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Valorization of food processing wastes and by-products for bioplastic production

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ABSTRACT

The global plastic production is reaching new altitudes every year. Growing production of petroleum-based plastics has incurred in disposal issues raising the concerns of plastic pollution and impact to the environment. These issues have encouraged innovation and research activities in the field of bioplastics, offering alternatives for conventional plastics. In recent years, global bioplastic production has also witnessed tremendous growth and expansion. Some of the main drivers of this growth are innovative biopolymers such as Polylactic acid (PLA) and Polyhydroxyalkanoates (PHAs). However, industrial expenses to produce bioplastics are much higher when compared to petroleum-derived plastics (e.g. industrial PHA production is estimated to be 5–10 times more expensive than petroleum-derived polymers). In this regard, globally many researchers have investigated for more environmentally friendly and cost-effective alternatives to produce plastics. One potential option to pursue would be to explore agri-food wastes and by-products for bioplastic production. This would not only reduce the volume of wastes and by-products, but also production costs incurred. This review paper provides an overview of bioplastics, including production methods and possibilities of industrial food waste valorization for bioplastic production.

1. Introduction

The global plastic production reached almost 360 million tons in 2018 (Plastics Europe, 2019). In contrast, bioplastics production capacity in 2018 was only 2.01 million tons, representing 0.56% of world's plastic production (European Bioplastics, 2020). It is obvious that increasing the market share of bioplastics can play a crucial role in reducing dependence on fossil-based resources, transitioning towards bio-based society and achieving circular economy (Geueke et al., 2018; Imre et al., 2019).

Linear consumption models are rooted in most developed economies (Russo et al., 2019). These models, also labelled as "throw away" (Shogren et al., 2019) or "take-make-dispose" (Blank et al., 2020) models, are not sustainable in long-term perspective. At this point, environmental, financial and social impacts derived therefrom require urgent intervention (Russo et al., 2019). As an example, European Commission has adopted a strategy for plastics in circular economy (European Commission, 2018). In circular economy concept resources are used as much and long as possible, maximum value is extracted whilst in use and at the end of service life products and materials are recovered and regenerated (Plastics Europe, 2020). The EU plastics strategy intends to protect the environment from plastic pollution whilst fostering growth and innovation by restricting intentional use of micro-plastics, reducing consumption of single-use plastics and enforcing recycling targets for plastic packages (European Commission, 2018).

Presently, about 80% of all the plastic produced globally is not recycled or re-used in other ways (Blank et al., 2020) and concerns on plastic pollution are growing. Bioplastics by definition are biodegradable and/or obtained from renewable sources (Imre et al., 2019; Sidek et al., 2019), offering a sustainable alternative for conventional plastics. It is appraised that capacity of bioplastic production will tend to increase up to 2.4 million tons by 2023 (Bioplastics and nova-Institute, 2019). Main drivers of this growth are innovative biopolymers such as PHA (Polyhydroxyalkanoates) and PLA (Polylactic acid) (European Bioplastics and nova-Institute, 2019).

Currently the industrial expenses to produce bioplastics are much higher than for petroleum-derived plastics (Raza et al., 2018). For example, industrial PHA production is estimated to be 5–10 times more

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expensive than of petroleum-derived polymers (Tsang et al., 2019). One option to reduce the manufacturing costs of bioplastics would be to use suitable wastes and by-products as input materials (Saharan and Sharma, 2012). Diverting bio-wastes from landfilling to new processing mechanisms in order to transform waste back to useable product or raw material has a lot of potential. In recent years, there has been great developments underway to improve bio-waste transformation processes to generate different raw materials, also for bioplastic production (Carmona-Cabello et al., 2018; Sindhu et al., 2019). Growing usage of renewable resources will not only help transitioning towards circular economy, but also will have environmental benefits such as lower greenhouse gas emission, reduced volume of harmful pollutants, conserve ecosystems and biodiversity and promote rural investments (Shogren et al., 2019).

With this background, the main aim of this review is to provide an overview of feasible bioplastic production methods from food industry processing wastes and by-products. The introductory part of this article focuses on terms and definitions related to bioplastics as many of these are often misunderstood and misused. Further, an overview of current situation, production methods and wastes valorization options is provided. This review is expected to better understand the present scenario, especially in the EU, identify gaps and overcome certain sustainability challenges in the bioplastics production arena.

2. Bioplastics and current status of bioplastic production

2.1. Bioplastics

In order to label a polymeric material as biopolymer or bioplastic, it has to be biodegradable, made from renewable source (bio-base) or be biocompatible (Babu et al., 2013; Imre et al., 2019). European Bioplastics describes plastic material as 'bioplastic' if it is biodegradable, bio-based or includes both the properties (European Bioplastics and nova-Institute, 2019). From environmental point of view, the material degradability and source of raw materials are the most important properties. To give a better overview, all polymers could be divided into four overlapping categories (see also Fig. 1):

(1) Fossil-based biodegradable polymers (e.g. polyvinyl alcohol and polyethylene adipate);
(2) Fossil-based non-degradable polymers (e.g. polyolefins and polystyrene);
(3) Bio-based biodegradable polymers (e.g. cellulose and PLA) and
(4) Bio-based non-degradable polymers (e.g. natural rubber and polyamides) (Imre et al., 2019).

Bioplastics could also be classified similarly to conventional plastics based on material properties like strength and toughness. Based on this, plastic materials could be divided as thermosetting (meaning that the material is hard and durable) or thermoplastics (compared to thermosetting materials, the material is less rigid) (Ganesh Kumar et al., 2020). As some of the bioplastics are also considered to be safe for human consumption as food (Sharif Hossain et al., 2018), bioplastics could also be classified as edible and non-edible. For example, starch and gelatin are widely used for the development of edible coating films or as a packaging material for food items (Bhat and Karim, 2009, 2014; Bhat et al., 2013; Thakur et al., 2019). This variety of classifications illustrates well that bioplastics form a diverse group of materials with different applications and properties (European Bioplastics and nova-Institute, 2019).

2.2. Bioplastic production methods

Bioplastic production methods can be divided into five main groups based on raw material origin and corresponding polymer production technology (see also Fig. 2):

1) Extracted directly from biomass;
2) Produced by natural or genetically modified organisms;
3) Synthesized from bio-based monomers;
4) Synthesized from petrochemicals;
5) Produced by combining above mentioned technologies and polymers derived thereof (Song et al., 2011).

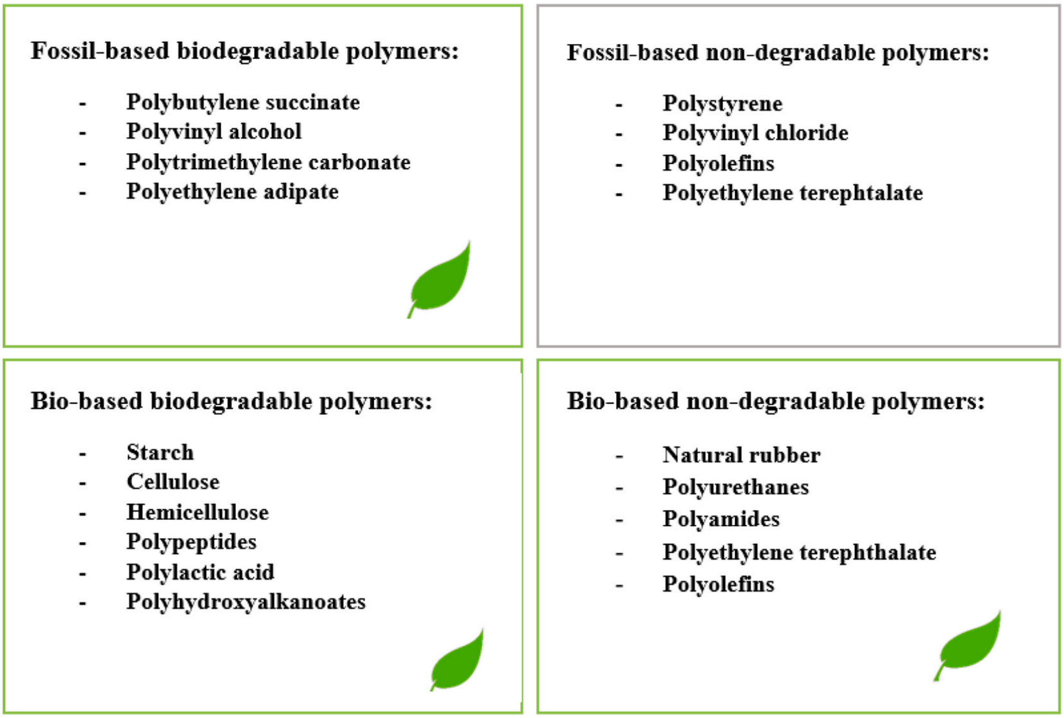
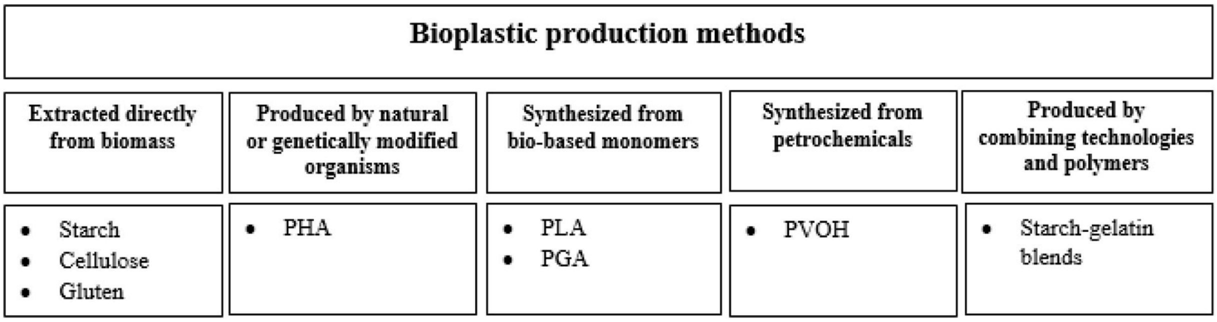


Fig. 1. Classification of plastics based on raw material origin and degradability.



Bioplastic production methods

Extracted directly from biomass	Produced by natural or genetically modified organisms	Synthesized from bio-based monomers	Synthesized from petrochemicals	Produced by combining technologies and polymers
• Starch • Cellulose • Gluten	• PHA	• PLA • PGA	• PVOH	• Starch-gelatin blends

Fig. 2. Bioplastic production methods.

2.2.1. *Bioplastics by direct biomass extraction*

Bioplastics could be produced by biomass extraction from naturally occurring biopolymers such as polysaccharides (e.g. starch, cellulose) and proteins. As an example, the industrial usage of lignocellulose biomass and starch is expanding rapidly mainly due to its low cost, abundance and renewable nature (Imre et al., 2019). In reality, most bioplastics obtained from biomass extraction require additives or mixing with other polymers to improve material properties (Geueke, 2014). To overcome poor material properties and usage limitations, material coating, blending, nanoparticle additives and different chemical or physical modifications are used (Bilo et al., 2018). Below some examples of widely used biopolymers for plastic production through direct biomass extraction are discussed.

2.2.1.1. Starch. Starch is considered to be the second most abundant biomass material on Earth as it is produced by variety of plants as a stored energy source (Le Corre et al., 2010). Some examples of starch producing plants include wheat, corn, potato, rice, rye, buckwheat and barley (Basiak et al., 2017). Starch is also one of the most used plant polysaccharide for bioplastic production at the moment (Thakur et al., 2019).

Starch polymers are composed of linked D-glucose units in two forms-amylose and amylopectin (Copeland et al., 2009). The polymer chain length and distribution pattern of amylopectin and amylose influence retrogradation profile and thermal properties of starch and materials derived thereof (Wang et al., 2015). Starch-based films with higher amount of amylose have better film-forming features like elongation, mechanical strength and gas barrier properties (Thakur et al., 2019). Starch based films are widely used as coating materials for food articles and thermoplastic starch (TPS) is used as an alternative for polystyrene (Geueke, 2014).

2.2.1.2. Cellulose. Cellulose is available in several forms of biomass and can be derived from a variety of sources, such as wood, seed fibers, bast fibers, grass, marine animals (tunicate), algae, fungi, invertebrates and bacteria (Nechyporchuk et al., 2016). Cellulose possesses many attractive physical properties, such as high Young's modulus (as high as 114 GPa) for a single fibril, high degree of crystallinity (89%), high degree of polymerization and high specific surface area (Gopi et al., 2019). Cellulose-based polymers (e.g. cellophane, cellulose acetates, and cellulose ethers) are mainly derived from de-lignified pulp or cotton (Geueke, 2014).

2.2.1.3. Gluten. Gluten is a plant protein found in rye, wheat, barley and their crossbred varieties and derivatives (Jasthi et al., 2020). Gluten is also a by-product from bioethanol production (Arifeen et al., 2009; Jiménez-Rosado et al., 2019) and presently is mainly used for feed production (Storebakken et al., 2015).

To produce bioplastics from gluten, conventional process technology for thermoplastics (e.g. extrusion) could be used. Extrusion is one of the most applied techniques for producing plastics (Michels et al., 2019), mainly because it has good molding and mixing efficiency for thermoplastics (Jiménez-Rosado et al., 2019). When it comes to plastic production from gluten, upon heating it may undergo crosslinking reactions that would increase the viscoelastic properties of the material (Jiménez-Rosado et al., 2019). Meaning that gluten could be extruded only under specific operating conditions at certain parameters, such as pressure, temperature, operating time, mechanical energy input and applied shear (Redl et al., 2003). Even tough gluten is not extensively used for plastic production, available research has shown great results also on industrial scale (Jiménez-Rosado et al., 2019).

Plastic material produced from wheat gluten has suitable properties for food packaging, including forming films, gas barrier, mechanical and biodegradation properties (Min et al., 2008; Chaiwong et al., 2019; Jiménez-Rosado et al., 2019). On downside, wheat gluten is associated with human autoimmune disorder called celiac disease, affecting about 1% of worldwide population (Mahadov and Green, 2011). According to recently published "Nutrition and Chronic Digestive Diseases: An Action Plan for Europe" the prevalence of celiac disease varies in Europe from 0.3% to 2.4% of population (United European Gastroenterology, 2019) limiting the usage of wheat gluten based bioplastics for food packaging applications (Gomez-Heincke et al., 2017).

2.2.2. *Bioplastics produced by natural or genetically modified organisms*

PHAs are compostable bio-based polyesters (Geueke, 2014). Poly (3-hydroxybutyrate), also known as [P(3HB)], is the most common PHA (Ishii-Hyakutake et al., 2018). The physical properties of PHAs are comparable to common petro-chemical polymers, which makes them sustainable alternatives for the growing global bioplastic market (Peelman et al., 2013). Different prokaryotic microbes produce PHAs as carbon storage, often under nutrient limitation (Dietrich et al., 2019). In general, the PHA-producing bacteria could be divided into two groups based on PHA synthesis and accumulation mechanism: (1) bacteria that require essential nutrient (e.g. oxygen, nitrogen, phosphorous) limitation for PHA biosynthesis from carbon source; (2) bacteria that synthesize and accumulate PHA without nutrient limitation (Albuquerque and Malafaia, 2018). Overall, about 250 types of natural PHA-producing bacteria have been identified, but only a limited number of bacteria have been adopted to industrial PHA production, including *Cupriavidus necator*, *Pseudomonas oleovorans, Bacillus megaterium* and *Alcaligenes latus* (Tsang et al., 2019). The most common and frequently used culture on industrial scale is *Cupriavidus necator* (Albuquerque and Malafaia, 2018). Besides unadulterated cultures, also mixed cultures and genetically recombined bacterial strains are used (Albuquerque and Malafaia, 2018; Tsang et al., 2019). Development of genetically modified bacterial strains for PHA production has a lot of potential also in terms of waste valorization. So far, there is a good example of recombinant *E. coli* that can produce 3HB from soybean oil (Tsang et al., 2019).

The industrial cultivation techniques for PHA production are conducted in batch and fed-batch reactors that are common for industrial fermentation processes (Tsang et al., 2019). The cultivation process could be divided into two steps: (1) bacterial cell growth until pre-determined cell mass concentration, (2) nutrient restricted growth with carbon source. The bacterial cells cannot reproduce in nutrient deficiency, but will increase in weight and size due to accumulation of intracellular PHA (Albuquerque and Malafaia, 2018; Tsang et al., 2019). The PHA biosynthesis process is illustrated on Fig. 3.

PHA production from food wastes and by-products has shown great potential, as wastes would offer a cheap and abundant carbon source (Dietrich et al., 2019). When using wastes as a feedstock for biosynthesis of PHA, purity of produced PHAs must be considered as viral, bacterial, plasmid or genetic contaminations may transfer to the final material (Raza et al., 2018). If the intended use is for food contact or medical application, additional washing and sterilizing procedures need to be applied, resulting also in possible rise in final material costs (Raza et al., 2018).

2.2.3. *Bioplastics synthesized from bio-based monomers*

2.2.3.1. PLA (polylactic acid). PLA is a biodegradable aliphatic polyester, primarily produced by industrial polycondensation of lactic acid and/or ring-opening polymerization of lactide (Castro-Aguirre et al., 2016; Jem and Tan, 2020). Conventionally PLA's are produced by converting carbohydrate source into dextrose, followed by fermentation to lactic acid that is further polycondensated (Peelman et al., 2013). Melt processing is the main technique used for mass production of PLA products for the medical, textile, plastic and packaging industries (Castro-Aguirre et al., 2016). As lactic acid has two optical isomers- L- and D-lactic acid, three different stereo-chemical compositions could be formed, determining also the final properties of the polymer (Peelman et al., 2013; Jem and Tan, 2020). PLA-based biomaterials have similar properties (e.g. elongation, tensile modulus and tear resistance) to conventional plastics like nylon, PP and PET (Jiménez-Rosado et al., 2019). For this reason, PLA is also one of the most used bioplastic after starch blends.

2.2.3.2. PGA (polyglycolic acid). PGA is a biodegradable aliphatic polyester that could be synthesized from glycolide by ring-opening polymerization under the influence of metal salt catalysts at low concentration (Hill, 2005; Yamane et al., 2014). The molar mass of the PGA polymer is determined by time, temperature, concentration of the catalyst and chain transfer agents (Hill, 2005). PGA-based materials are resistant to most organic solvents, but are still relatively sensitive for hydrolysis (Song et al., 2011). Currently PGA is mainly used in medical applications, but it is expected to have wider use also in other fields such as food packaging (Yamane et al., 2014).

2.2.4. *Bioplastics synthesized from petrochemicals*

Bioplastics that are synthesized from petro-resources are much more expensive than conventional petrochemical plastics, for this reason, these materials are rarely used alone for packaging applications and are often combined with cellulose or starch (Song et al., 2011; Alashwal et al., 2020).

Polyvinyl alcohol (PVOH or PVA) is a synthetic water-soluble polymer that is synthesized from petroleum resources (Rudnik, 2019). PVOH can be produced by polymerization process of vinyl acetate to polyvinyl acetate (PVAC) and subsequent hydrolysis (Song et al., 2011). PHOV as a material is biodegradable, hydrophilic and has good biocompatibility (Rudnik, 2019).

2.2.5. *Bioplastics from co-polymers and bio-composites*

In reality, most bioplastics are used as bio-composites or co-polymers to improve the material properties, including biodegradability, mechanical properties and cost-effectiveness. One of the most widespread bioplastic blends is food gelatin and potato starch with compatible plasticizers such as glycerol and sorbitol (Fakhouri et al., 2013; Podshivalov et al., 2017). Starch and gelatin as raw materials are low cost an available on large scale (Sagnelli et al., 2016; Lv et al., 2019). The final material has relatively high performance of mechanical properties and is comparable with conventional plastics such as polyvinylchloride (Podshivalov et al., 2017). If the material is produced from food grade raw materials, the final material may also be edible.

2.3. *Current status of bioplastics (market data)*

According to European Bioplastics market data, the global bioplastic production in 2019 was 2.11 million tons (European Bioplastics, 2020). Based on material type, bio-based PP (Polypropylene) and PHAs have shown the highest relative growth rate in production quantities. As PP is commonly used plastic material with wide range of applications, the bio-based alternative is expected to have continuous growth also in following years (see also Table 1). Table 1 illustrates the global bioplastic production based on material type in 2019 and prognosis to 2024. As seen, starch blends were the most common type of bioplastic in

Table 1
Global bioplastic production by material type in 2019 and 2024. The material types marked with * are bio-based, but not biodegradable. Source: European Bioplastics and nova-Institute, 2019.

Bioplastic material type	2019	2024	Bioplastic material type
Starch blends	21,3%	18,5%	Starch blends
PLA	13,9%	13,1%	PLA
PBAT	13,4%	12,5%	PA*
PE*	11,8%	12%	PE*
PA*	11,6%	11,6%	PBAT
PET*	9,8%	8%	PTT*
PTT*	9,2%	6,6%	PHA
PBS	4,3%	6%	PET*
Other (biodegradable)	1,4%	5,3%	PP*
PHA	1,2%	3,8%	PBS
Other (bio-based/non-biodegradable)*	1,1%	1,3%	Other (biodegradable)
PP*	0,9%	0,9%	Other (bio-based/non-biodegradable)*
PEF*	0%	0,2%	PEF*

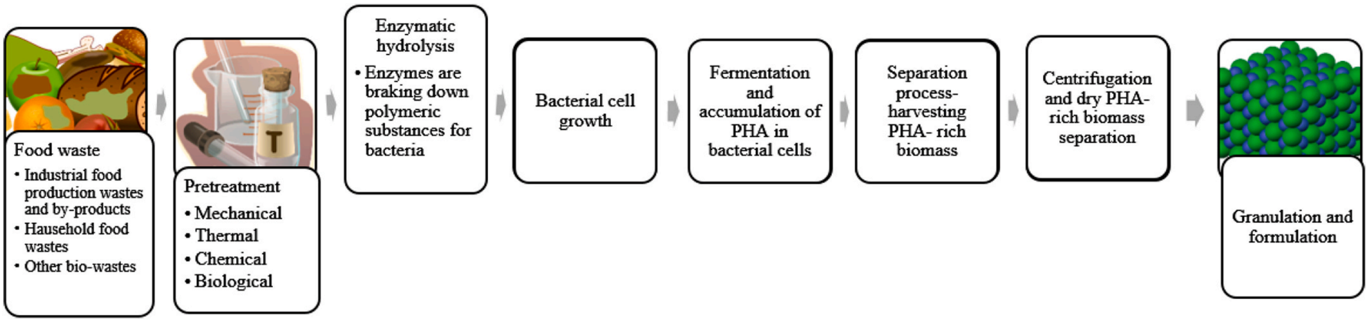


Fig. 3. PHA biosynthesis process.

2019 and continue to hold the position for following years also.

As an alternative to PET (Polyethylene terephthalate), new polymer PEF (Polyethylene furanoate) is expected to enter bioplastics market by 2023 (European Bioplastics and nova-Institute, 2019). Polyethylene furanoate (PEF) is produced from renewable resources through polycondensation process (Rosenboom et al., 2018). However, the production process at industrial scale still has some challenges (such as degradation and discoloring) to overcome (Terzopoulou et al., 2017).

In 2019, biodegradable bioplastics (including PLA, PHA and starch blends) accounted for 55.5% of all produced bioplastics. As per the 2019 market data, by region, Europe ranks top in research and development activities related to bioplastics. However, Asia still has the highest production capacity-about 45% of globally produced bioplastics were manufactured in Asia, followed by Europe (25%), North America (18%) and South America (12%) (European Bioplastics, 2020).

Similarly to conventional plastic materials, bioplastics could be used for different applications, ranging from electronics, textiles, packaging and other consumer products. According to European Bioplastics, the largest segment for bioplastics is packaging application with almost 54% (1.14 million tons) of total bioplastics market in 2019 (see also Fig. 4) (European Bioplastics, 2020).

As the demand for more sustainable products by consumers and brands is continuously growing, the portfolio for bioplastics usage applications is also diversifying. Now, there are already alternative bioplastics to almost every conventional type of plastic. Many bioplastics have the same material properties as conventional plastics offering additional value by reduced carbon footprint and more environmentally friendly waste management options such as biodegrading or industrial composting.

3. Biodegradability and recyclability of bioplastics

3.1. Biodegradability

Biodegradable plastics includes those which can be completely degraded through biological activity (e.g. through the interaction of microorganisms like archaea, bacteria, fungi or microalgae). Under aerobic conditions, the process outcomes are biomass, carbon dioxide and water, whilst under anaerobic conditions the resulting products are biomass, carbon dioxide, methane and water (Dilkes-Hoffman et al., 2019).

The biodegradability of bioplastics depends on physico-chemical structure of polymer. For example, aromatic polyesters are most susceptible to microbial degradation and aliphatic polyesters are degraded through hydrolysable ester bonds (Rajmohan et al., 2019). In addition, environmental conditions such as medium pH, temperature, moisture and oxygen content have strong impact on biodegradability (Emadian et al., 2017; Qi et al., 2017). This means that even (bio)plastics that are considered to be biodegradable may not be biodegradable under the same conditions (e.g. PLA-often referred to as biodegradable, should be technically categorized as industrially compostable as it requires higher temperature conditions in compost and degrades through abiotic hydrolysis) (Dilkes-Hoffman et al., 2019). Generally, biodegradation of biopolymers involves polymer erosion by breaking hydrolytically or enzymatically sensitive bonds (Nair and Laurencin, 2007). Based on this, the biodegradable biopolymers could further be classified as hydrolytically degradable polymers and enzymatically degradable polymers. Most of the naturally occurring polymers undergo enzymatic degradation (Nair and Laurencin, 2007). It has been suggested that biodegradation of polymers occurs through enzymatic action of hydrolases such as ureases, proteases and esterases and environmental degradation of synthetic polymers through abiotic hydrolysis (Ganesh Kumar et al., 2020). When discussing about plastics, often other terms as 'compostability' and 'oxo-degradability' are also used.

***Compostable plastic*:** According to the European standard EN 13432, a set of requirements needs to be met in order to declare a plastic material compostable. Some of the most relevant criteria listed in the standard include: (1) the material must be degraded by at least 90% in weight in 6 months in carbon dioxide rich environment; (2) at least 90% of the mass of the material must be reduced to fragments of less than 2 mm if in contact with organic materials for a period of 3 month; (3) the presence of material should not lead to any type of negative effects on composting process, and (4) amounts of heavy metals presence in the composted materials should not surpass the specified limits (Calabro and Grosso, 2018). This standard refers to so called industrial composting at designated facilities, not covering composting plastic materials in regular household conditions (European Bioplastics, 2016). Currently there is no harmonized standard to evaluate plastic material compostability in household conditions, but some counties like Australia, France and Italy have established national standards for home

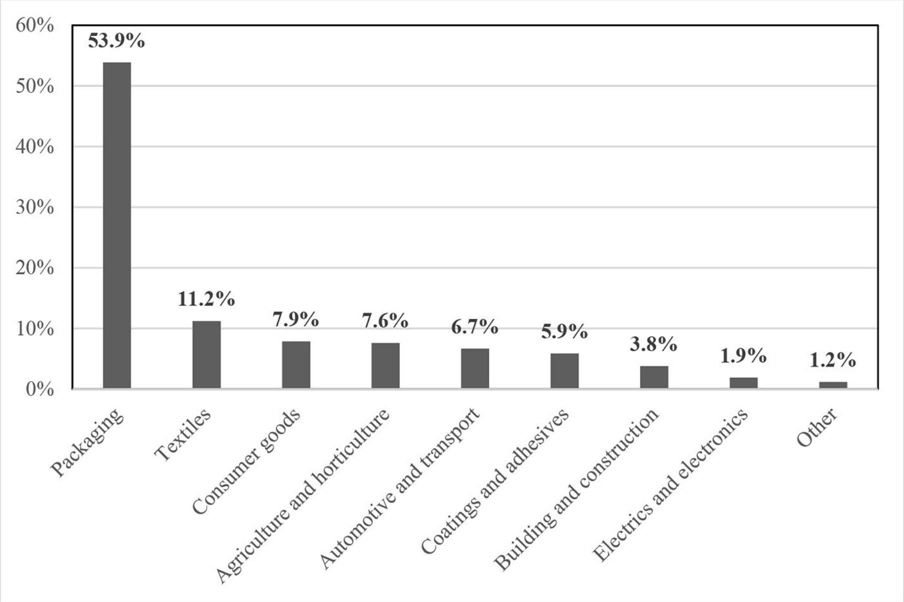


Fig. 4. Bioplastic production by market segment.
Source: European Bioplastics (2020).

compostability of plastic materials (European Bioplastics, 2016).

Oxo-degradable plastic: Plastic material that contains additives that accelerate its fragmentation, triggered by temperature or UV radiation, typically in the presence of oxygen (Dilkes-Hoffman et al., 2019). The fragmentation process breaks down a material into smaller fragments, which is referred to as 'microplastics', and these can be left in the environment for a much longer time until finally broken-down (Green Dot Bioplastics, 2020). In recent years, the issue of microplastics in the environment has also gotten more attention. The small particle size of microplastics makes it possible for them to pass biological barriers, to penetrate to tissues and to accumulate in organs (von Moos et al., 2012). As a result, these particles are bioavailable to different marine animals and get bio-accumulated in various food chains (Ganesh Kumar et al., 2020). In addition to that, several researchers have warned about the potential distribution and transfer of microplastics into groundwater and hyporheic zone (Chae and An, 2018). Moreover, microplastics can act as a vector for different contaminants such as human pathogens, organic pollutants and heavy metals (Qi et al., 2020).

3.2. *Recyclability*

As recyclability is one of the key elements in circular economy model, it is also a concern when it comes to bioplastics. Now, most conventional plastics have well established recycling operations in place, but when it comes to bioplastics, the recovery system is still under development (Soroudi and Jakubowicz, 2013). The disposal system of bioplastics needs to be carefully considered: it should be technologically viable and effective, without jeopardizing the existing recycling system (Soroudi and Jakubowicz, 2013; Dilkes-Hoffman et al., 2019). If the bio-based materials are not sorted from conventional plastics before the recycling process, it may lead to serious implications like contamination, lower quality and physical integrity of recycled material (Cornell, 2007; Soroudi and Jakubowicz, 2013). When discussing on drop-in bio-based plastics (e.g. bio-PE), there are no exemption from conventional structurally identical fossil-based plastics and the materials could be recycled through the same processes (Geueke et al., 2018; Dilkes-Hoffman et al., 2019). Other bio-based and/or biodegradable plastics, on the other hand, are chemically-structurally distinct and exhibit a new group of materials, meaning that other type of disposal method need to be considered (Dilkes-Hoffman et al., 2019).

4. Industrial food wastes and by-products

It has been projected that on a global scale, roughly one-third of food produced is lost or wasted, corresponding to about 1.3 billion tons of food per year (FAO, 2019). Moreover, approximately 3.49 billion tons of carbon dioxide equivalent of greenhouse gases are generated by lost or wasted food along the supply chain (Chalak et al., 2016). Food wastes from primary (pre-consumer food processing step) sector comprise of those food items that does not reach the consumer, as it is either disposed or recycled, including non-edible food parts, nonconforming food to organoleptic, technical or microbiological standards. Food waste from post-consumer supply-chain includes household food wastes and wastes from food service sector (Carmona-Cabello et al., 2018).

The European Union has also compiled guidelines on preferable food waste disposal technologies, also known as food waste hierarchy, that stipulates prioritized actions from most to least preferable: (1) prevent, (2) redirect to human consumption, (3) redirect to animal feed production and industrial use (4) recovery (e.g. soil enrichment and renewable energy), and finally (5) disposal (FoodDrinkEurope, 2019). Currently in use, most conventional waste management options include landfilling, anaerobic digestion, composting, thermal treatment and animal feed production (Esparza et al., 2020). Due to different diseases that can be transmitted via animal origin wastes, recycling food wastes to feed in EU has many restrictions (Salemdeeb et al., 2017). Still, there are successful examples outside EU, like South Korea, where about 45% of all food waste is directed to feed production (Dou et al., 2018).

4.1. *Food waste valorization*

Wastes from food industry constitute a great loss in nutrients and biomass that could be used as functional foods or as a source for obtaining other bio-products, such as enzymes, antibiotics, biofuels or biopolymers (Esparza et al., 2020). Currently not many food waste valorization techniques have been implemented on large scale as continuous waste management options. The main reason is cost effectiveness, due to high transportation and storage costs of wastes and overall process viability. In many cases, the process costs raise the price of final product on a level that it cannot compete with conventional alternatives. Other hurdles include technical constraints to convert extracted compounds to value-added products and insufficient legal framework regarding usage of wastes.

For the time being, four main food waste valorization techniques have been adopted (see Fig. 5) (Nayak and Bhushan, 2019):

(1) Generation to biofuels;
(2) Recovery and extraction of value-added compounds;
(3) Production of bio-adsorbents for wastewater treatment, and
(4) Production of biomaterials.

4.1.1. *Generation to biofuels*

Valorization of food wastes and by-products for biofuel production has a lot of potential (Matsakas et al., 2017; Kannah et al., 2020), as it would increase the value of waste biomass and reduce the general dependence on fossil fuels (Carmona-Cabello et al., 2018). Biofuels in general could be classified by state as gaseous, liquid or solid biofuels (Bundhoo, 2018). Bio-methane (gaseous), bio-hydrogen (gaseous), bio-ethanol (liquid), bio-diesel (liquid) are some of the most known alternatives of biofuels. The biofuel production technologies may include microbial fermentation, aerobic digestion, anaerobic digestion or thermal processes such as carbonization and hydrothermal liquefaction (Nayak and Bhushan, 2019). To maximize the process yield different waste pre-treatment technologies have been adopted, including biological, physical, chemical and physico-chemical methods (Bundhoo, 2018; Banu et al., 2020). Food wastes by nature are heterogeneous and have high moisture content (Sindhu et al., 2019), making it difficult to establish standardized pre-treatment processes. This also influences the overall process efficiency and cost effectiveness (Nayak and Bhushan, 2019). In general, the need for biofuels is constantly growing and integrating technologies for efficient and cost effective processes is still a challenge to overcome.

4.1.2. *Recovery and extraction of value-added compounds*

Food wastes and by-products are composed of different organic and inorganic components (such as proteins, sugars, lipids, fibers, antioxidants, pigments, vitamins and flavor compounds) that could be valorized for the production of cosmetics, nutraceuticals, food and feed additives (Nayak and Bhushan, 2019; Sindhu et al., 2019; Sharma et al., 2020). The processes to separate value-added compounds from food waste matrix may include different pretreatment and extraction operations, followed by additional isolation process step to remove residues and impurities (Nayak and Bhushan, 2019).

Some examples of value-added compounds form food wastes and by-products include:

- Antioxidants extraction from winery wastes and by-products (Barba et al., 2016);
- Nutraceuticals from tomato processing waste (Poojary and Passamonti, 2015);
- Citric acid from apple pomace, carrot waste and pineapple peel (Varshney, 2016).

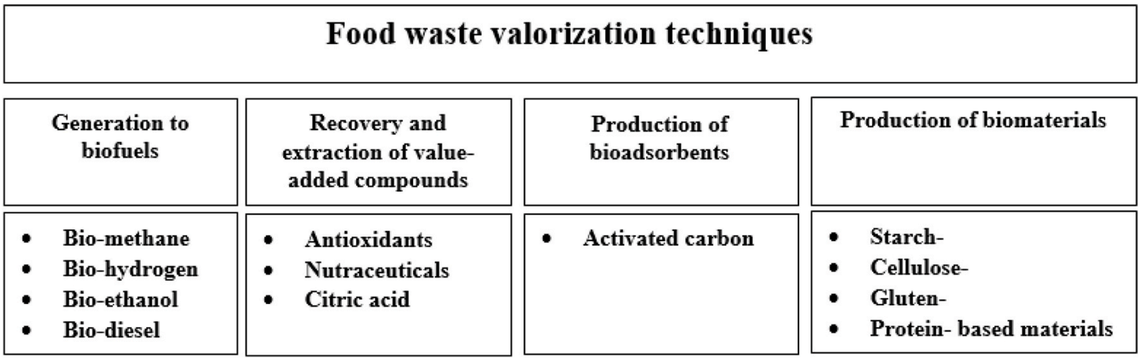


Fig. 5. Food waste valorization techniques.

Currently, most extraction and recovery approaches with waste materials are performed on laboratory scales and implementation for industrial use requires further studies (Contreras et al., 2019).

4.1.3. Production of bio-adsorbents

Clean water is one of the most sought-after resources due to limited availability (Nayak and Bhushan, 2019). This has enhanced demand for sustainable and cost effective technologies for wastewater treatment (Hossain et al., 2020). The conventional wastewater treatment methods include flocculation, coagulation, reverse osmosis, nanofiltration and carbon adsorption (Laufenberg et al., 2003; Shamsollahi and Partovinia, 2019). As most of these methods have downsides such as low efficiency, high cost and risk of producing secondary pollutants (Shamsollahi and Partovinia, 2019), interest for more sustainable and economical alternatives is rising. Compared to other wastewater treatment methods adsorption has proven to be effective and relatively inexpensive (Nayak and Bhushan, 2019; Shamsollahi and Partovinia, 2019). Different food wastes like orange peels, grape and olive pomace, coffee beans and wheat bran have demonstrated suitability for synthesis of activated carbon (Nayak and Bhushan, 2019). As adsorbents bind radicals, ions, atoms or molecules from the surrounding liquid onto the adsorbing surface (Laufenberg et al., 2003), the functional groups (ethers, aldehydes, phenols, ketones, alcohols) in bio-adsorbents enhance the binding capacity, improving also removal of pollutants from wastewater (Nayak and Bhushan, 2019). At the moment, lignocellulose rich biomass based bio-adsorbents are mostly studied, but there is potential to produce bio-adsorbents also from other types of wastes (Ochedi et al., 2020).

4.1.4. Production of biomaterials

Wastes from different sources are environmental burden if disposed inappropriately (Bilal and Iqbal, 2019; Saqib et al., 2019; Tsang et al., 2019). Valorizing wastes and by-products to create value-added products will reduce the volume of wastes and move us towards more sustainable consumption model. When it comes to producing bioplastics from food waste, two main production techniques could be considered: (1) direct extraction form biomass, and (2) bioplastic production via natural or genetically modified organisms.

4.1.4.1. Direct extraction from biomass. Above-mentioned examples of direct biomass extraction included starch, cellulose and gluten. Gluten for example is a by-product from wheat processing (Hertrampf and Piedad-Pascual, 2000). Based on rooted food processing techniques, some wastes and by-products from food industry could be used directly for bioplastic production without the need to implement specific pre-treatment processes or production techniques. As an example, potato protein concentrate (co-product from industrial potato starch industry) could be used in compression molding process to produce bioplastics (Newson et al., 2015). Compression molding is one of the most common thermoset and thermoplastic polymer composite manufacturing processes, allowing to produce composite components in high production volumes (Asim et al., 2017). Another example, rapeseed oil industry by-products (press cake and meal) that could be used in injection molding process for bioplastic production (Delgado et al., 2018). Injection molding is widely used technique for mass production of thermoplastic objects (Ebnesajjad and Khaladkar, 2018).

Using widespread technologies in conventional plastic production (like injection molding or compression molding) for generating bioplastics offers an economically viable option for replacing petrochemical plastic materials (Jiménez-Rosado et al., 2019).

4.1.4.2. Bioplastic production by natural or genetically modified organisms. To use food waste as source for microbial activity, biorefinery platforms should be implemented. Adoption of biorefinery platforms that would allow producing value-added products (such as bioplastic) while reducing the volume of waste would be beneficial for material producers, waste management bodies and environment (de Paula et al., 2018; Nayak and Bhushan, 2019; Russo et al., 2019).

In addition, to use food or other type of organic wastes for bioplastic production, pre-treatment procedures must be applied to enhance or modify biological, chemical or physical properties (Morone et al., 2019; Nayak and Bhushan, 2019; Tsang et al., 2019). Some of the commonly used pre-treatment technologies include mechanical and thermal conversion, chemical conversion, biological conversion and enzymatic hydrolysis of organic waste material, often categorized as biological, physical or chemical means of pre-treatment (Matsakas et al., 2017; Strazzera et al., 2018; Morone et al., 2019; Tsang et al., 2019). The main scope of the pre-treatment process is to reduce the substrates size, extract smaller and simpler chemical compounds and to remove inert materials that are not suitable for following processes (Strazzera et al., 2018; Tsang et al., 2019). Successful conversion process concludes with release of monomers from the waste so that the lipids, polysaccharides and proteins from the waste matrix would be accessible (Strazzera et al., 2018; Tsang et al., 2019; Sharma et al., 2020). Combination of different conversion methods have shown great potential for using bio-wastes as possible raw material for bioplastic production (Tsang et al., 2019). As the composition of waste materials might significantly vary, some of the functional parameters like pH, temperature and hydraulic retention time must be determined specifically to maximize the outcome (Strazzera et al., 2018).

As mentioned before, when using wastes as a feedstock for biosynthesis of bioplastic compounds (such as PHA), purity of produced polymers must be considered as viral, bacterial, plasmid or genetic contaminations may transfer to the final material (Raza et al., 2018).

5. Conclusion

Growing concerns on plastics pollution and accompanying negative impact to the environment has encouraged research and innovation in the field of bioplastics to find alternatives for conventional petrochemical plastics. Global demand for bioplastics is continuously growing and now there are already alternatives for most of conventional plastics with identical material properties. Cost-effectiveness is the main aspect that limits the production and usage of bioplastics. To reduce the production costs of bioplastics, cheap and abundant raw materials, such as food wastes and by-products can efficiently be explored. Now, there are not many food waste valorization techniques implemented on large scale for waste management and bioplastic production, but future research activities are directed to genetic engineering, waste pretreatment processes and biorefinery platforms. As the production quantities of bioplastics are expected to grow, more emphasis should also be put to develop sustainable recycling routes for bio-based materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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