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Sustainable utilization of fruit and vegetable waste bioresources for bioplastics production

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Abstract

Nowadays, rapidly increasing production, use and disposable of plastic products has become one of the utmost environmental issues. Our current circumstances in which the food supply chain is demonstrated as containing plastic particles and other plastic-based impurities, represents a significant health risk to humans, animals, and environmental alike. According to this point of view, biodegradable plastic material aims to produce a more sustainable and greener world with a lower ecological impact. Bioplastics are being investigated as an environmentally friendly candidate to address this problem and hence global bioplastic production has seen significant growth and expansion in recent years. This article focuses on a few critical issues that must be addressed for bioplastic production to become commercially viable. Although the reduction of fruit and vegetable waste biomass has an apparent value in terms of environmental benefits and sustainability, commercial success at industrial scale has remained flat. This is due to various factors, including biomass feedstocks, pre-treatment technologies, enzymatic hydrolysis, and scale-up issues in the industry, all of which contribute to high capital and operating costs. This review paper summarizes the global overview of bioplastics derived from fruit and vegetable waste biomass. Furthermore, economic and technical challenges associated with industrialization and diverse applications of bioplastics in biomedical, agricultural, and food-packaging fields due to their excellent biocompatibility properties are reviewed.

Keywords: Bioplastics; Biodegradable; Biomass-Feedstock; Pre-treatment; Enzymatic hydrolysis; Industrialization

Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), approximately 1.3 billion tonnes of food are lost or wasted worldwide each year. According to Xue et al. [1], this accounts for one-third of all food resources produced for human use. Food waste can come from a variety of sources, including municipal, commercial, industrial, and agricultural operations, and its composition varies widely depending on the source and type of waste [1-4]. In addition, other resources such as land, water, energy, and labor are also lost due to food waste. Landfilling, composting, and fermenting are the most common current methods of food waste (FW) disposal. Even though European Union guidelines recognise that FW should be used first and primarily as animal feed where it is safe to do so, millions of tonnes of organic surplus remain undervalued, or are managed as waste [5-7].

During the FW epidemic, the French government has already implemented a policy to encourage the valorization of FW by recovering energy (e.g., biogas) and value-added materials (e.g., a bioplastic) with a punitive law and saved 88 million tonnes of FW per year equivalent to $167 billion [8, 9]. However, this policy approach is not universal. Every year, 15 million tonnes of FW arises in the United Kingdom [5]. Malaysia is estimated to generate 6.7 million tonnes of FW per year by 2020 [10]. The US generates between 567 and 726 million tonnes of FW per year (equal to up to 40 percent of total food output) (US EPA, n.d.). This is the same as USD 218 billion in FW [11]. Hence, FW may become a key future material stream to reduce resource intensity across resource streams as wastes are valorised as high-value products, which is a fantastic equitable and pragmatic end-use.

Lignin, cellulose, and hemicellulose are converted into biofuels and other platform chemicals in biorefineries [12-15]. However, due to several characteristics such as biomass source, type, and recalcitrance level, there is no uniformity in converting lignocellulosic biomass into these end products [16-19]. To purify lignocellulosic biomass into more than 200 other value-added chemicals, a range of valorization techniques can be applied [20]. **Fig. 1** described value-added products like biofuels, biofertilizers, biochemicals, and biopolymers from fruit and vegetable waste biomass. The conversion of polysaccharides determines the cost-effectiveness and efficiency of the bioconversion process into monomeric sugars [21-24].

To set up full-scale biochemical and bioenergy production from biomass, several fundamental challenges that affect product output and energy input required in the bioconversion process must be addressed. Lignocellulosic biomass is a complex resource consisting of carbohydrates (cellulose and hemicellulose) firmly enclosed in a framework lignin polymer structure [12,25,26] with the structure varying with the specific source of biorefinery biomass feedstock. On the other hand, the presence of the lignin polymer considerably reduces the ability of the required enzymes to attack the cellulose and hydrolyze it into sugars, resulting in low yields [21,27,28]. A further pre-treatment stage is necessary to breakdown this refractory structure and enable separation and subsequent treatment of the biomass constituent. Numerous pre-treatment procedures have been developed over the years to separate the lignocellulosic structure and render it susceptible to hydrolysis [29,30]. Pre-treatment helps with the development of second-generation (2G) sugars, which are normal intermediates in synthetic and natural conversion and are a significant component in biorefineries [31]. On the other hand, pre-treatment is a time-consuming and costly technique that differs significantly, relying upon the feedstock and the ideal end-product [21]. Thus, it is very important to follow this procedure though assessing the overall techno-economic viability and sustainability of the lignocellulosic biorefinery.

As a result of negative externalities, many countries and corporations are looking into bioplastics to replace traditional plastics. Many of them are said to be biodegradable and could be a key answer to plastic pollution. Galalith and Polyhydroxyalkanoates (PHAs) were among the first bioplastics found about a century ago [32]. Many bioplastics are currently available in the market, including polylactic acid (PLA), poly (butylene adipate-co-tereph-thalate) (PBAT), Mirel, and Bio-PET. The market is now dominated by starch-based polymers for example mixtures with polycaprolactone (PCL) and polybutylene succinate (PBS) [33]. MakeShaper [34] reported that poly(3-hydroxybutyrate), or P (3HB), the most popular kind of PHA, cost around US$ 5.5 per kilogram in 2017, whereas PLA filaments cost around US$ 21. The possibility of reusing fruit and vegetable waste for bioplastic production, as well as novel methods for lowering extraction costs in the production of commercially accessible cellulose/hemicellulose/lignin-based bioplastics, have also been examined [35].

PHAs have attracted a lot of interest because of relatively quick (one-year) biodegradability in a variety of circumstances [36]. PHA has been produced using a variety of bacteria (including *Alcaligenes* spp., *Azotobacter* spp., *Methylotrophs*, *Pseudomonas* spp., *Bacillus* spp., and recombinant *Escherichia coli*) from several low-cost substrates. In addition, organic wastes and by-products can be used to make PHA, which can be used to replace petrochemical-derived polymers. In actuality, because the cost of the substrate has the greatest impact on the production cost of PHAs, significant efforts have been made to developing bacterial strains and more effective fermentation/recovery procedures to reduce the cost of production [37]. The key prospects for making bioplastic production more realistic for industrial use are the promotion of less expensive substrates, enhanced microbe growing strategies, and simpler downstream processing processes, all of which are necessary for lowering production costs [37]. As a result, sucrose, starch-based materials, cellulosic and hemicellulosic materials, sugars, wheys, oils, fatty acids, and glycerol, as well as organic matter from fruit and vegetable wastes, have all been explored as potentially promising biopolymer substrates [37].

Several researchers reported that simultaneous conversion of FW to energy and bioplastics focused on bioplastic production processes, operating conditions, and novel bacterial/archaeal species used in the fermentation process [38]. However, only a few studies have considered the possibility of producing bioplastics from FWs such as fruits [39] and vegetable wastes [40]. Over the last decade, significant efforts have been made to convert fruit and vegetable waste (FVW) biomass into bio-based biodegradable polymers. Indeed, as the world's attention shifts to sustainable development and renewable resources, the question of how to convert FVW efficiently into bioplastic has become more prominent. Though, it has a lot of commercial potentials and is financially viability is yet to ascertained. Hence, this review intends to explore the initiatives being made by regulatory and governing agencies throughout the world to advance the circular economy and more environmentally friendly, sustainable production of bioplastics utilizing natural fruit and vegetable ingredients. Moreover, this review highlights current progress in addressing the challenges facing the economic, and technical implications of biodegradable polymers with immense applications in food packaging, agriculture, and biomedical approaches.

Bioplastic Trends and Development Driver

Bioplastic, a renewable alternative to petroleum-based plastics, is made from renewable feedstocks. Carbon dioxide emissions could be reduced by 30 to 70 percent. This translates to a 42 percent reduction in carbon footprints. Bioplastic is produced using 65 percent less energy than petroleum-based plastics. Companies are increasingly focusing on expanding and consolidating research and development activities to increase production capacity in the global bioplastics market. Because of its improved qualities and utility, bioplastic is now widely used in various applications. Bioplastics have nearly taken over the plastic business in recent years, thanks to favorable legislation enacted by several governments worldwide. As a result, bioplastics are gaining popularity and will continue to grow year after year. According to researchers, bioplastics will have a 5 percent market share of total plastics by 2020 and a 40 percent share by 2030, making bioplastics a $324 billion-dollar enterprise in just over a decade. The key factors behind these projections are consumer desire/market pull, business vision, design practicality, and cost. Consumers are becoming more aware of the risks of petroleum-based plastics and the advantages of environmentally friendly biobased polymers [32].

Global Environmental Challenges

The high energy density of traditional fossil fuels makes them a reliable energy source for the planet's growth, development, and industrialization [41]. Demand for energy and raw materials will continue to rise as the global population grows to 9.2 billion people by 2050, placing natural resources and environments under strain beyond their capability [42]. According to the Food and Agriculture Organization [43], feeding this population will require an increase in cultivable land of over 1 billion ha (by 2030). The disruption of ecological balance, which puts biodiversity at risk and the loss of aqueous systems and air quality, is a little-noticed side-effect of this constant use of resources [44]. Polyethene (PE), polypropylene (PP), and polyethylene terephthalate (PET) are the most common plastic resins used in packaging today, accounting for more than 80 percent of all plastic packaging [44]. Many of these plastics wind up in the environment, where they degrade into nano plastics [45], causing harm to marine [46] and terrestrial [47] ecosystems as well as human health [48]. All of these restrictions on the use of fossil fuel-based plastics would drive up demand for bioplastics, therefore it's critical to understand the environmental consequences of making the changeover. The transition to biomass is frequently referred to as a step towards a circular economy, to reduce greenhouse gas (GHG) emissions and environmental impacts. Most countries have adopted circular economy [49] and bioeconomy [49] initiatives. Alternative feedstocks are developed and employed for bioplastic synthesis in these techniques, to replace fossil-based alternatives.

From 2021 to 2026, the biodegradable production capacity growth rate is much larger than the bio-based/biodegradable growth rate, with total output rising from 2.42 million tonnes in 2021 to

7.59 million tonnes in 2026, as shown in **Fig. 2** [50]. However, as indicated in **Fig. 3**, the area used to develop renewable feedstock sources for bioplastic manufacture makes up less than 0.02 percent of worldwide agricultural land. As a result, despite expected market growth, traditional agriculture and bioplastic production face limiting competition, with pasture, feed, and food already accounting for roughly 97 percent of the worldwide agricultural land area [50].

EU framework for sustainable development

The EU has devised a strategy to minimize reliance on non-renewable energy sources while increasing production and use of sustainable green resources, considering global agreements. In 2012, the European Union released its European Bioeconomy Strategy, which aimed to provide a platform for resource efficiency and innovation in a circular economy. The purpose of the bioeconomy is to include all industries that use bio-based resources such as plants, animals, and biomass, as well as organic waste. In addition, the EU is a major producer of plastic, accounting for 17 percent of global output [51]. According to the European Bioplastics Association, bio-based/non-biodegradable plastics will account for 87 percent of worldwide bioplastics capacity by 2016 [51]. The EU has developed policies to improve plastic recyclability, increase demand for recycled plastics, decrease the use of single-use plastics and microplastics in products, provide guidance to national governments and businesses on how to reduce plastic wastes at the source, and collaborate to develop global solutions and international standards [52].

US Bioeconomy development focus

The Biomass Research and Development Act of 2000, which established an Interagency Biomass R&D Board, a Technical Advisory Committee, and the Biomass R&D Initiative (BRDi), marked the beginning of the bioeconomy in the United States in the early 2000s [53]. In the United States' National Bioeconomy Blueprint of 2012, the economy was characterized as "one centered on the utilization of biological sciences research and innovation to promote economic activity and public benefit." [54]. The bioeconomy was defined in 2014 as "a global industrial revolution based on the sustainable use of renewable aquatic and terrestrial biomass resources in energy, intermediate, and final products for economic, environmental, social, and national security benefits " [55]. The United States Department of Agriculture (USDA) BioPreferred program was established by the Farm Security and Rural Investment Act of 2002 (FSRIA) and reauthorized by the Food, Conservation, and Energy Act of 2008 to promote the procurement and use of biobased items as well as economic development through the utilization of renewable resources [56]. In 2017, the US bioproducts market was estimated to be worth $520 billion [56]. As part of the Billion-Ton Bioeconomy Initiative, the United States has likewise established a goal of becoming a bioeconomy superpower by 2030 [53].

Asian bioeconomy for sustainable development

Bioplastics have quickly grown in popularity as a partial replacement for traditional plastics, which negatively influence the environment [57]. Surprisingly, several Asian bioplastic producers, such as Thailand, Singapore, and China, have benefited from direct government support, primarily in the form of subsidies for R&D and biotechnology clusters, to attract industrial hubs. Countries such as Japan, South Korea, Singapore, Malaysia, Thailand, and China also provide financial and non-financial incentives to enterprises participating in bioplastic research [58]. Asian countries are better positioned to obtain bio-based building blocks as a precursor for bio-based polymer synthesis due to favorable policy frameworks [57]. For example, biotechnology's growth is closely linked to China's political interest in the bioeconomy [59]. The Biomass Nippon Strategy in Japan has spurred corporations like Toyota and NEC (Nippon Denki Kabushiki-gaisha) to increase their biobased plastics research and development, as well as biobased component of their goods. Toyota planned to transition 20 percent of its car plastics to bio-sourced plastics by 2015, and bioplastics were expected to assist the company to reduce CO_2 emissions [60]. Bioplastics had been categorized as a key industry by the Thai government since 2006, as part of its long-term growth and development strategy that the National Innovation Agency released in 2008 [61,62].

Generation of Bioplastic value: economical and technical implications

Feedstocks and their accessibility

Renewable plant components such as starch, cellulose, oils (e.g. rapeseed oil), lignin (wood), proteins (e.g. maize zein), and polysaccharides can be used to make bio-based polymers (e.g. xylans). Organic waste materials and petro-plastics (e.g. PET) can now be utilized to manufacture synthetic bio-based plastics (such as polyhydroxyalkanoates or PHAs, PLA, and so on) thanks to recent technological developments [63]. Depending on availability throughout the year, a wide range of lignocellulosic biomass sources can therefore be used as feedstock. As a primary feedstock, several countries use the most abundant biomass supply available to them [64]. For example, corn stover and sugarcane definition leftovers are widely used in the United States and Brazil. Sugarcane bagasse is used by countries with predominantly agricultural economies, such as India and China [65]. With the UK government intending to cut greenhouse gas (GHG) emissions by 80 percent by 2050 compared to 1995 levels, using renewable and sustainable materials and fuels is more important than ever to reduce our environmental effects. In Europe, starch is now the most frequently used bio-based polymeric material. These materials are currently used to make waste and carrier bags, and food and consumer goods packaging in the United Kingdom.

The most popular first-generation feedstocks utilized in commercial bioplastics include corn, wheat, potato, sugar beet, maize, and sugarcane [13]. Manufacturing these bioplastic feedstocks necessitates large inputs, such as fertilizer and land use, which may contradict the bio-based materials claimed environmental efficiency [66]. If the market expansion continues, land utilization for bioplastics is predicted to reach 0.7 million ha (0.015 percent of global land area) in 2020, rising to 0.020 percent of the global land area in 2025 [67]. Non-food crops (cellulosic feedstock) or waste materials from the first-generation feedstocks can be used as second-generation feedstocks (e.g. waste vegetable oil). Wood, short-rotation crops like poplar, willow, or miscanthus (elephant grass), wheat straw, bagasse, corncobs, palm fruit bunches, and switch grass are examples of second-generation feedstocks. However, using second-generation feedstocks like lignocellulosic or waste biomass can help to reduce the stress of cropland development and related GHG emissions from land-use change [68]. Bioplastics' potential environmental benefits will not be realized if the potential credits earned from avoided petrochemical plastic manufacture, avoided end-of-life procedures, and/or long-term sequestered carbon exceeds the bioplastic production emissions [66]. As a result, understanding bioplastics' long-term niche is critical, as is anticipating the production load constraints required for environmental neutrality from various bioplastic feedstocks to determine how bioplastics may be produced in a net-zero carbon future. Marine-based biomass, such as seaweed [69] and microalgae [70], is an emerging avenue or third generation of biomass feedstock that has recently attracted research attention due to its high growth rate and photosynthetic ability, as well as the fact that it does not rely on traditional arable land. It also applies to bioplastics made from CO_2 or methane.

The production cost and economic viability of PHA generated from waste are calculated using a techno-economic analysis. According to Shahzad et al. [71], the manufacturing cost of PHA when employing offal waste ranges from 1.41 €/kg to 1.64 €/kg, with a payback period of 3.25 to 4.5 years. The fermentation capacity of PHAs from citric molasses of *Cupriavidus necator* is 166 m^3, with a PHA production capacity of 2000 tonnes per year. The total cost of production for PHA is between \$4.26 and \$4.72 per kilogram [72]. PHA was produced with biogas from an anaerobic waste treatment plant, costing 4.2 €/kg. The most expensive components of PHA manufacturing are separation and purification, which account for a considerable portion of the total operating cost. In addition, the carbon supply for fermentation is critical in biopolymer synthesis. This study is unusual in that it examines both the economic viability of producing PHAs from FW and the parameters that influence profitability and the MSP of PHAs [73].

Pre-treatment of FVW biomass

Pre-treatment, which breaks down the biomass's refractory structure and releases the cellulose and hemicellulose from the lignin matrix structure, is a critical step in maximizing the utilization of biomass. This procedure facilitates saccharification and improves the end product yield [13]. Even though FVW is an excellent feedstock for bioplastic production, it is important to develop or modify the different pretreatments such that physical (extrusion, milling), chemical (ionic liquids, alkali, concentrated acid hydrolysis), physicochemical (ammonia fibre expansion, CO2 explosion, and steam explosion), and biological (fungi, bacteria, and enzymes) properties can be tailored for better improvement of bioplastic production as per Tsang et al. [35].

On the other hand, traditional pre-treatment procedures, have several disadvantages, including high energy consumption and cost, inhibitory intermediates, and by-product production, all of which reduce the overall appeal of biomass valorization [21]. For example, most physical pre-treatment techniques, require a lot of energy and complicated equipment, which increases the overall cost and limits industrial scalability from the lab scale [74]. In contrast, chemical pre-treatment uses less energy but requires the use of digesters and chemicals that can increase the cost and decrease the process's overall greenness [75]. To improve the efficiency of biomass breakdown, these pre-treatments are typically combined with thermal processes associated with high pressure and temperature [74]. Furthermore, the hydrolysate is usually neutralized by inhibitors before saccharification, increasing the overall valorisation cost [76]. Toxic inhibitor derivatives generated during the process are dangerous to the environment and must be handled before disposal, increasing the overall cost. As a result, biological pre-treatments are becoming more popular because they are environmentally friendly, require less energy, produce no by-products, and are generally less expensive. Pre-treatment microorganisms can also be used to synthesize enzymes, lowering the cost of enzyme sourcing. Hence, large-scale hydrolysis necessitates massive bioreactors, and both microbial growth and enzymatic hydrolysis rates are slow, inhibiting widespread use of these technologies [77].

Due to various factors influencing the properties and mechanisms of lignocellulosic biomass, developing and implementing a consistent pre-treatment strategy is difficult. Jambul seeds were dried in a 60°C oven to reduce moisture content before being ground into fine particles to produce PHA. A steam-explosion process (160 to 260 °C and 0.7 to 4.8 MPa) can be used to remove lignin and hemicellulose from cellulose in lignocellulosic waste [78]. Elbeshbishy et al. [79] investigated ultrasonication and heat, ultrasonication and acid (i.e., 1 N HCl, pH = 3.0, 24 h at 4 °C), and ultrasonication and base (i.e., 1 N NaOH, pH = 11.0, 24 h at 4 °C). Alkaline ultrasonication has the largest growth rate of 30 percent soluble chemical oxygen demand (COD) and 40 percent soluble protein, according to the findings. At a loading rate of 20 FPU g^{-1} of pretreated paddy straws, the hydrolysis yield was 0.84 gg^{-1}. PHA production requires a combination of physical and chemical treatments to maximize performance and increase ultimate yield. The use of microorganisms to change lignocellulosic biomass to increase the accessibility of cellulose, hemicelluloses, and lignin for product development is known as biological pretreatment [80]. In comparison to other methods, this approach is more selective in its application and consumes less energy. For example, Tomizawa et al. [81] investigated the synthesis of polyesters from lignin derivatives, whereas Sandhya et al.

[82] stated that *Ralstonia eutropha* is a strain capable of producing PHA and PHB from lignocellulosic biomass. Xia et al. [83] reported that the lignocellulosic wood biomass was converted into a high-performance bioplastic using a simple *in-situ* lignin regeneration method. This method fibrillates the wood while also dissolving the lignin using the deep eutectic solvent (DES)~~,~~ a group of environmentally friendly solvents that combine the properties of both ionic liquids and organic solvents. Oxalic acid and choline chloride serve as the acceptor and donor of hydrogen bonds in the DES, respectively. As a result, lignocellulosic bioplastic has improved thermal stability, water stability, mechanical strength, and UV radiation resistance. **Table 1** provides an overview of different parameters of the pretreatment along with a breakdown of FVW biomass for the production of bioplastic materials. **Fig. 4** summarizes how fruit and vegetable biomass is converted into polysaccharides for the synthesis of PHA.

Biomass conversion by enzymatic hydrolysis

Following the pre-treatment, the carbohydrates are converted into soluble sugars via enzymatic hydrolysis. Enzymatic hydrolysis has proven to be a highly effective and cost-effective way of hydrolyzing biomass into reducing sugars, with polysaccharide conversion rates surpassing 90 percent. Pre-processing, transportation, and storage of biomass account for nearly half of the total cost [84], whereas enzymatic hydrolysis accounts for nearly a quarter of the total cost [85], making optimization of the step critical to achieving profitable levels of hydrolysate production. A critical issue is the development of a high-efficiency enzyme cocktail capable of hydrolyzing polysaccharides from lignocellulosic biomass. Cellulases and hemicellulases are enzymes that hydrolyze cellulose and hemicelluloses, respectively. Polysaccharide monooxygenases that can undergo oxidative chain breakage can also be used to degrade cellulose [86]. Hydrolysis of hemicellulose requires a complicated combination of enzymes, including xylosidases, mannanases, xylanases, and arabinofuranosidases, due to the diversity of hemicellulose. **Table 2** lists selected examples of enzymatic hydrolysis performed on FVW biomass for bioplastic production. **Fig. 5** describes the enzymatic hydrolysis of microorganisms and FVW biomass for the production of biobased polymers.

Hydrolysis is primary mechanism for converting polymers into monomers and/or intermediates. Enzymatic hydrolysis enhances FW hydrolysis and reduces volatile suspended solids. Heng et al. [87] used microorganisms *Burkholderia cepacian* USM (JCM 15050) to improve a three-step PHA generation process from rice husks that included alkaline pretreatment, enzymatic hydrolysis, and biosynthesis conversion. As a result, multi-step treatment approaches can improve most carbon sources' biodegradability, leading to improved PHA production performance and efficiency. According to Lin et al. [88], platform chemicals for bioplastics production, such as succinic acid, lactic acid, fumaric acid, and PHB, can be generated through sugar fermentation in domestic FW, such as fruits, vegetables, and dried food products.

Halophilic bacteria *Halobacillus alkaliphilus* (type strain FP5; DSM18525), and thermophilic bacteria *Bacillus thermantarcticus* and *Geobacillus thermoleovorans* subsp *stromboliensis* (type strain Pizzo; DSM15392) as well as halophilic archaeon *Haloterrigena hispanica* (type strain FP1; DSM18328) produce PHB using carbon from agro-industrial wastes such as tomato, lemon, and carrot. Carrot waste as a sole carbon source generates a comparable amount of PHB (1.25 mgg^{-1} dry cell) to complex media (1.35 mgg^{-1} dry cell) [89]. As a result, vegetable waste can be used to produce bacterial biomass and biopolymers as a fermentation medium. Wine lees and crude glycerol serve as nutrition and carbon sources in batch and fed-batch fermentations of PHB utilizing the *Cupriavidus necator* DSM 7237 strain. The yield was approximately 30.1 gL^{-1} [90]. As a result, biorefining food waste could lead to developing a cost-effective method for producing biopolymers.

Apricot, grape, and cherry pomace can be used as substrates for *Pseudomonas* cultures to produce mcl-PHA (*P. putida* KT2440 and *P. resinovorans*). mcl-PHA was made from wasted frying oil and the microorganism. The yield of mcl-PHA with apricot as substrate was 1.4 gL (of pomace)$^{-1}$ and 21.3 gL (of pomace)$^{-1}$ for solaris grape [91]. *C. necator* has also been found to utilize enzyme-treated grape pomace from winery waste as a carbon source to manufacture PHA [92]. Using genetically modified *C. necator* H16 strains, butyrate can enhance the content of (R) 3 hydroxyhexanoate in poly (3 hydroxybutyrate co 3 hydroxyhexanoate) (PHBH) synthesis [93]. While other vital elements like oxygen, phosphorus, or nitrogen are scarce, their synthesis occurs; they can be processed in the same way as polypropylene after being extracted from cell cultures, including extrusion and injection molding, to produce a material with similar properties.

The performance and cost of enzyme cocktails made by combining extracts from various microorganisms can be designed and validated using statistical approaches [94]. The cost of producing cellulase enzyme was estimated using an open-access process model. The cost of producing enzyme ranged from 0.09 € per liter (loading of 5 FPU/g) to 0.389 € per liter (loading of 10 FPU/g) when using the *Trichoderma reesei* fungus with a cellulase production rate of 100 g/L in 8 days [13]. As a result, a wide range of enzyme sources must be investigated and evaluated to generate innovative enzyme blends capable of hydrolyzing various types and sources of lignocellulosic biomass. Microorganism bioprospecting, metagenomic analysis, and heterologous expression are some of the strategies that can be utilized to improve enzymatic activity and minimize the cost of enzymatic hydrolysis [94].

Scale-up and circular bioeconomy towards bioplastic production

Biorefineries must be scaled up from lab-scale to industrial installations as worldwide demand for bio-based products grows. Due to the volume of biomass that must be processed to reach industrial-scale bioproduct production, lignocellulosic biorefineries have the same technical problems as any other refinery. Resource management, process improvements, and innovation are all required to scale up lignocellulosic biorefinery operations [95]. As a result, identifying appropriate characteristics required for scaling up from the laboratory-scale to the pilot-scale to the commercial-scale is crucial. Due to the vast array of variables that can affect the yield and compounding of deterrents at the large scale, it is not always possible to replicate bench-scale or pilot-scale results on large volumes of lignocellulosic biomass. As a result, developing techno-economic models based on processing flows, process models, and simulations to conduct risk and cost sensitivity studies, life cycle evaluations, and projections is crucial [96]. A scaled-up biorefinery's performance is also contingent upon the right combination of process design and biomass feedstock selection. It is possible to conclude that biomass type, content, and pre-treatment conditions all have significant implications for biorefinery design and scale-up [95].

Morone et al. [97] investigated the potential of bio-waste for bioplastics manufacturing using social network analysis and the Italian bioplastics industry as a case study. It reveals that the network of Italian bioplastics producers has tremendous potential for the development of a biowaste valorization-based technological niche. However, the system is flawed, especially when it comes to people who hold important positions within the network and have typically low expectations. If no appropriate governmental steps are taken, this weakness could threaten the niche development process. By increasing knowledge development and dissemination, and fostering strategic collaboration schemes, this research could assist policymakers in developing strategies to maximize the vast potential of bio-waste and the bioplastics sector. For example, government actions could be used to improve social learning as a driver of expectations [98].

Sustainable development strategies have grown in popularity in recent years as fossil fuel supplies have depleted and environmental concerns have grown, and bio-based polymers have sparked a lot of attention. Bio-based polymers have yet to find widespread use in industries as a replacement for traditional plastics due to their high manufacturing costs and occasionally poor performance characteristics. Biopolymers are now priced between 2.0 and 7.0 times more than conventional resins, which cost less than 2 € kg^{-1} [87,88]. The disparity is caused by fluctuations in oil prices as well as the type of bioplastics used, such as starch or PHAs, which are produced through fermentation rather than dedicated crops [98]. The most expensive parts of bioplastic manufacturing include the fermentation process, carbon supply, PHA yield on specific carbon and other energy sources, process productivity, and downstream processing [99]. As a result of these reasons, PHA commercialization continues to lag behind synthetic polymers. On the market, synthetic polymers such as polypropylene and polyethylene cost 1.35-1.96 €/kg, but PHA costs 3–4 times more, ranging from 5.07 to 6.20 €/kg [100]. **Table 3** represented the production of PHAs has been commercialized by various industries worldwide. **Fig. 5** described the scaling up of biodegradable polymer production from laboratory to commercial scale with their techno-economic analysis and global circular economy.

Application of Bioplastics

Food packaging

In recent years, the food business has focused heavily on plastic packaging challenges, which are a different industry in and of themselves [101]. This industry is continually changing to meet the needs and criteria of the food manufacturing industry. Its focus on new polymer-based packaging is critical for the food industry's long-term sustainability and quality standards, resulting in cleaner and more sustainable supply chains that span manufacturing facilities, internal storage systems, and transportation, among other things [102]. Compostable or degradable biomaterials may fulfill the desire for packaging that is low in cost, has a low ecological effect, is not difficult to modify, and has a little natural impression as well as meeting the prerequisite for elevated requirement capacities [103]. This industry is continually answering the requirements and rules of the food creation world, and its accentuation on the improvement of new biopolymer-based packaging is basic for the general food industry's sustainability and quality guidelines, bringing about cleaner and more feasible delivery chains from creation offices and inward stockpiling frameworks to transportation offices, and commercial centers (**Fig. 5**). Compostable or degradable bioplastics can address both the requirement for excellent capacity properties and the desire for packaging that has a low natural effect, is not difficult to rebuild, and is light in weight [103].

The main disadvantages of bio-based polymers in the food industry are their higher cost and lower water barrier qualities than conventional plastics; however, starch-based films are the most widely used materials in this field for fruit and vegetable packing and transportation. The primary advantage of this material is that it breathes well, which is essential for extending the shelf life of fresh foods [104]. Fruits and vegetables have a high rate of respiration, which causes ideal conditions to degrade quickly; they are especially sensitive to water, carbon dioxide, and ethylene concentrations. A good carbon dioxide/oxygen ratio in the surrounding atmosphere, a decent barrier against light, good mechanical attributes, and an odor barrier are all-important package characteristics.

PLA containers (Versapack®, 8 oz., Wilkinson Industries Inc., USA) can be used for blueberry post-harvest packing [105]. PLA containers, as opposed to traditional PET containers, have the potential to create an environment with a more balanced balance. As a result, blueberries' shelf life was extended. According to Haugaard et al. [106], fresh, unpasteurized orange juice can be stored in PLA packaging (thermoformed cups, Auto bar, France) at 4 °C for 14 days. PLA was found to be the most effective at preventing color changes, ascorbic acid (AA) degradation, and limonene scalping when compared to polystyrene (PS) and high-density polyethylene (HDPE). The pasteurization of a beef salad packaged in traditional (polyethylene [PE] and polypropylene [PP]) and biobased (PLA, PHB) packaging, and discovered that PHB films can be used to pack this type of food successfully [107]. Haugaard et al. [108] state that, commercial juices, other acidic drinks, dressings, and other fatty foods may contain PHB. They discovered that dressing packaged in PHB and orange juice stimulant-induced the same quality alterations as dressing packaged in HDPE. Physical, mechanical, sensory, and dimensional (dimensions, volumetric capacity, weight, and thickness) tests indicate that PHB can replace PP in the packaging of high-fat foods (mayonnaise, margarine, and cream cheese). Additionally, Popa and Belc's [109] reported that cellophane's barrier properties were improved by being covered with nitrocellulose or PVdC (polyvinylidine chloride), making it ideal for use in the packaging of baked goods, processed meats, cheeses, and chocolates.

Polymeric films are used as a substrate for various active compounds, such as natural extracts, that can be added during the assembling system of packaging [110]. Antimicrobials can be integrated into the film or covered on the film's or alternately food's surface (as eatable film). Grapefruit seed and green tea extracts, which are active as antioxidants and against various human-causing pathogens (e.g., *Escherichia coli* and *Listeria* spp.), are two of the most effective examples of natural component inclusion in films [111].

Agricultural

Nets, grow bags, silage wraps, mulch films are examples of agricultural applications for PHA-based bioplastics. Bioplastic-based nets are gaining traction as a feasible option in contrast to HDPE, which has historically been used to further develop the quality and productivity of crops while maintaining it from birds, insects, and the elements [101]. Grow bags, also known as planter bags or seedling bags, are constructed primarily of inexpensive low-density PE. However, grow bags composed of PHA would be biodegradable, root-friendly, and non-toxic to nearby water sources. Bioplastics in mulch films must replace fossil-based polymers in mulch films to maintain superior soil structure, moisture retention, weed control, and pollution avoidance [112]. Overall, both agriculture and horticulture could make extensive use of bioplastics [113].

Water retention, fertilizer, and pesticides are all examples of applications where bioplastics are utilized as frameworks (**Fig. 5**). For example, bioplastics can be used as insect and microbe traps to avoid the use of pesticides [114]. This method is ideal for organic farming because it protects plants from the harm caused by the use of harmful chemicals. However, various additives must be added to increase the attractiveness of these materials to microbes and insects. Typically, naturally occurring chemicals with enticing aromas, such as imidacloprid, are used for this [115]. The biodegradation of bioplastics allows for the controlled release of these compounds, extending the useful life of the systems. Droughts are increasing in frequency as a result of climate change, and irrigation systems are becoming increasingly necessary in many places [116]. However, due to scarcity of nearby water sources, this irrigation is either prohibitively expensive or impossible to implement in many areas [117]. Commercial plastics, such as Evonic's Creasorb and BASF's Luquasorb, have been developed in this field to make it easier to feed water to crops. These plastics may capture a large amount of water, regardless of whether it is restricted, during rainy periods and then gradually feed water to suit the plant's requirements. However, because these polymers are single-use, they should be taken out after use to avoid spreading harmful substances to food, which raises the cost of using these systems [118]. Bioplastic matrices may be a viable option in this case.

The increased recognition of the damage to the subsurface and groundwater caused by excessive fertilizer use in agriculture is noticeable [119]. As a result, various options, such as using conservation tillage or avoiding the use of anthropogenic residues, have been considered; however, these alternatives are not competitive due to the variety and speed with which fertilizers stimulate crop growth [120]. The most recent trend is to investigate systems for controlled fertilizer release, tailoring them to crop needs and, as an outcome enhancing assimilation efficiency while decreasing contamination. Different plastic frameworks have been popularized in this field (Nutricote by Projar and Multicore by Haifa), however, they face issues because of the low biodegradability of the polymers utilized, which remain in the soil and are challenging to eliminate. As a result, bioplastic matrices are gaining popularity in this field. As a filler material, these bioplastic matrices can support fertilizers. The fertilizers can then be delivered in a regulated manner, either through irrigation water or biodegradation of the bioplastic matrix [121]. As a result, fertilizer efficiency may be developed, and the challenges associated with removing the systems can be avoided because they decompose into non-toxic chemicals ideal for growth [122].

Biomedical

Bioplastics are also extensively used in biomedical applications, including medical equipment, gloves, and blood containers (**Fig. 5**). They are also used in implants due to their biodegradability [123]. Emerging biodegradable plastics for biomedical applications have resulted in the development of drug delivery systems and therapeutic devices for tissue engineering, such as implants and scaffolds [123].

Polymers are used in a variety of biological and medical applications [124]. The use of cellulose as the major green bioplastic can help these fields. Cellulose has been widely explored in the disciplines of inserts, tissue, and neurological engineering because of its non-toxicity, absence of mutagenicity, and biocompatibility in drugs [125]. Fibrils, which have cell widths of 10 nm, are organized macroscopically to form cellulose fibres. Cellulosic membranes made from bacterial cellulose are used in tissue repair scopes [126].

Cellulosic membranes made of bacterial cellulose will be used in tissue healing scopes. The pores on these membranes range in diameter from 60 to 300 micrometers. Bacterial nano-networks with modified cellulose matrices have also been investigated [127]. Nanocelluloses and their composites are fundamentally utilized in any green plastic examinations in the manufacture of clinical inserts, whether in the dentistry, orthopedic, or biomedical fields. Current research is focusing on 3D printing and magnetically responsive nano-cellulose-based materials [128].

Another application worth focusing on is wound dressing nano-cellulosic membranes, which give advantages like injury reepithelialization speed increase, wound torment decrease, contamination decrease, and expelling maintenance. Bioprocess®, XCell®, and Biofll® are examples of such patented goods that are now available [101]. Biopolymers are used in cardiovascular patches, cartilage, stents for nerve regeneration, sutures, implant valves, and bone graft substitutes for tissue engineering, according to Rodriguez-Contreras [129]. PGA-functionalized chitosan nanoparticles (CS-PGA NPs) were utilized to produce oral insulin formulations, instead of regular transdermal distribution. Through calcium-detecting receptors and amino acid carriers, the PGA coating expanded the digestive take-up of the NPs, permitting polymeric NPs to withstand harsh stomach conditions. Moreover, when compared to regular subcutaneous insulin administration, CS-PGA NPs caused a 1.7-fold increase in cumulative hypoglycemia in Sprague–Dawley rats, most likely due to a more consistent insulin release pattern that resembled the physiological pattern [130]. Bacterial polymers are being used more frequently to regenerate tissue. Salt leaching of macroporous scaffolds made of polyhydroxybutyrate/bacterial cellulose (PHB/BC) blends, for example, resulted in an interconnected porous structure with pore diameters of 5–50 m and Young's modulus of 1.2–14 GPa, which was comparable to bone rigidity (5–10 GPa). In contrast, BC supported the advancement of osteoblasts *in vivo* [131].

The ability of PLA to biodegrade and be biocompatible with the human body has stimulated numerous medical studies. Two applications of synthetic polymers in the biomedical sector include implant delivery systems and tissue engineering [132]. PLA's importance in the healthcare sector has been demonstrated by the development of biomaterials, tissue engineering, and wound healing [133]. Biodegradable materials have been thoroughly studied in the context of medicine throughout the past few decades. Electrospinning, particle leaching, and foaming were used to generate PLA/octadecylamine-functionalized nanodiamond (ND-ODA) composites for tissue engineering [134]. In order to enhance PLA's mechanical characteristics, it was dissolved in chloroform and combined with ND-ODA to create these composites. Vascular grafts and tissue engineering scaffolds need to have similar mechanical properties to the patient's natural blood vessels or tissues to be successful. They also need to be biocompatible, antithrombogenic, and have a degradation profile tailored to the application [135]. Research has been done on the application of PLA nanoparticles in the treatment of leukaemia. The PLA-adsorption of bovine seminal ribonuclease revealed in vivo aspermatogenic and anti-embryonic effectiveness [136]. Tetraheptyl ammonium-coated magnetic Fe3O4 nanoparticles and PLA nanofibers showed preferential absorption for the leukaemia K562 cell lining [137].

Future perspectives

Despite the fact that plastic pollution is a serious problem, most people are unaware of it or have chosen to ignore it as a result of the fast-paced, convenience-obsessed lifestyle prevalent in most cities. Despite numerous advertisements, many Singapore supermarkets have discovered that customers are unwilling to use biodegradable shopping bags [138]. This could be because, as a result of greenwashing strategies, consumers have returned to using conventional plastics, decreasing their interest in efforts to promote bioplastics in general. However, everyone should be aware of the various types of bioplastics and how to properly dispose them at this point. Some businesses have exacerbated the issue under the pretext of sustainability by moving to oxo-degradable plastics or failing to inform customers of the same disposal options as the bioplastic provider [139]. To maximize the environmental benefits of these polymers, it is critical to educate customers about the various biobased product types and disposal procedures [140].

Adding reinforcement with other natural materials, such as maize or wheat hulls, has been shown in studies to improve starch-based polymeric blends, which have a low gas barrier. The components worked well together because the materials were hydrophilic. By dividing the foaming system into two phases, the cost of shipping these polymers can also be reduced [141]. In order to increase overall cost-effectiveness, it is still necessary to improve the capacity to collect and reuse chemicals and byproducts from the pretreatment step, despite improvements in process efficiency. For example, after breaking down the lignocellulosic waste biomass, fungal enzymes could be regenerated with little to no loss of efficiency. Acetic acid, one of the inhibitors produced during the pretreatment process, is a useful reagent for recycling enzymes [142]. The secretory production of the methylotrophic yeast Pichia pastoris makes it an attractive candidate for the production of protein-based polymers because of its high product yields and simplicity of downstream processing [143]. Additionally, methods for decreasing proteolysis and increasing protein expression in this host are also being researched. Most prominently, governments, legislation, businesses, the general public, and consumers must all collaborate to reduce the current environmental burdens associated with food waste and to develop a method for producing biopolymers from waste materials.

Conclusion

Countries are under pressure to make considerable progress toward developing a modern bioeconomy due to global environmental issues. Biorefineries and the circular economy concept~~s~~, which advocates the use of bio-based feedstock such as fruit and vegetable waste, are driving this strategy. Concerns about plastic pollution and its negative environmental impact have fueled bioplastics research and development to find alternatives to traditional petrochemical plastics. Bioplastics are in increasing demand all around the world, and most standard polymers now have bioplastic substitutes with comparable material properties. The cost-effectiveness of bioplastics is a major impediment to their production and use. Bioplastic production costs can be reduced by utilizing inexpensive and abundant raw materials such as fruit and vegetable wastes and by-products. Given the expected rise in bioplastic production, more emphasis should be placed on establishing sustainable bio-based material recycling routes. This study summarizes the global scenario for bioplastic manufacturing using fruit and vegetable waste materials, as well as their preparation, procedures, and applications in various sectors. There is now a lot of research being done to overcome the challenges of pre-treatment and saccharification, such as cost-cutting and combining multiple techniques to empower versatile tasks. Even though chemical and physicochemical pre-treatment techniques have been demonstrated to be viable in converting biomass into reducing sugars, they are nevertheless hampered by environmental concerns, high costs, and inhibitor generation. Biological pre-treatments, such as microbial and enzymatic pre-treatments, are beneficial to the environment but are time-consuming, reducing the overall cost-effectiveness. The use of biodegradable plastics to irradiate medical equipment and food packaging materials has proven to be highly effective. The primary issues that need to be solved are the high production costs and poor performance of some biodegradable polymers, which demand further investigation to avoid competing with other natural impacts. Recycling appears to be the best choice for disposing of bio-based products going forward to reduce environmental effects while conserving renewable resources. Some of the major aspects to consider while conducting techno-economic analyses for industrial scale-up are biomass availability, pre-processing, transportation, and handling. Closed-loop systems should be a priority for every country to promote sustainable living and a greener future in this day and age when it is vital to reduce our dependency on as many non-renewable resources as possible.

Author contributions

LG: Validation, Visualization, Writing – Reviewing & Editing. **AKP:** Writing – original draft, Data curation, Investigation, Formal analysis, Editing. **CY:** Writing – Reviewing & Editing. **VKT:** Visualization, Writing – Reviewing & Editing. **JN:** Writing – Reviewing & Editing. **WC:** Writing – Reviewing & Editing. **YJ:** Visualization, Writing – Reviewing & Editing. **VKG:** Conceptualization, Validation, Visualization, Investigation, Supervision, Writing – Reviewing & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests.

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Figures Legends

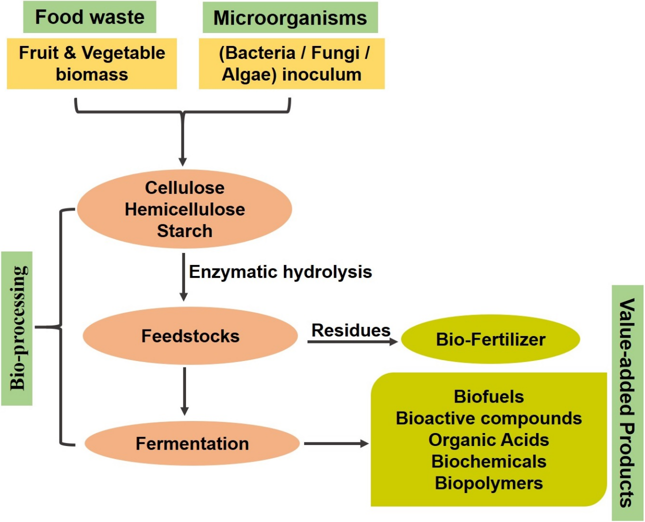
Fig.1 Production of value-added products like biofuels, biofertilizers, biochemicals, and biopolymers from fruit and vegetable waste biomass.

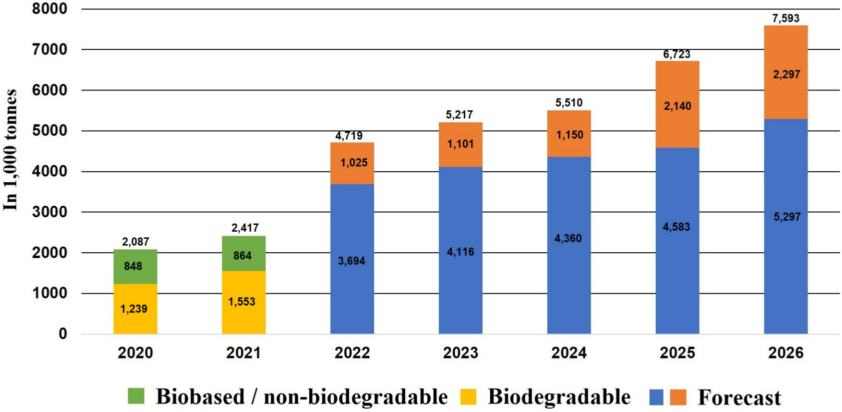
Fig.2 Global bioplastic production information from www.european-bioplastic.org/market and www.bio-based.eu/markets

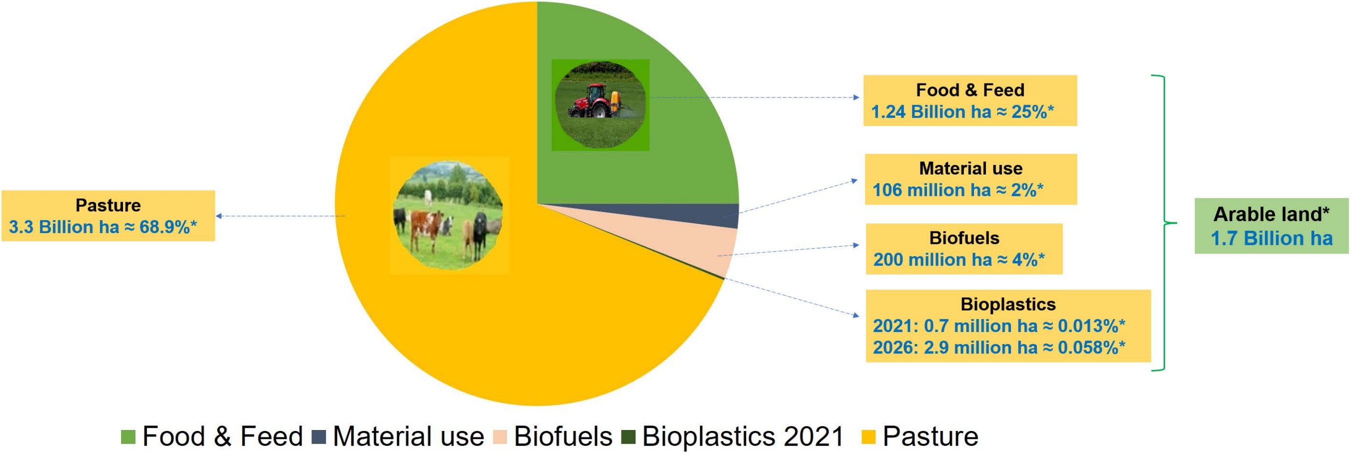
Fig.3 Information on global land area use for bioplastic production from www.european-bioplastics.org

Fig.4 Pretreatment of fruit and vegetable waste biomass converts to polysaccharides for the synthesis of PHA

Fig.5 Overview of bioplastic production based on fruit and vegetable waste biomass and global commercialization with their application


Food waste
Fruit & Vegetable biomass
Microorganisms
(Bacteria / Fungi / Algae) inoculum
Cellulose
Hemicellulose
Starch
Enzymatic hydrolysis
Feedstocks
Residues
Bio-Fertilizer
Fermentation
Biofuels
Bioactive compounds
Organic Acids
Biochemicals
Biopolymers
Bio-processing
Value-added Products


8000
7000
6000
5000
4000
3000
2000
1000
0
In 1,000 tonnes
2,087
848
1,239
2,417
864
1,553
4,719
1,025
3,694
5,217
1,101
4,116
5,510
1,150
4,360
6,723
2,140
4,583
7,593
2,297
5,297
2020
2021
2022
2023
2024
2025
2026
Biobased / non-biodegradable
Biodegradable
Forecast



Pasture
3.3 Billion ha ≈ 68.9%*

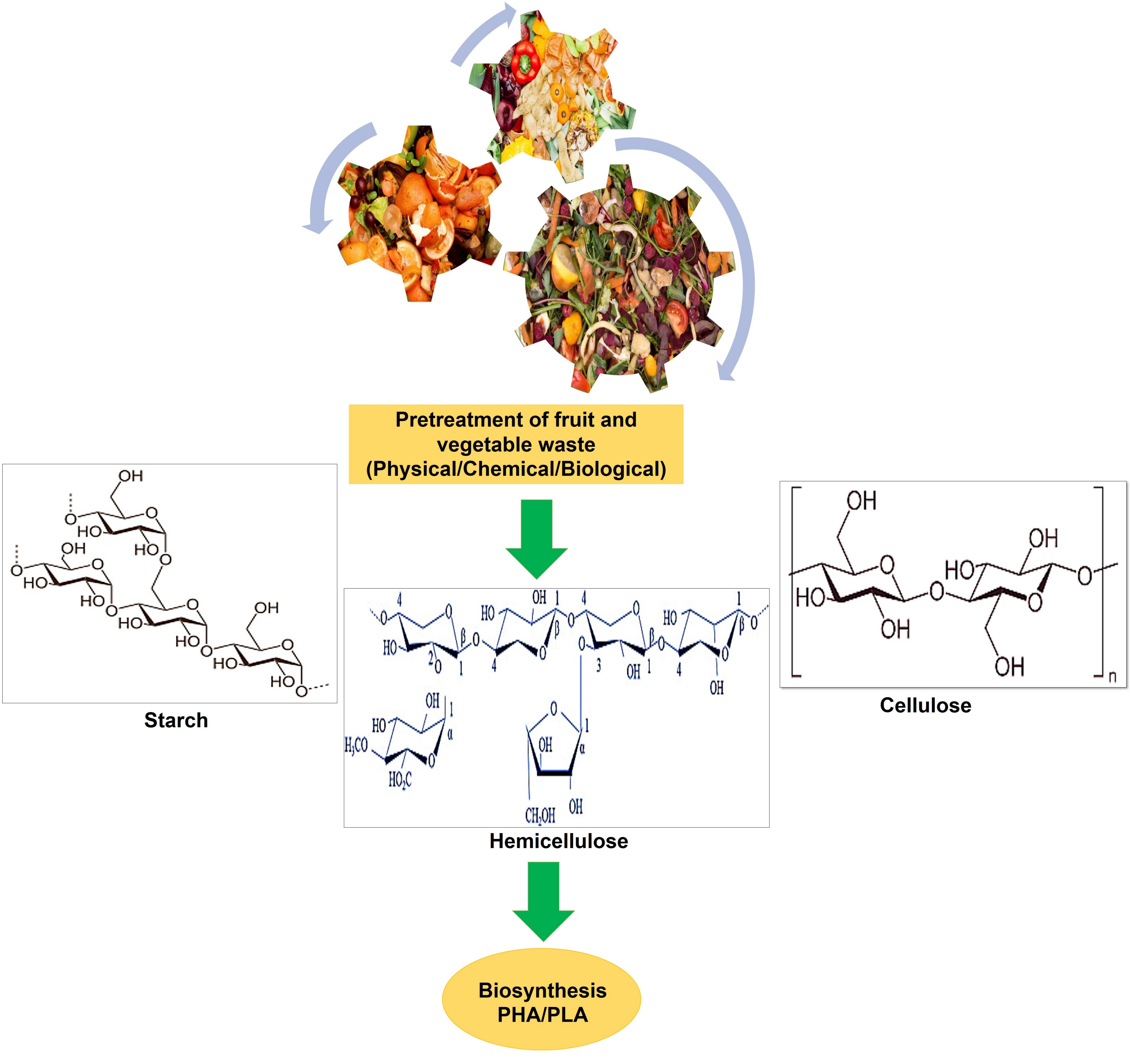
Food & Feed
1.24 Billion ha ≈ 25%*

Material use
106 million ha ≈ 2%*

Biofuels
200 million ha ≈ 4%*

Bioplastics
2021: 0.7 million ha ≈ 0.013%*
2026: 2.9 million ha ≈ 0.058%*

Arable land*
1.7 Billion ha


Pretreatment of fruit and vegetable waste (Physical/Chemical/Biological)
Starch
Hemicellulose
Cellulose
Biosynthesis PHA/PLA

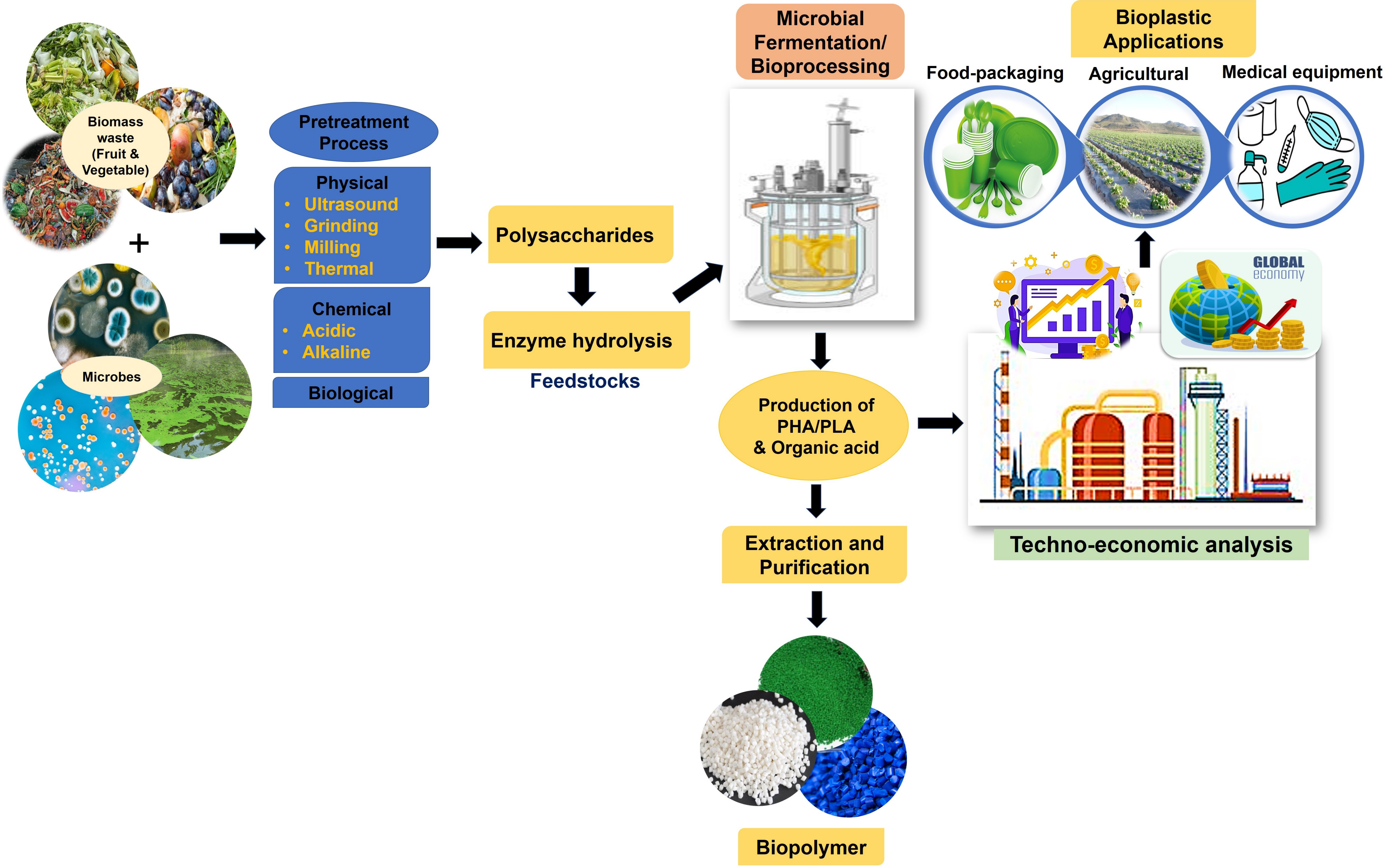

Biomass waste (Fruit & Vegetable)
+
Microbes
Pretreatment Process
Physical
Ultrasound
Grinding
Milling
Thermal
Chemical
Acidic
Alkaline
Biological
Polysaccharides
Enzyme hydrolysis
Feedstocks
Microbial Fermentation/ Bioprocessing
Production of PHA/PLA & Organic acid
Extraction and Purification
Biopolymer
Techno-economic analysis
GLOBAL economy
Bioplastic Applications
Food-packaging
Agricultural
Medical equipment

Table 1. Summarizes the pretreatment methods with a breakdown mechanism of fruit and vegetable waste biomass for the production of bioplastic materials

Sl. No	Pretreatment method	Technology	Source	Biomass	Reference
1	Physical	Ultrasound	Fruit	Spent coffee grounds	[144]
2		Grinding		Pineapple peel	[145]
3		Milling		Sugarcane	[146]
4		Thermal	Vegetable	Domestic Vegetable mixture	[147]
5	Chemical	Acidic	Fruit	Banana peels	[148]
6			Vegetable	Carrot, Cauliflower, Parsley, and Radicchio	[149]
7		Alkaline	Fruits	Apple pomace	[150]
8			Vegetable	Soyabean straw	[151]
9	Biological	Microorganisms (*Cupriavidus necator, Pseudomonas citronellolis*)	Fruit	Apple pulp waste	[152]
10		Microorganisms (*Halomonas campilasis*) + Drying, Milling, Aqueous extract		Banana peel, Orange peel	[153]

11	Microorganisms (*Pseudomonas resinovorans*) + Enzymatic hydrolysis	Grapes	[91]
12	Microorganisms (*Cupriavidus necator*) + Milling, acid hydrolysis with H_2SO_4	Pineapple peel and core	[154]

Table 2. Enzymatic hydrolysis of fruit and vegetable waste biomass for bioplastic production

Order No	Source	Strain	Process	CDW (g/L)	Bioplastic (wt %)	Characterization technique	Scale	Reference
1	Oil plum empty fruit bunch (OPEFB)	*Bacillus megaterium R11*	Enzyme hydrolysate	15.93	58.3	GC	500 mL Erlenmeyer flask	[155]
2	Water hyacinth	*Cupriavidus nacator*	Enzyme hydrolysate	6.2	59.68	FTIR, GPC & DSC	500 mL Erlenmeyer flask	[156]
3	Jackfruit seed	*Bacillus sphaericus* NCIM 5149	Enzyme hydrolysate	4.5	48.9	Central Composite Design (CCD)	Bench scale Submerged Fermentation (SmF)	[157]
4	Grapes	*Pseudomonas resinovorans*	Enzyme hydrolysate	6.1	23.3	GC-FID	3.7 L bioreactor	[91]
5	Grape pomace	*Cupriavidus necator*, *Halomonas halophila,* *Halomonas organivorans*	Enzyme hydrolysate	4.1 3.1 3.9	47.2 7.0 55.4	ATR-FTIR & SEC-MALLS	2 L fermenter	[158]
6	Potato starch	*Bacillus cereus* 64-INS	Starch hydrolysis	1.72	34.68	GC-MS	5 L fermenter	[159]