Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing

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Abstract

Processing of food is linked to unavoidable and inedible food waste that, despite efforts to minimize waste, will persevere. It nevertheless represents a stable feedstock for the future bioeconomy value chains and products. This study presents a systematic review of 149 examples from the scientific literature using inedible, unavoidable food residues and wastes for the production of value-added bio-based compounds that could substitute synthetic chemicals production. The main high-value products investigated are organic acids, bioplastics, colorants, enzymes and other platform chemicals. We found 44 examples of acid production with high variability in output (from 43 to 640 g kg^{-1}waste), 9 examples of bioplastics (from 0.28 to 49 g L^{-1}), 26 examples related to colorants (from 0.04 to more than 400 mg per 100g), 22 cases of enzyme production (from 6.8 to 34,000 Ug^{-1}), 4 examples of protein (23.6 to 38.5 %wt. DM) and 44 cases of other high-value molecules such as pectin and single cell oils. Our findings highlight fermentation as a key technology for the valorization of the studied feedstock, with 76 examples out of the 149 reviewed. The review process also uncovered important limitations related to the lack of standardized food waste definitions, a barrier that is discussed and for which solutions are proposed. At the light of our findings, we further proposed guiding criteria towards the sustainable development of future biorefineries based on food waste. This work touches upon several Sustainable Development Goals, in particular goals 8.2, 9.5, and 12.3.

Keywords: food waste definition, circular economy, circular bioeconomy, bioplastic, platform chemicals, enzyme

1. Introduction

In the last decade, it became clear that the food sector (i.e. activities related to producing and consuming food) is a large contributor to global warming (Vermeulen et al., 2012). Besides production-side mitigation options targeting improvements of the primary production (i.e. agriculture), or demand-side measures targeting diets, several studies pinpoint the reduction of food waste as a readily accessible measure to significantly reduce the environmental impacts from the food sector (Foley et al., 2011; Hiç et al., 2016; Springmann et al., 2018). In fact, FAO (2011) highlighted that 1.3 billion tonnes of edible food is lost or wasted globally each year. Recently, the project FUSIONS reported that the EU-28 countries account for 88 million tonnes of inedible and edible food waste per year (Stenmarck et al., 2016). It is evident that the food sector needs to undergo important changes, both in terms of improved supply chains and food waste valorization, in order to achieve European and global sustainability ambitions. More precisely, the United Nations (UN) Sustainable Development Goal (SDG) 12.3 targets "the reduction of the food losses along production and supply chains by 2030" (UN, 2016) and EU-28 target to decrease 30 % of the food waste by 2025 in manufacturing, retail/distribution, food service/hospitality sectors as well as households (EC, 2014). These aims to decrease large quantities of food waste coupled with its documented valuable content attracted attention from both the industry and the scientific community (Schieber, 2017). Upon proper design, capturing and re-circulating unavoidable, inedible food waste streams and residues as the new products within the economy could contribute to the sustainability growth goals listed in the European Bioeconomy Strategy, namely: i. Food security, ii. Managing natural resources sustainably, iii. Reducing dependence on non-renewable resources iv. Mitigating (and adapting to) climate change; v. Creating jobs and maintaining EU competitiveness (EC, 2018). Existing studies of food waste biorefineries have highlighted an untapped potential for the extraction of valuable biomolecules leading to high value compounds from biopesticides, bioplastics, and enzymes to antioxidants, proteins, nutraceuticals and colorants (Vea, Romeo and Thomsen, 2018; Mirabella, Castellani and Sala, 2014; Machmudah *et al.*, 2012; Galanakis, 2012).

Food waste and food losses are generated throughout the whole food supply chain from farm to fork. It accounts for the biomass intended for human consumption that is discarded, lost, degraded or contaminated. However, addressing food waste valorization alternatives is challenged by definitional differences influencing the qualitative and quantitative evaluation of these alternatives. This definitional challenge has also been pointed out in previous studies (Parfitt et al., 2010; Xue et al., 2017), as well as in the recent EU Bioeconomy Strategy (EC, 2018). First, there is a distinction to make between food loss and food waste, the loss being “the decrease in quantity or quality of food” and waste the “food that has been left to spoil or expire as a result of negligence by the actor (predominantly, but not exclusively, the final consumer)” (FAO, 2014). FAO further defines food loss as occurring during the production, post-harvest and processing stages and food waste as occurring during the retail and final consumption stages (FAO, 2011). This definition excludes, both for food loss and food waste, the waste intended for feed as well as parts of biomass that are not edible, implying that streams such as bones may not be accounted for in the waste statistics, as well as the inedible post-consumption streams, such as cooking oil or coffee grounds.

A distinction between edible and inedible food wastes is often made (Xue et al., 2017). The EU project FUSIONS (Östergren et al., 2014) and the “Food Loss and Waste Accounting and Reporting Standard”, also known as the FLW Protocol (WRI, 2016), include inedible parts of food in their definitions of food waste. Both exclude biomass not intended for human consumption, such as feed and biomass intentionally produced for energy and industrial use, while FUSIONS also leaves out all pre-harvest (not mature) biomass. Further differentiation of waste types are avoidable, unavoidable and possibly avoidable (WRAP, 2008). WRAP (2008) defines unavoidable wastes as inedible parts of post-harvest food like fruit cores, peelings, and bones while possibly avoidable can include peels from potato or carrot as it can be eaten or used in processing, depending on the process specifics, consumer preference and regional regulations.

Using food waste for the production of high-value products is foreseen to increase its share in the global market. Bioeconomy is projected to grow rapidly in the future, having generated 2.2 trillion euros in Europe with 18.6 million people employed in 2014 (Ronzon et al., 2017). Bio-based chemicals are expected to reach a share of 15% of the global chemical market by 2025 (Alexandri and Venus, 2017), and to generate 102.76 US$ billion in 2022 (Zion Market Research, 2017).

However, incorporating food waste into the bioeconomy poses the risk of rebound effects encouraging waste generation (Zink and Geyer, 2017). Therefore, this review focuses on inedible, unavoidable food waste that can be partly minimized, but not prevented (see above definition from WRAP 2008). This will, from this point onwards, be referred to as inedible, unavoidable food waste (IUFW). It further focuses on IUFW stemming from food processing operations, as this can generate important and accessible streams in comparison to e.g. waste from the post-consumption stage. These types of wastage are sometimes referred to as by-products or residue streams. It should also be highlighted that in the EU, post-processing streams that leave supply chains are often considered as inedible as residue/waste and are often not eligible for direct human consumption (Östergren et al., 2014). Even though detailed quantifications of food waste from the processing sector, at a variety of geographical scales, have been performed and are still on-going (e.g. Parfitt et al., 2010; Tonini, Hamelin and Astrup, 2016; Panoutsou, Eleftheriadis and Nikolaou, 2009), little efforts have attempted to explore and compile the available knowledge on optimal transformation pathways for inedible food waste such as pits, fruit core or peels. The capture and reuse of the residual side streams from the food processing industry and the waste streams prior to moving down the waste hierarchy (landfilling, incineration) is paramount for the circular economy and a key focus for the future research and technology promotion.

In order to bridge this gap, and supply insights for future food waste biorefinery investments, the overall aim of this study is to provide a quantified overview of the emerging bioconversion processes using the IUFW fraction from the food processing industry, and the ability of these processes to supply high-value products to the market.

2. Method

2.1 Definitions

The two most widely used food waste definitions in Europe are those of the FUSIONS project (applied in the EU-28 countries) (Östergren et al., 2014), and of the FLW Protocol (WRI, 2016). The EU project FUSIONS defined food waste as “food and inedible parts of food removed from the food supply chain”, where food has or had the potential to be eaten. This encompasses any food waste that has been lost or diverted from the food supply chain, excluding pre-harvest crops and pre-slaughtering animals, which are labelled as “not mature”. The food waste may be disposed or recovered through a variety of technologies/techniques, including “composting, crops ploughed in/not harvested, anaerobic digestion, bioenergy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea” (Östergren et al., 2014).

While the FLW Protocol definition also includes inedible parts of food, it expands the end-of-life treatment by including “bio-based materials/biochemical processing, controlled combustion, land application, and refuse/discard/litter” (WRI, 2016). The boundaries of the FUSIONS and FLW Protocol exclude the biomass not directly intended for human consumption, such as crops intentionally grown for bioenergy, animal feed, and industrial use.

The FLW Protocol is supported by a steering Committee involving institutions such as the World Resources Institute (WRI), the UK Waste and Resources Action Programme (WRAP), the FUSIONS project, the United Nations Environment Programme (UNEP) among others (FWL, 2013).

In this study, we build on the definition of the FLW Protocol, i.e. inedible and unavoidable parts of processed food items are “food waste”, even if used for the production of biochemicals and biomaterials. We propose a slight adaptation by including animals and fish dying prior to leaving the farm (“non-mature dead animals and fish” in FUSIONS) as “food waste”, as proposed in Hartikainen *et al.*, (2018). The definition boundary considered in this study is represented in Figure 1. It should also be highlighted that this review does not distinguish between food loss and waste due to a lack of transparency and inconsistencies (e.g. using different or overlapping definitions) found in the reviewed literature. In scientific literature, authors often do not clearly define the difference between food loss and waste or account for both of them aggregated.

2.2 The scope of the review and data treatment

We reviewed quantitative studies focusing on the use of unavoidable inedible waste streams from the food processing industry that were used for the production of higher-value products. The key words applied to the search engine were “**biorefinery**”, “**food waste**”, and **“value-added product”.** These keywords were applied with the Boolean operator “AND” into Google Scholar using the multi-character wildcard “*” search for five targeted bio-based products, namely: **acids*, bioplastics*, colorants***, **enzymes*, protein***. The keywords were selected based on the pre-screening of the literature using different keywords variations. The five above-mentioned bio-based products for wildcard search were chosen as the most mentioned ones in the pre-screened literature (as detailed below), and were kept broad (rather than specific with terms such as e.g. “chitin”, “acetone” or “pectin”) in order to generate broader search results. Acids, colorants, enzymes and proteins were chosen based on two influential food waste reviews; the highly cited studies of Mirabella et al. (2014) (colorants mentioned as lycopene, and β-carotene) and Galanakis (2012), respectively. Bioplastics were selected based on Uçkun Kiran et al. (2015) and their foreseen importance in the future bioeconomy (EC, 2018; Ronzon et al., 2017). The literature search deliberately excluded output products such as bioenergy production and energy carriers, as well as lower-value products such as organic fertilizers as these have been addressed and explored many times in the literature.

The review method applied herein was inspired by the PRISMA framework for systematic reviews and meta-analysis (see Supporting Information 1). Firstly, the review only considered the literature published in English after 2010. Cases that included input biomass deriving from soybean and palm tree (*Elaeis*) were also excluded, as these crops are drivers for tropical deforestation (West *et al.*, 2014; Henders, Persson and Kastner, 2015), itself representing ca. 10% of global annual CO_2 emissions (Le Quéré et al., 2018; Pan et al., 2011).

The initial search yielded 358 hits; after applying the above-mentioned selection criteria (English, after 2010, no soy or palm) and removing duplicates, only 81 scientific articles and one PhD thesis remained. In the second stage, the abstract and methods of these 81 studies were screened. Those judged not to be related to the present research were discarded from further examination. After this step, a total of 31 articles were selected to be included in the review (SI1). As this review endeavors to report the data on production flows (linking the input and selected output products of waste-based biorefineries), original references were included when the quantified yield and/or productivity were lacking. This especially applied for colorants, for which no quantified output flows were reported in the selected 31 articles. For these additional references, the same selection criteria as above-mentioned were applied. As a result of this step, the final count of scientific literature to review was 53 articles, and one PhD thesis (SI1). Out of these, 37 reported quantitative data of laboratory experiments; these were included in Tables 1-6 and Supporting Information 2 (SI2).

3. Results

Out of the 37 studies with quantitative data, we identified five studies related to the conversion of inedible food waste to bio-based organic acids, six related to bioplastics, eleven related to colorants, six related to enzymes, two related to proteins and eleven included other high-value products (pectin, essential oils etc.).

Figure 1 Supply chain and definition boundary. The dotted line indicates the definition boundary of food waste. The top part outside of the boundary is considered as agricultural waste. The first column to the left shows the stages of the food chain. The second column represents the different activities, within the food chain stages, that can generate waste. The last column shows the fate of food waste. The terminology is taken in accordance to the FUSIONS project and the FLW protocol.

The reviewed studies covered a broad spectrum of food processing waste, including a variety of peels (potato, tomato, kiwi, orange, banana, etc.), plant biomass (tomato, barley hulls), spent coffee grounds, and several pomace wastes (apple, tomato, olive, grape), among the most prominent. This section provides a general overview of the quantified input and output flows from the reviewed literature, linking IUFW to the targeted high-value products. The full detailed results are available in SI2.

It can be argued that some of the wastes included are edible (and thus partly avoidable; e.g. tomato and potato peels), but their final fate is in many ways dependent upon the final consumer's preferences and therefore differs from case to case. However, it should be highlighted that this review only focusses on processing waste; this waste being generated in large amounts with homogeneous quality and often regarded as inedible for human consumption. Retail and consumption (inedible) food waste is outside the scope of this study.

3.1 Bio-based organic acids

Bio-based organic acids, like their fossil alternative, are platform chemicals (Takkellapati et al., 2018) that have many uses and can be further refined as bioplastics and other high-value products. Fermentation processes are generally preferred for acid production from food waste and food residues as they provide a suitable substrate for the acid-producing fungi and bacteria, given their high moisture content. Feedstock with moisture content from 60% to 85% is favorable for bacteria while fungi require moisture content around 40% to 60% (Abu Yazid, 2017). Using IUFW as a substrate for acid production offers many advantages such as cheap substrates with suitable carbohydrate content for microbial fermentation that does not require extensive physicochemical and enzymatic pre-treatment, as in the case of starchy and lignocellulosic biomasses (Uçkun Kiran et al., 2015). During fermentation, glucose and sucrose are metabolized by bacteria, such as lactic acid bacteria, into lactic acid (LA) (Uçkun Kiran et al., 2015).

Lactic acid (LA) is a platform chemical that has been used for many years in various industries from pharmaceutical to leather and textile industries. It contains both carboxylic and hydroxyl groups and therefore can be further transformed to many chemicals, such as acrylic acid, 1,2-propanediol and others (Uçkun Kiran et al., 2015). Bio-based LA production has been already established in China, USA (NatureWorks) and Europe (Corbion, Total-Corbion, Galactic) (Alexandri and Venus, 2017). Uçkun Kiran, Trzcinski and Liu (2015) reported lab-scale productivity as high as 5.41 g lactic acid L^{-1} h^{-1} from apple pomace.

Succinic acid is one of the most significant platform chemicals and its market has been constantly growing as shown in IEA Bioenergy (2012). Its production from bio-based feedstock is competitive with the petrochemical-based production, with a market value over 108 million USD (2013) for bio-based and 100 million USD for petroleum-based productions (Alexandri and Venus, 2017). It is commercially produced from plant-based substrates by the companies Myriant (corn glucose), Succinity and Reverdia (starch-based sugars), among others (Mika et al., 2018). There are natural microbial strains that are capable to produce up to 70 g succinic acid per liter from lignocellulosic substrates (Mika et al., 2018), the global market was projected to be about 90,000 tons for the year 2015 (IEA Bioenergy, 2012). A more recent example includes Li et al. (2018) who were able to produce 0.46 g g^{-1} of succinic acid from fruit and vegetable hydrolysate in batch treatment fermentation with engineered *Yarrowia lipolytica*. Further, 0.77 $g.g^{-1}$ of succinic acid per total sugar from citrus peels was achieved by microbial fermentation with *Actinobacillus succinogenes* (Patsalou et al., 2017).

Citric acid (CA), similarly to succinic and lactic acid, is widely used in the production of materials and chemicals of numerous industries. It is becoming popular in the biomedicine sector for the biopolymer production, which is further used in nano-medicine, but also as an active compound in drug delivery. Due to this recent development, the global production of citric acid is rising with 3.7% annual growth (Cavallo et al., 2017), and it was reported to be 1.4 million tons in 2013 (Uçkun Kiran et al., 2015). Another high-value acid is levulinic acid with increasing use as a food additive and in pharmaceutical applications, with a selling price between 1000 and 3000 USD per ton (Mika et al., 2018).

Table 1 provides several examples of organic acid production from food waste and food residues. The extensive review of inventoried data can be found in the Supporting Information (SI2), with 44 examples ranging from 43 g to 640 g bio-based acid kg^{-1} IUFW.

Table 1 Organic acid production from food waste and food residues.

Feedstock	**Output Product**	**Technology/Processes**	**Note**	**Productivity/yield**	**Reference**
Apple pomace	Lactic acid	Fermentation with *Lactobacillus rhamnosus* ATCC9596	Dried, ground, made in packed bed reactor	0.465 g/ g waste, 5.41 g /L/h	(Uçkun Kiran et al., 2015)
Apple pomace waste	Citric acid	Fermentation via *Aspergillus niger* NRRL 567	fermentation was optimized by RSM[b] method	0.45 g/g	(Yang et al., 2015)
Banana peel [c]	Citric acid	SSF[a] with 1% (v/w) methanol and 10 ppm of copper ions	72 h fermentation	82 g/kg	(Abu Yazid, 2017)
Date waste	Citric acid	Fermentation with *Aspergillus niger* ATCC16404	Heated, filtered, decanted 3 L reactor with 1L working vol.	0.76 g/g sugar	(Uçkun Kiran et al., 2015)
Orange peel	Citric acid	3-fold SSF[a] with *Aspergillus niger*		193.2 g/kg	(Abu Yazid, 2017)
Tomato plant waste	Levulinic Acid	10 wt % concentration of feedstock, catalyst HCl 1 M, T is 225 °C, 2 min		Yield 63 %, 45 wt%	(Mika et al., 2018)
Waste bread [c]	Succinic acid	Fermentation with *Actinobacillus succinogenes* ATCC 55618	Ground, dried, limonene separation, 125 mL bottles, anaerobic conditions	0.55 g/g waste, 1.16 g/g sugar, 1.12 g/L/h	(Uçkun Kiran et al., 2015)

[a] SSF: solid-state fermentation; [b] RSM: response surface methodology; [c] from processing, but could also occur on the consumption stage

3.2 Bioplastics

The global production of plastics is dominated by thermoplastics and thermosetting plastics obtained from crude oil refining or natural gas. The utilization of organic wastes for bioplastics production can play important role in transitioning from a linear economy, which uses mainly finite resources. For example, plastic packaging uses 98% oil-based raw feedstock while recycling uses only 5% raw material. Further, the global plastic packaging production consumes 6% of the global annual oil supply which is approximately equal to the world's oil consumption by the aviation sector (Kaur et al., 2018).

There has been an increase in bioplastic demand, which was facilitated with accessible cheap feedstock from the food and agricultural sector. This is enhanced by raising consumer concerns about marine litter and overall fossil resources consumption. There are a variety of examples and potentials for food waste-based bioplastics. For instance, chicken feathers have been studied for keratin-based thermosetting plastics, as keratin is a strong natural polymer (Tesfaye et al., 2017). A thermosetting plastic, similarly to epoxy resins, cannot be re-melted once hardened, as opposed to thermoplastics like polystyrene, polyethylene and others, which can be reshaped when heated. Therefore, the base feedstock for thermosetting plastic should be carefully chosen as the options for recycling are limited. Starchy and/or sugary substrates, like maize and sugarcane, are suitable for thermoplastics production with high recycling potential (Tesfaye et al., 2017).

Polyhydroxyalkanoates (PHAs) are plastic-like materials that can be made from zero to low-value feedstock like food waste. They are biodegradable while having physical and chemical characteristics similar to their conventional fossil alternatives (Zhu et al., 2010). Using waste material and residues is foreseen to decrease the operational costs of bio-based plastics, which is the main bottleneck in a large scale commercial PHA production (Ravindran and Jaiswal, 2016). PHAs are especially attractive as a multi-purpose material since they have good elastomeric properties (Alexandri and Venus, 2017), and are degradable in soil, compost and oceanic sediment (Roland-Holst et al., 2013). The biodegradability is dependent upon various factors, ranging from microorganisms present in the environment (Ciesielski et al., 2015), to exposed surface areas, pH and temperature (Roland-Holst et al., 2013). Queiroz and Collares-Queiroz (2009) reported degradation of biobased PHAs in 45 to 56 days.

PHA is used in packaging films, bags, containers, coatings and more recently in razor handles, bottles and cups (Roland-Holst et al., 2013). Poly-3-hydroxybutyrate (PHB), a type of PHAs, is a very versatile plastic that can be used for flexible and sturdy products through crystallinity manipulation (Roland-Holst et al., 2013).

PHAs are produced by microorganisms that can thrive on various wastes, such as olive pomace (Waller et al., 2012) rapeseed meal hydrolysates, sugarcane bagasse hydrolysates, whey and other food derived waste streams (Alexandri and Venus, 2017). Obruca *et al.* (2015) reported productivity of 49.4 g PHA L^{-1} using spent coffee grounds via the microorganism *Cupriavidus necator* (additional data on this experiment are reported in Table 2 and SI 2). Table 2 provides various examples of bioplastic production from food wastes, with additional cases included in SI2.

The industry has been attracted to the possibility to use food waste for biopolymer production. Bio-on, for example, is an Italian company using food and agricultural residues to produce PHA. Some feedstock used include wine marc (stalks, seeds and peels residuals from the wine production process), animal fat, fruits, vegetables, potatoes, sugar cane and sugar beet. Their technology has production capacities ranging from 5 and 10 thousand tons of PHA per year (bio-on.it, 2018).

The cheaper alternative of compostable (and degradable) thermoplastic to PHA is polylactic acid (PLA). PHA is sometimes added to PLA to increase its resistance (Alexandri and Venus, 2017). Fermentation of lactic acid (see section 3.1) is often applied to produce PLA. However, the market price of PLA is still considerably higher than the conventional fossil-based plastics, such as polyethylene terephthalate (PET) (Roland-Holst *et al.*, 2013; it should be highlighted that with the use of bio-based ethanol, PET can also be bio-based, e.g. Tsiropoulos et al., 2015). PLA is used in many plastic products such as plant pots, food packaging, beverage containers, disposable foodservice tableware and disposable napkins (Roland-Holst et al., 2013). It is also used as a common base material for 3D printing (via the Fused Deposition Modeling technology; FDM) such as PLA based filaments (Cicala et al., 2018).

Table 2 Bioplastic production from food waste and food residue.

Feedstock	Output Product	Technology/Processes	Note	Productivity/yield	Reference
Olive pomace	PHA	Anaerobic fermentation in a sequencing batch fermenter (SBF), centrifuge, buffer pretreatment, fermentation via mixed culture from activated sludge	The frozen olive pomace was thawed and diluted in deionized water at concentrations between 75 and 300 g/L olive pomace. The solution was mixed on a stir plate for 10 min; then filtered through a 1-mm sieve bench-scale sequencing batch reactors (SBRs)	HRT 1 day, SRT 6 days fermentate, productivity: 0.042 g/L/day, yield: 0.28 g/L fermentate eq. 0.84 g/L	(Waller et al., 2012)
Potato waste	PHB	Fermentation with *Alcaligenes eutrophus*		0.37 g/g sugar, 0.77 g/g cell	(Uçkun Kiran et al., 2015)
Spent coffee grounds	PHA	Fermentation via *Cupriavidus necator* H16	Oil extraction from ca. 15% of biomass. Highest yield and productivity obtained from the fed-batch fermenter.	49.4 g/L; 0.82 g/g of oil	(Obruca et al., 2015)
Rapeseed oil waste	PHA	*Pseudomonas sp.* Gl01	Fed-batch treatment	PHA content: 44%, yield: 2 g/L	(Ciesielski et al., 2015)
Wheat milling by-product	PHB	Fermentation with *Wautersia eutropha* NCIMB 11599	Enzymatic, saccharification & liquefaction; Bioreactor with 1 L working volume.	0.3 g/g waste, 0.47 g/g sugar, 0.93 g/g cell, 0.9 g/L/h	(Uçkun Kiran et al., 2015)
Wheat straw hydrolysate	P(3HB-co-3HV)	Fermentation via *Burkholderia sacchari* DSM 17165	Ground wheat straw using the AFEX (The Ammonia Freeze Explosion) process as pretreatment followed by enzymatic hydrolysis of the cellulose and hemicellulose fractions. Fed-batch for 61 hours.	1.6 g/L; 0.22 g PHB/ g total sugar consumed	(Cesário et al., 2014)
Wine lees (WL)	P(3HB-co-3HV)	WL hydrolysates and crude glycerol as nutrient and carbon source for fermentation via bacterial strain *Cupriavidus necator* DSM 7237	WL was initially fractionated for the production of antioxidants, tartrate and ethanol and the remaining stream was used for fermentation. Hydrolysis with enzymes from SSF.	30.1 g/L; 0.56 h/L/h (from initial 700mg/L FAN (Free Amino Nitrogen)	(Dimou et al., 2015)

3.3 Bio-based colorants

The pomace side stream from the processing of fruits is a good source of carotenoids, especially in the case of citrus residues. Carotenoids have many health benefits, such as antioxidant activity, enhancement of the immune system, decreased risk of cancer, cardiovascular diseases and muscular degeneration, they have a neuroprotective effect and help with age-related muscular degeneration (Freitas et al., 2015; Strati and Oreopoulou, 2014; Mustafa et al., 2012). They are often used as natural dyes (Papaioannou et al., 2016), food colorants (Martins et al., 2016) and dietary supplement (Guerin et al., 2003) due to their health improving properties. Lycopene and β-carotene are the most common carotenoids extracted from fruits. β-carotene can be found in fruits like oranges (Moraes et al., 2013) and vegetables like carrots with concentrations as high as 419.3 mg per 100 g (Mustafa et al., 2012).

The strongest antioxidant amongst carotenoids is lycopene, with very high content in tomatoes (Urbonaviciene et al., 2012), and concentrations up to 410.53 mg kg^{-1} (Kehili et al., 2016). Papaioannou et al. (2016) provided an overview of lycopene downstream processing, and its bioavailability in tomatoes, while Strati and Oreopoulou (2014) summarized the available extraction methods of lycopene and other carotenoids from tomato processing side streams. More examples are provided in SI2.

β- Carotene is the precursor of vitamin A, which is essential in several body systems like vision, cell differentiation, synthesis of glycoprotein, and growth and development of bones. It also helps to ameliorate age-related muscular degeneration and decreases cataract formation (Dutta et al., 2005). Due to these benefits, carotenoids have been used in cosmetics (Machmudah et al., 2012). Besides their health benefits, they also help to extend the shelf life of food. As a colorants, lycopene and β-carotene of natural origin are accepted as natural dyes for various food products (Strati and Oreopoulou, 2014). The global market for carotenoids was 1.2 billion

USD in 2015 (Strati and Oreopoulou, 2014) and is expected to rise to 1.4 billion USD, with β-carotene worth 334 million USD in 2018 (BCC Research, 2011).

Table 3 Colorant production from food waste and food residue.

Feedstock	**Output Product**	**Technology/Processes**	**Note**	**Productivity /yield**	**Reference**
Blanched tomato peel	β-carotene	Solvent extraction with hexane. Stability of colorant was analyzed by high-performance liquid chromatography (HPLC).	Waste from greenhouses. Blanched tomatoes have approximately 2 times more β-carotene than in non-blanched tomato peels.	24.7 mg/100g	(Urbonaviciene et al., 2012)
Carrot pomace	β-carotene	Pressurized Hot Ethanol Extraction. HPLC-DAD (Diode-Array Detection) and HPLC-UV (Ultraviolet Detection) for carotenoid content.	Soft soggy carrots and orange carrots. Extraction time (2–10 min) and the temperature (60–180 °C). Highest yields at achieved at 60 °C.	Soggy carrots 22.9 mg/100g ; orange carrots 419.3 mg/100 g	(Mustafa et al., 2012)
Grape pomace	Anthocyanins	Accelerated solvent extraction (ASE). Anthocyanins quantified by HPLC-MS (Mass Spectrometry)	Freeze-dried, ground Sunbelt red grape pomace. Highest yields achieved at 100 °C.	450 mg/100 g of DW	(Monrad et al., 2010)
Orange peel	β-carotene	Acetone extraction	Carotenoids extracted with chilled acetone, saponified overnight with 10 g/L KOH in a methanol solution at room T. Then washed to remove the alkali and concentrated in a rotary evaporator (T < 35°C)	1.21 mg/100 g DM	(Moraes et al., 2013)
Pineapple	β-carotene	UV-C radiation. Extraction using several solvents, e.g. ethanol and hexane.	UV-C radiation in closed wooden coated box (28cm height×46cm width×52cm length), radiation dose of 1.6 kJ/m2, 3 min per side.	rind, 2537–3225µg/100g DW; core, 960–994µg/100g DW	(Freitas et al., 2015)
Tomato peel and seeds	β-carotene	Semi-continuous supercritical carbon extraction. Carotenoids extracted by chloroform soxhlet extraction and analyzed by HPLC	Optimum conditions for lycopene extraction: 90 °C, 40 MPa, and a ratio of tomato peel to seed of 37/64.	1.51 mg/g dry tomato peel	(Machmudah et al., 2012)
Tomato peel and seeds	Lycopene	Supercritical CO_2 extraction	Tomato waste from processing plant in Tunisia. DM 35/65 seed/peel	peel: 410.53 mg/kg DW; seed: 27.84 mg/kg DW	(Kehili et al., 2016)

Another fruit colorant, anthocyanin, can be found in the red grapes. Anthocyanin may be extracted from red grape pomace (or marc in the case of wine production); Monrad et al. (2010) report laboratory productivity of 450 mg of anthocyanin per 100 g of pomace dry weight (DW).

It is a natural phenolic compound that is known for its blue, red and purple pigmentation. It has several health benefits including oxidative stress reduction, free radical scavenging properties, assisting in cancer and disease risk reduction, as well as cholesterol regulation (Stevenson and Hurst, 2007). Table 3 provides examples of colorant extraction from the various feedstock. An extended version of the source data can be found in SI 2 (Table 2), with 26 examples related to colorants (from 0.04 to 463 mg per 100g). Another recent example that was not found in the reviewed references is yellow pigment produced by fungal strain *Monascus purpureus* ATCC 16365 applying SSF using orange peels that yielded 9 absorbance units (AU) per gram of dry fermented substrate (Kantifedaki et al., 2018).

3.4 Bio-based enzymes

Enzymes are one of the oldest used high value bio-based products (Haddadi et al., 2017). Various microorganisms are used to produce enzymes, such as *Saccharomyces cerevisiae*, *Aspergillus sp.* and *Bacillus sp.* (Haddadi et al., 2017). These species are able to degrade complex polymers found in plants and utilize the released sugars to metabolize enzymes (Ravindran and Jaiswal, 2016). Food waste is a good substrate for these microorganisms and supports future commercial production as low-cost feedstock (Haddadi et al., 2017). Some examples of suitable industrial food waste substrates are orange bagasse (leftover material from juice extraction), pineapple peel (Haddadi et al., 2017), banana peel, tomato pomace (Yang et al., 2015), pea peel (Verma et al., 2011), sugarcane bagasse (Abu Yazid, 2017), and chicken feathers (Villa et al., 2013).

Food waste and food residues are feasible feedstocks to produce oxidative enzymes like laccase, xylanase and cellulase (Ravindran and Jaiswal, 2016) as well as starch hydrolyzing enzymes, α-amylase and glucoamylase (Wang, 2013) and many others.

Cellulase is an important enzyme used in numerous industries, waste management and bioconversion processes (Verma et al., 2011). Fungi or bacteria can naturally produce free cellulase, which can be used in solid state fermentation (SSF) and submerged fermentation (SmF) technologies (dos Santos et al., 2012). Optimization of the production is crucial for large-scale facilities, and using SSF to produce cellulase is 10 times cheaper than SmF (Haddadi et al., 2017). The unit cost for production of cellulase through SSF is 15.67 USD per kg while applying SmF costs 40.36 USD per kg, with a market price around 90 USD per kg cellulase (Abu Yazid, 2017). Verma, Bansal and Kumar (2011) achieved a production of 2.86 IU of cellulase mL^{-1} from pea peel waste applying SSF with *Trichoderma reesei*. They have noticed significant production increases when incorporating whey and wheat starch hydrolysate to the feedstock. However, using homogeneous residue streams (such as tomato pomace) is seen as a more feasible option for cellulase production based on food waste in comparison to the use of very heterogeneous food waste mixtures, which require additional processing steps such as isolation and purification (Ravindran and Jaiswal, 2016).

Laccase can be found in many plants, fungi, and microorganisms. The enzyme also contains copper and is used for various applications like delignification of lignocellulose and detoxification of waste (Wang, 2013). Yang *et al.* (2015) reported amounts of laccase ranging from 9 U g^{-1} DW of apple residues (via SSF using white-rot fungus *Pleurotus ostreatus* and *Trametes versicolor*) to 167 U g^{-1} DW of sugarcane bagasse (via SSF with *P.ostreatus*). More information is provided in Table 4 and SI2 (Table 2), with 22 cases of enzyme production ranging from 6.8 U g^{-1} to 34,000 U g^{-1}.

Amylases are another enzyme that can be produced from processing food waste and can be used in biofuels as they are efficient in hydrolyzing starch (Mushtaq et al., 2017). Some examples include amylase production from potato peels via Bacillus subtilis K-18 (KX881940) (Mushtaq et al., 2017), and other processing food waste such as papaya waste, fruit peels, orange peel, and rice bran (see Table 5 in Sadh et al., 2018). Quantitative data on these, however, were not available in the selected references.

Table 4 Enzyme production from food waste and food residue.

Feedstock	**Output Product**	**Technology/Processes**	**Note**	**Productivity/ yield**	**Reference**
Apple residues	Laccase	SSF via two fungi *Pleurotus ostreatus* and *Trametes versicolor*	Obtained without addition of nutrients.	9 U/ g DM	(Yang et al., 2015)
Chicken feathers	Keratinase	Enzymatic hydrolysis and submerged fermentation with *Bacillus subtilis* AMR. Protein and enzymes analyzed by HPTLC and MALDITOF-MS (Matrix Assisted Laser Desorption Ionization-Time Of Flight-Mass Spectrometry)	Grown for 5 days, at 28°C with agitation. The final product has low molecular weight predominantly in the range of 800 to 1079 m/z, commercial keratin 900-1400 m/z.	Feathers were degraded by 90-95%	(Villa et al., 2013)
Kiwi peels	Laccase	SSF by white-rot fungus *Trametes hirsute*	Initial ammonium concentration of 0.150 g/L and with 2.5 g of pre-treated peelings of kiwi fruit.	90,000 nkat/L or 5.4 EU/mL	(Wang, 2013)
Pea peel [a]	Cellulase	SSF via *Trichoderma reesei, centrifuge*	Peel from local market. Optimal conditions: 30 °C temperature and pH 5.0. *T. reesei* have the tolerance to grow in the phenolic environment.	2.86 IU/mL	(Verma et al., 2011)
Orange peel	Polygalacturo-nases	Fermentation via *Aspergillus niger* on fixed bed reactor without aeration.	This process has promising production at the industrial level.	5.3 U/ mL	(Yang et al., 2015)
Potato peel	Xylanase	SSF via *Aspergillus niger*	81.92 h, water content 50.72% and temperature 28.85 °C. Biomass from agro-industry.	25 IU/mL	(dos Santos et al., 2012)
Tomato pomace	Laccase	SSF via *Pleurotus ostreatus* and *Trametes versicolor*		36 U/g DM	(Yang et al., 2015)

a Could also occur at the retail stage as authors use peel waste from the local market

The overall market price for industrial enzyme production was estimated to be around 4 billion USD in 2015 with 4% compound annual growth rate (CAGR) rise each year (Yang *et al.*, 2015; Panda *et al.*, 2016).

3.5 Proteins

There have not been many studies reported for the protein production from food waste and food residues. Despite the high content of protein in plant and animal wastes (Aggelopoulos et al., 2014), there have been only 4 examples reported in the reviewed literature, as shown in Table 5. Several examples of protein extraction from milk and cheese processing residues were found in the literature without quantitative data (Mirabella et al., 2014). The protein itself is often not separated as a purified fraction from plant-derived side streams and wastes, but it is incorporated within food products to enhance the protein content (Ritala et al., 2017).

Table 5 Protein production from food waste and residue.

Feedstock	Technology/Processes	Note	Productivity/yield	Reference
Food waste mixtures (Cheese whey, molasses, brewer's spent grains (BSG), malt spent rootlets (MSR), potatoes and oranges-waste from the market)	SSF via *Kluyveromyces marxianu*		33.7 % wt. DM	(Aggelopoulos et al., 2014)
Food waste mixtures (Cheese whey, molasses, brewer's spent grains (BSG), malt spent rootlets (MSR), potatoes and oranges-waste from the market)	SSF via *Saccharomyces cerevisiae*		38.5 % wt. DM	(Aggelopoulos et al., 2014)
Food waste mixtures (Cheese whey, molasses, brewer's spent grains (BSG), malt spent rootlets (MSR), potatoes and oranges-waste from the market)	SSF with kefir		23.6 % wt. DM	(Aggelopoulos et al., 2014)
Chicken feathers	Enzymatic hydrolysis using *Bacillus subtilis* AMR in submerged fermentation	Grown for 5 days, at 28°C with agitation. Protein and enzymes analyze by HPTLC and MALDI-TOF-MS	1.5 mg/ml, 42.8% of total protein	Villa et al (2013)

3.6 Other bio-based high-value molecules

Pectin is a hydrocolloid found in all plant matter. It is used as a gelling agent, fat replacement in meat products (Ravindran and Jaiswal, 2016), and thickening agent in foods, cosmetics, and pharmaceuticals (Schieber, 2017). Pectin is also a widespread biopolymer used in food packaging and biofilms (González-Rivera et al., 2016).

The technologies applied to extract pectin use diluted mineral acids to transform insoluble proto pectin to soluble pectin (Schieber, 2017). It can be extracted from citrus peels by nitric acid and it represents a significant fraction of apple pomace (Schieber, 2017). Recently, González-Rivera et al. (2016) extracted essential oils (EO) and pectin from orange peels using microwave irradiation with coaxial configuration, which is reported as an environmentally sound technology in comparison to technologies requiring mineral acids input. After yielding 1.57% (wet weight; w/w) of EO, the post-extraction residues were further used to isolate pectin by conventional hydrodistillation. A maximum yield of 17.4% (w/w) in 90 seconds was reached, representing approximately 25% (w/w) of the overall pectin content in orange peel waste. According to González-Rivera et al. (2016), 10 USD per kg market price of citrus pectin makes this process very feasible for future business expansion.

Another interesting compound found in food waste and residues is chitin. Chitin is a natural amino polysaccharide and the second most abundant natural biopolymer following cellulose (Ravindran and Jaiswal, 2016). It has good structural features allowing many uses, ranging from coagulating agent in wastewater treatment, a coating agent for plant seeds, or production of biomaterials in biomedical and other industries (Liu et al., 2016). Chitin is mainly found in shells of fishery waste (Haddadi et al., 2017), crustacean insects, and can also be produced by fungi (Liu et al., 2016). Animal farm wastes have been documented to be a feasible substrate for fungal fermentation to produce chitin, where 17 g of fungal biomass per 1 kg dry animal waste contains 12 % of chitin (i.e. 2.04 g of chitin per 1 kg DW) (Liu et al., 2016). The production of chitin via fungal fermentation has several advantages over chemical extraction from shellfish: it has no geographic and seasonal variations and the product can be used as biofertilizer enhancing plant immune response (Liu et al., 2016).

Kernel wastes from grains like corn and wheat germs contain high concentrations of protein, minerals and high-value lipids. They represent a suitable substrate to extract several nutraceuticals such as policosanols, fibers, and free fatty acids (Wang, 2013). Other products that can be extracted from kernel waste are reducing sugars (Chaturvedi and Verma, 2013) and limonene (liquid hydrocarbon, used among others as a solvent in cleaning products), while wine production residues can be used to produce calcium tartrate (Dimou et al., 2016) as shown in Table 6 (additional details in SI2).

Recent examples that were not included in SI2 as published after April 2018 include a review on garlic processing waste, where the production of animal feed, phenolic compounds, and nanocelluloses, among others, were assessed (Kallel and Ellouz Chaabouni, 2017), as well as a detailed review by Sharma *et al.* (2017) who evaluated citrus waste for the production of various chemicals such as phenolic compounds, flavonoids and D-limonene.

Table 6 Other products extracted from food waste and food residue.

Feedstock	**Output Product**	**Technology/Processes**	**Note**	**Productivity/ yield**	**Reference**
Animal farm wastes [a]	Chitin	Enzymatic hydrolysis and fungal fermentation	17 g fungal biomass /kg DM containing 12 % of chitin	2.04 g/kg DM	(Liu et al., 2016)
Meat product fat	Single Cell Oil	*Yarrowia lipolytica* NC1		1.61 g/g fat	(Uçkun Kiran et al., 2015)
Olive tree biomass	Reducing sugars	Acid pre-treatment, 170°C, 1% acid	Adv: Increase in porosity, increased enzymatic hydrolysis. Disadv: Synthesis of furfural/ hydroxymethyl furfural, need for recycling, costly	Yield 48.6%	(Chaturvedi and Verma, 2013)
Orange peel (from canteen)[b]	Limonene	Clevenger hydrodistillation with a coaxial dipole antenna to apply microwave energy inside the aqueous extraction medium.	Short retention time below 60 min, because of the process longer than 60 min starts de-esterification.	Yield 1.57 wt% EO, inside EO limonene 94.7%	(González-Rivera et al., 2016)
Orange peel (from canteen)[b]	Pectin	Clevenger hydrodistillation with a coaxial dipole antenna to apply microwave energy inside the aqueous extraction medium.	Orange peel waste has around 25% (w/w) of pectin. Conventional hydrodistillation resulted in the highest pectin amount.	17.4 ± 3.3 (w/w)	(González-Rivera et al., 2016)
Wine lees	Calcium tartrate		The solids that remain after the extraction of phenolics.	6.5% (w/w) of the initial wine lees	(Dimou et al., 2016)

[a] From processing stage, but could also occur in primary production; [b] could also occur on the consumption stage as reported by the authors

4. Discussion

Inedible, unavoidable waste from food processing activities was shown to have great potential for producing high-value chemicals ranging from platform chemicals like acids to bio-based materials like bioplastics. The review presented in section 3 includes emerging technology with a technology readiness level (TRL) of 2 to 4, as well as some examples of mature technologies based on conventional biomass feedstock (TRL 9, not included in SI2).

Using IUFW and residues for the production of high-value bioproducts contributes to waste prevention. It further allows moving up the waste hierarchy while recycling carbon from these otherwise waste feedstock and thus reducing the overall carbon demand. Of course, this only applies if the biowaste conversion process does not induce the extraction of additional carbon (compared to what would have happened with producing the raw material in a conventional way). In the perspective of the urgent need to stabilize the global climate (and thus to reduce GHG emissions), the ability to recycle inedible food waste appears coherent with the future societal needs.

4.1 Proposition of guiding criteria towards the sustainable integration of IUFW into a circular economy

Figure 2 represents a proposal of the hierarchical guiding criteria to consider for prioritizing the future biorefineries from IUFW to develop. This proposal was established with the effort of contributing to the maximum number of the SGDs (UN, 2015).

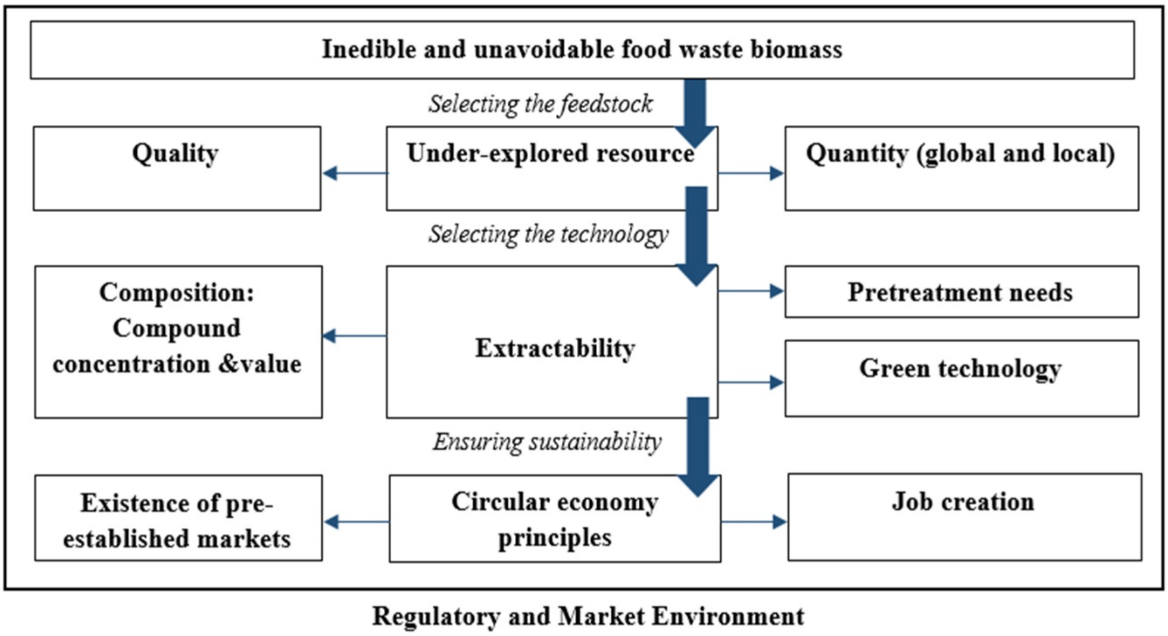

Figure 2 Proposed hierarchical guiding criteria for the new investments in waste-based biorefineries, starting from the top. The vision is that all steps should be met when introducing food waste derived products in circular economy. The middle row represents category of criteria, which are detailed in the left and right rows.

Selecting the base feedstock: focus on under-explored streams, maximize quality and quantity

Using IUFW can limit unforeseen negative effects, such as (involuntarily) supporting the generation of additional waste. The vision is thus that the prime guiding criteria (or premise for developing future food waste biorefineries) are to determine if a given food waste (or food residue) fraction is edible, in which case it is considered that it should not leave the food chain. Further, under-explored feedstock excludes any stream derived from soy and palm production, for the reasons explained in section 2.2. The quality of biological feedstocks degrades with time, hence its processing and use require timely intervention. Long value chains and long-distance transportation of IUFW can result in decreased feedstock quality. This degradation further implies the loss of carbon and nitrogen flows, among others, which forms greenhouse gas (GHG) emissions (CO_2, N_2O, and eventually CH_4 if anaerobic storage conditions are involved) as well as other volatile emissions (NH_3, NO_X, etc.). Secondly, the amount of feedstock required for a given production needs to be considered; in other words, are local or global resources of a particular selection of IUFW sufficient to allow a profitable production? Due to the existing regulatory regimes, some IUFW streams are generated in a larger quantities than others: for example, the global potato production and processing activities waste up to 129 million metric tons of peels annually (Schieber, 2017) while the food processing industry in Europe discards 4 million tonnes of tomato pomace per year (Ravindran and Jaiswal, 2016), which could among others be used for high-value natural colorant production (Table 3).

In a nutshell, this first guiding criteria is to ensure that the base stream is not only inedible, but also unavoidable, and does not stem from the production of resources that are key contributors of deforestation. Then, the possibility to preserve the quality of the stream (once it reaches the biorefinery) and the magnitude of the available quantity of the stream should be regarded. This first guiding criteria is coherent with SDG 2.4, 8.4, 12.3 and 12.5, and 15.2 (UN, 2015).

Selecting the technology appropriate for the input stream and desired output product: Targeting extractability and ensuring environmentally sound technologies are used

Several factors influence the extractability of high-value molecules, among others the feedstock itself (or rather its biochemical composition) as well as the type of technology used.

In particular, food waste feedstock includes many high-value chemicals, and not all of them are interesting in the perspective of implementing sustainable business models for waste-based biorefineries. Here, we consider three aspects that should be taken into account: (i) the magnitude of the compound concentration in the feedstock; (ii) the market value of the compound and (iii) the amount of the compound that can be extracted through different technologies. Among the high-value products considered in this review, acids have the lowest price (see Figure 5) but lead to high productivities and yields, such as those of citric acid (CA). For example, CA yields as high as 0.45 g g^{-1} in apple pomace (Yang *et al.*, 2015;) and 0.64 g g^{-1} in orange peels were reported (Abu Yazid, 2017). On the other hand, the price for the colorants can reach as high as 40,000 € per kilogram of lycopene (Cristóbal et al., 2018), but has substantially lower content in the feedstock (1.34 g kg^{-1} of blanched tomato peel) in comparison to CA (Urbonaviciene et al., 2012). When considering the final product, the price should be considered together with productivity/yield and technology intensity. In fact, products of lower market price like acids can generate profitability with their high yields while products involving lower yields but higher market price like colorants can generate just as much margin. Hence, energy-intensive technologies, such as those of colorant extraction, should be considered in case of high-price and “harder” to extract products while simpler technologies, such as fermentation for acid production, should be considered for lower-priced products. This could help to allocate the environmental burden of intensive production and help to identify the hotspots for green chemistry and technology use in bioeconomy.

Moreover, the overall characteristics and biochemical composition of the waste feedstock strongly influence the importance of the technologies required for the bio-based production, and thus the investment (and potentially operation) costs, such as the costs related to pre-treatment. Soggy and soft biomasses require minor pre-treatment while lignocellulosic substrates often require physical (e.g. milling), chemical (e.g. acid hydrolysis) and biological pre-treatments (e.g. fungal pre-treatment) (Bansal et al., 2012). The pre-treatment of the biomass, in turns, often have a significant influence on the final recovered content of the chemical.

Further, the possibility to use a maximum of so-called “green technologies” should be considered as an important step towards sustainable production. These are technologies that use less energy and toxic materials than conventional process engineering technologies. Some examples of technologies pinpointed as “green technologies” for the production of high-value products are supercritical CO_2 extraction (Mirabella et al., 2014), microwave assisted treatments (Papaioannou et al., 2016), enzymatic treatments (Papaioannou and Karabelas, 2012), and microbial processes, such as solid state fermentation (Abu Yazid, 2017), as seen in Tables 1-6 and SI2.

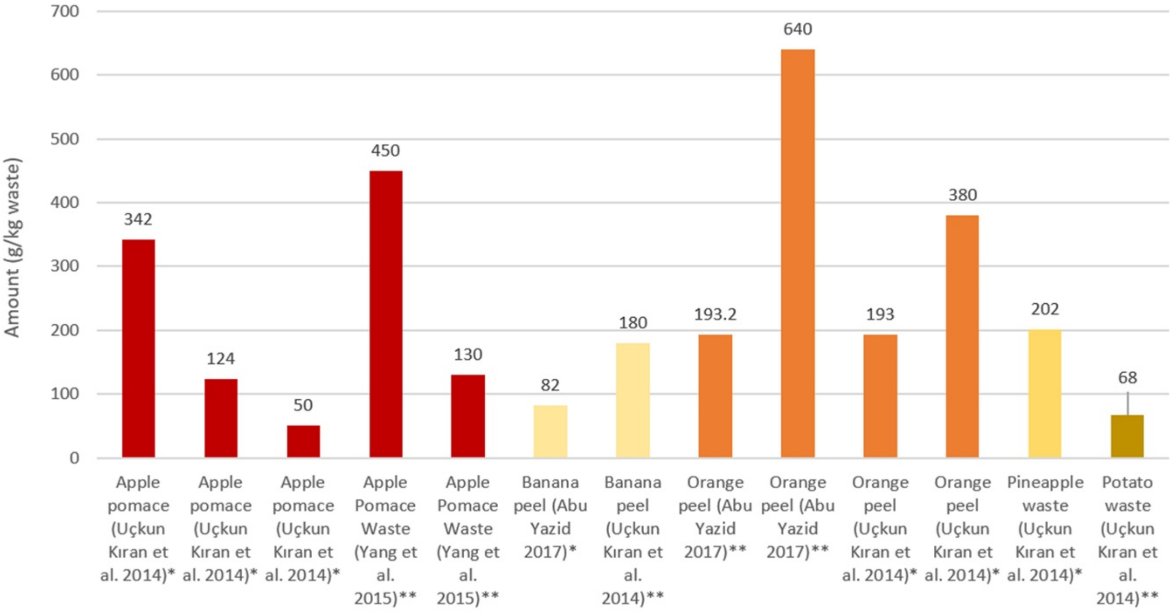

Figure 3 Recoverable content of citric acid in different food wastage and residues. They are all based on fermentation techniques, but these consider different technologies and bacteria streams. Red bars show apple pomace streams, yellow bars banana peel streams, orange bars orange peel streams, dark yellow bars pineapple waste and brown bars potato waste. *reported per DW ** assumed WW

Through an example for citric acid production, Figure 3 summarizes many of the issues related to this second guiding criteria. It is based on the results from Table 1 (and SI2), considering a variety of food waste residues. Figure 3 highlights, among others, the high variability of recovered citric acid amounts (i.e. ranging from 50 to 640 g kg^{-1} of waste), depending on the stream and the fermentative processes used. Even though the same technology and bacteria species is applied to the same waste, different strain can influence the recoverable amount of end-product significantly. For example, fermentation of apple pomace using the same species of bacteria (*Aspergillus niger*) but different strains (van ThieghemMTCC281 and MTCC282) can result in nine times higher amount of citric acid (van ThieghemMTCC281 50 g kg^{-1} and MTCC282 450 g kg^{-1}). A similar situation has been observed using fermentation with *Aspergillus niger* for orange peels, where one strain (van Tiegh 1867) had double productivity of citric acid. Yet, it is, among all reviewed examples, the addition of molasses and methanol (3.5%) in the medium that allowed to reach the highest yield from orange peels (640 g kg^{-1}; SSF with *Aspergillus niger;* Abu Yazid, 2017).

In a nutshell, this second guiding criteria relates to the importance of recovering a pre-defined quantity of the targeted output products, among others based on the value of these output products. Yet, this recovery is limited by the type of technology used (with/without pre-treatment), and by prioritizing environmentally sound technologies. This second guiding criteria is coherent with SDG 8.2 and 9.5 (UN, 2015).

Circular economy principles

Besides ensuring that the extraction technologies are environmentally-efficient, the same should be ensured for the overall system performance. This can be evaluated by the use of holistic environmental assessments methods, such as Life Cycle Assessment (LCA). LCA is a methodology used for quantifying environmental impacts of the products considering their lifetime from production to final disposal. The World Resources Institute (WRI) and the European Commission highlighted LCA as a preferred tool to assess the environmental performance of products and systems (Bhatia et al., 2011; EC, 2003).

Prior to this, however, it should be first ensured that the biorefinery to be established is in line with circular economy principles as a leading concept that uses waste fractions. Circular bioeconomy integrates the concept of closed-loop systems with the biorefining of organic waste, agricultural, and forest biomass into biomaterials and biochemicals. The closed-loop concept is based on the cradle-to-cradle approach, where recycling is either indefinite or where wastes are disposed with no harm to the environment (Vea et al., 2018). Circular economy principles aim at reducing externalities by directly substituting primary with secondary resources. As the circular economy is one of the strategies pinpointed for sustainable economic growth, these circular systems should support job creation and overall business creation, and maintain competitiveness on the market through diversification as mentioned in the Global SDG Indicators (UN, 2017).

As stressed out in the second guiding criteria, the value of the final product in waste-derived biorefineries is significant to consider. Equally important is the existence of a market for this product, and how established that market already is. This review gave examples of various bio-based materials presenting alternatives to petrochemicals. Introducing bio-based alternatives can provide the advantage of benefitting from an already established market of synthetically produced chemicals. This avoids the costs of extensive marketing to create new demands (for new waste-based products) if the product is a direct substitute of its fossil alternative or product using primary resources. Figure 4 illustrates the connection of the market size and price of high-value products. Bulk chemicals, such as organic acids, tend to have a much larger market size than other products as they are used as platform ingredients in many applications (including bioplastic production). Higher value products, such as carotenoids, have more niche markets with a specific focus. Their unique target use (colorants, dietary supplements) also induce higher prices for the final product; on top of this, their extraction uses energy and resource-intensive processes. The review performed herein identified a lack of market research for natural colorants in the literature, hence carotenoids were used as a representative of overall colorants.

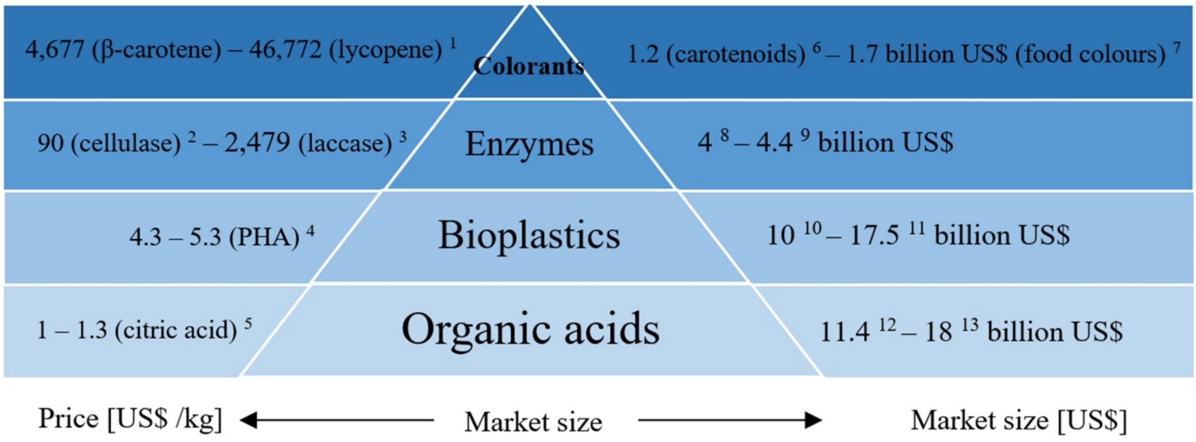

Figure 4 Market prices of selected high-value compounds and their relationship to market size. References: [1] (Cristóbal et al., 2018); [2] (Abu Yazid, 2017); [3] calculated from (Osma et al., 2011); [4] (Cesário et al., 2014); [5] (Singh Dhillon et al., 2011); [6] (Strati and Oreopoulou, 2014); [7] (Kandansamy and Devi Somasundaram, 2012); [8] (Panda et al., 2016); [9] (Yang et al., 2015); [10] (Bezirhan Arikan and Duygu Ozsoy, 2015); [11] (Zion Market Research, 2018); [12] (Markets and markets, 2017); [13] (Allied market research). The conversion rates from euro to USD were made on date 8.30.18, using rates from Bloomberg Markets (2018).

In a nutshell, compliance with circular economy principles should be ensured when considering the implementation of new IUFW-based biorefineries, ensuring that IUFW support phasing-out of fossil-fuel resources (SDG 12c), economic diversification (SDG 8.2) and employment in the sustainable industry sector (SDG 9.2), where the existence of a pre-established market for the targeted output should be verified. Then, the overall environmental performance in terms of climate change mitigation services (SDG 13.2) and reduction of food waste and losses (SDG 12.3) should also be validated (e.g. via LCAs) (UN, 2015).

4.2 Lowering the costs of production

Using IUFW from food processing offers several advantages, such as more homogenous stream (compared to food waste streams further downstream the food chain, e.g. consumer waste) with zero to low costs for the feedstock, and with relatively stable production in terms of volume and composition (Alexandri and Venus, 2017). Another solution to decrease operational costs of biorefineries is enhancing the geographic proximity of the biorefinery to the feedstock, which also decreases the microbial deterioration of the biomass (Galanakis, 2012), as previously discussed.

Further, food waste biorefineries represent an opportunity for food processing to expand according to the concept of economies of scope, i.e. creating synergic production where simultaneous manufacturing of different products becomes more cost-effective than manufacturing them separately (Chavas and Kim, 2010). While economies of scale and scope are often positively correlated, the economy of scope originating from food processing side streams are often independent of scale. This may give an advantage for small and medium scale, short-chained biorefineries, implying less loss of resources and emissions (compared to large biorefineries). Combining different technologies in food waste valorization to produce multiple-line products from multiple markets would diversify the product portfolio and could potentially increase the revenues.

Economies of scope can be realized by cascading production, where integration of several products in one biorefinery can minimize waste generation by using the waste from one production as a secondary resource for another product. This decreases not only the cost for the acquisition of raw materials but also the cost of waste treatment. Even though the yields of the high-value products are important in the recovery processes, the CAPEX (or investment costs) of these technologies are critical. The addition of the new product to already established production can minimize the CAPEX expenses related to that product. Examples can be found in the integration of high-value bio-based materials with the well-established bioenergy production. There are several experiments showing the feasibility of this concept: Nguyen *et al.* (2017) produced D-mannose and bioethanol from coffee ground residue waste; Dimou *et al.* (2015) studied integrated biorefinery of wine lees producing not only bio-ethanol but also antioxidants, tartaric acid and PHB; while Rivas et al. (2006) recovered tartaric acid from wine lees hydrolysate after ethanol production and aromatic flavors extraction. Further, residue streams from ethanol production can be fermented into various chemicals ranging from succinic and lactic acid to xylose and 1,3-propanediol (De Corato et al., 2018).

5. Conclusion and perspectives

This review study documents the potential of existing and emerging bio-based industrial productions of high-value molecules from unavoidable, inedible food processing waste. We have identified effective lab-scale bio-based production technologies with TRL from 2 to 4 (SI2), as well as some examples of mature technologies (TRL 9). We presented 149 examples, such as the citric acid from orange peel, PHA from spent coffee grounds, lycopene extraction from tomato peel, and laccase from sugarcane bagasse, among others. Our review highlighted that fermentation is a key technology for using processing food waste and residues in biorefineries, with 76 examples for production of high-value products.

It was highlighted that inedible, unavoidable food waste and food residues represent an attractive and secure feedstock for biowaste-based biorefineries, besides being consistent with the UN SDG 12.3 to reduce “the food losses along production and supply chain by 2030”. Further, the use of food waste in biorefineries could provide feasible feedstock for closed loop economic systems, and keep the carbon in biomass bound in technosphere for longer time. This carbon recycling strategy would replace emission intensive waste treatments by transitioning towards circular upcycled biowaste value chains while substituting fossil-based products. The biorefineries can be coupled as pre- and/or post-treatment technologies to existing bioenergy plants, resulting in cascade production and decreased costs.

However, the study showed that the future implementation of food waste within bioeconomy faces many challenges. There is a need for comprehensive and uniform definitions of food waste and food loss, aiming at clarifying reporting. The definitions are tied to the quantification of currently used feedstocks, which may compromise the future valorization and usability of these wastes. Another gap identified relates to the lack of market research for natural colorants. Moreover, holistic assessments such as life cycle assessments are still needed to evaluate the sustainability of inedible food waste biorefineries, under commercial operation.

Additional research is needed in order to address these trade-offs, the challenges of definitional and regulatory framework as well as to investigate the prioritization of the value chains and investments in a future regenerative circular economy.

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