and phytase lipase [Ravindran and Jaiswal, 2016]. Various fruit and vegetable by-products have been analyzed as starting materials for lignocellulosic enzyme production, including banana, grape, apple tomato, mango, passion fruit, carrot, and potato [Uçkun Kiran et al., 2014]. Laccases have been produced by fermentation from agricultural wastes, such as sugarcane bagasse, wheat bran, rice straw brewers spent grain, and potato peels. They have applications in food and beverage, pulping, bleaching, environmental pollutants removal, and pharmaceuticals [Sadh et al., 2018b].

In addition to lignocellulosic waste, many other waste products have also been explored. Fishery waste has been used to produce food-grade microbial enzymes such as protease, lipase, chitinolytic, ligninolytic [Patel and Shukla, 2017], polyphenol oxidase, laccase, and xylanase [Nazzaro et al., 2018]. Bromelain, a mixture of protease enzymes from pineapple waste, has value as a meat tenderizer and application within brewing and baking and the leather industry for pre tanning and softening [Banerjee et al., 2018]. Pectinase has also been produced using agricultural wastes such as apple and grape pomace [Uçkun Kiran et al., 2014], orange peels, and corn husks using submerged/liquid fermentation [Sadh et al., 2018b]. Solid-state fermentation of oil cakes has been used to produce industrial enzymes such as protease, lipases, amylase, xylanase, glutaminase, inulase, asparaginase, and glucoamylase phytase [Ancuţa and Sonia, 2020]. Recovery of such enzymes is particularly advantageous as they can be integrated with other food waste valorization processes [Uçkun Kiran et al., 2014].

9. Textiles

The fashion industry is a significant producer of excess waste. In particular, non-recoverable materials are a significant challenge, and alternative materials are being developed to address this. New materials can be generated using food waste by extraction or fermentation (with or without pre-treatment) [Provin et al., 2021], and such biomaterials offer potential advantages over synthetic alternatives, the most significant of which is biodegradability [Ranganathan et al., 2020].

Several products are produced from recycled food waste, such as bacterial cellulose, which offers a sustainable leather alternative. Bacterial cellulose does not contain polymers usually found in cell walls (hemicellulose, lignin, pectin) and is safe in contact with human skin. Agro-industrial wastes are generally the chosen substrate, but kombucha, citrus waste, and sugar cane bagasse have also been used as starting materials. Microorganisms aerobically perform the production of bacterial cellulose, and by controlling the thickness of the cellulose film and drying, this can be used to generate a leather-like material. The low requirement for water and energy makes this process particularly attractive as a sustainable alternative [Provin et al., 2021].

Polylactic acid (PLA) is another example of a biomaterial. Generally, it is used to form bioplastics [Ranganathan et al., 2020], but it can also be used to form textiles. Its production has been documented from agricultural residues such as pineapple fibers and wheat straw/husks. Compared to synthetic synthesis, it can be combined with other polymers to create non-woven leather alternatives to improve sustainability [Hildebrandt et al., 2021].

Nylon-6 and Nylon-66 are examples of traditional petrochemical materials that can be synthesized from food waste instead. Food waste is converted to glucose, hydroxymethylfurfural, and levulinic acid, then converted to the building blocks (adipic acid and hexamethylenediamine or ε-caprolactam) of nylon-66 and nylon-6, respectively. Several food wastes substrates can produce the base chemicals, including rice, bread crusts, fruit or vegetable waste, or even mixed wastes. Unfortunately, the waste-produced nylon cannot compete economically with petroleum-synthesized nylon, primarily due to lack of commercialization of the extraction of compounds from food waste. In addition, the choice of catalyst and solvents used in the process must also be considered for this to truly be regarded as sustainable [Lee et al., 2019].

Many products have already been introduced to the market which use waste food as a starting material. Piñatex, a biomaterial from cellulose and pineapple leaves, is being used as a leather alternative in several luxury brands (Bourgeois Boheme, and Hugo Boss) and Orange Fiber (from orange peels) has been used in H&M's Conscious collection. In addition, footwear, handbags, and clothing are also being produced from apple waste (happy genie), coffee grounds, corn waste, and pineapple fibers (Nat2™), and fish and eel skin waste (KHOGY) [Nayak et al., 2020].

10. Challenges & Limitations

Although the use of food waste to produce value-added products which can replace synthetic chemicals or processes which rely on petrochemicals is a promising step towards the circular economy, commercialization and implementation still face many challenges. These range from the quality and location of the substrate to process design and operation, and the current standards and regulations. The overall challenge of making these processes economically competitive is also something that researchers and industry must consider.

Seasonal and geographical variability is a complex challenge [P. Sharma et al., 2021]; many factors can influence foods' nutritional composition, such as seasons, maturity, cultivar, location, climate, and farming practices [Campos Vega et al., 2020]. Similarly, the transportation of the food waste for processing can contribute to the environmental footprint and overall cost; therefore, it is important to consider how the regionally specific wastes can serve their local markets [Lin et al., 2013].

The design and operation of valorization processes is another challenge that must be addressed. Despite the significant research done at laboratory scale, scale-up of these processes is limited [P. Sharma et al., 2021; Provin et al., 2021]. The fundamental challenges associated with scale-up include changes in thermodynamics, chemical equilibrium, and physical changes, which can affect material properties. In addition, changes in material and services requirements affect the operational costs and profitability [P. Sharma et al., 2021].

Integrated processes are needed for extracting full value and therefore full economic potential from food waste, such as a biorefinery approach. By coupling together value-adding processes, operators can first extract high-value products before sending them to a catch-all technology, such as composting or anaerobic digestion to maximize economic opportunities. The challenge then lies in the successful extraction of a particular compound, which can be challenging to do without damaging the target molecule while maintaining environmental benefits. The use of green techniques/solvents and incorporation of material/solvent recovery are essential to success; green extraction techniques such as MAE, UAE, supercritical fluid extraction, and deep eutectic solvents are all popular choices that come with an expense [P. Sharma et al., 2021]

Where synthetic chemicals can be derived from petrochemicals, a huge challenge exists in making alternatives from food waste equivalent and economically competitive [Lee et al., 2019]. Although many processes have the potential to compete economically with synthetics, facility size and product portfolio are considerable factors in success. Very few of the processes developed have conducted a techno-economic analysis [Engelberth, 2020].

Products from food waste, particularly those meant for human consumption, must meet the requirements of existing legislation. The purpose of the legislation is to ensure product safety, particularly for products that are designed for consumption. Concerns are similar to those present in general food production, such as residual pesticides, mycotoxins, microbial or enzyme contamination, pathogens, metal contamination, and biogenic amine presence. Pasteurization, sterilization (by heat or radiation), and separation techniques (such as membrane and filtration techniques) can all be deployed to address these problems [Pop et al., 2021], but this increases the energetic and economic cost of processes.

Finally, caution is needed for marketing and consumption of these waste-generated products. Simply including one waste-generated material does not make a product sustainable and could lead to greenwashing. Therefore, a holistic approach to sustainability is required, and tools such as lifecycle assessment should be utilized to evaluate sustainability accurately.

11. Conclusion & Future Perspective

The opportunity to valorize food waste offers a lot of promise. By monetizing this nutrient-rich resource, we can reduce the quantity sent to landfills, thereby reducing greenhouse gas release and potentially displacing synthetic production. The compounds in food waste have applications across many sectors, from food and beverage, cosmetics, fine chemicals, and health and wellbeing.

The potential for high-value chemicals from food waste is far-ranging. There are few other waste resources that have the diversity and complexity of food waste and extraction, or production of food additives, nutraceuticals, supplements, and functional foods are all significant areas of interest due to the existing and sizeable markets for these products. Bioplastics and textiles are another focus area, and strong market drivers exist to reduce our reliance on traditional plastics and synthetic materials. In addition to these opportunities, food waste-derived pigments, fragrances, and other fine chemicals have potential applications across a range of sectors. Overcoming the associated techno-economic barriers is essential for the commercialization of these products.

Despite the opportunities, many challenges and limitations need to be addressed. Processes at the laboratory scale face the technological and operational challenges of scale-up. At the same time, those at commercialization must navigate any existing regulation or legislation as well as logistical challenges. The use of tools such as techno-economic assessments and life cycle analysis must be used to ensure new products are priced realistically for consumers and fulfill their remit to be more sustainable than synthetic production. It is also likely that valorizing food waste will generate redundant materials. Therefore, coupling processes or combining with catch-all technologies, such as anaerobic digestion or composting by adopting a biorefinery approach, is critical to extract full value from these materials. Doing so will minimize costs, maximize profits and help move towards a more sustainable future.

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