Exploiting sugar-rich feedstocks for sustainable polyhydroxyalkanoate production

Varucha Misra[#*] and Ashutosh Kumar Mall[#]

ICAR-Indian Institute of Sugarcane Research, Lucknow 226002, Uttar Pradesh, India
[#] Authors contributed equally: Varucha Misra, Ashutosh Kumar Mall
* Corresponding author, E-mail: misra.varucha@gmail.com

Abstract

Plastic pollution is an international issue, with petrochemical plastics promoting waste build-up, aquatic ecosystem impairment, and microplastic pollution. Polyhydroxyalkanoates (PHAs) have gained a lot of attention as an alternative material owing to their similar mechanical characteristics to traditional plastics, together with biodegradability and ecological inertness. These bacterial biopolymers, which are polymerized by bacteria like *Cupriavidus necator* and *Bacillus megaterium* as intracellular carbon and energy stores, can be made from biotic feedstocks, aligning with circular economy and sustainability objectives. The main limitation to mass adoption is high production price, which is generally determined by substrate cost. Sugar-rich feedstocks such as sugarcane molasses, beet molasses, and corn syrup have the potential to cut costs by 30%–40% relative to glucose-based fermentation. The use of agro-industrial by-products not only reduces raw material expenses but also favours waste valorization as well as local economic advantages. The efficiency of production is greatly influenced by process parameters and feedstock properties, wherein optimization of pH, dissolved oxygen, and carbon-to-nitrogen ratios greatly improves yield and polymer quality. Additionally, PHAs blends and composites with enhanced thermal, mechanical, and barrier properties present suitable solutions for packaging and allied applications. With growing consumer consciousness and regulatory demands, PHAs from sugar feedstocks offer both economic and ecological benefits. Engineered microbial strains and inexpensive downstream processing are future work priorities for scalable and sustainable production. The present review examines the viability of using sugar-rich substrates as economically viable feedstocks to produce PHAs and their role in the development of sustainable bioplastics.

Introduction

Environmental pollution and plastic waste have emerged as urgent issues of global importance, fuelled by many years of excessive consumption and overproduction[1]. Although petrochemical plastics are prized for their resistance and versatility, their longevity presents severe waste disposal issues, disturbing ecosystems and greenhouse gas emissions in the manufacturing process[2,3]. As a green substitute, polyhydroxyalkanoates (PHAs) have attracted significant interest because they are biodegradable, biocompatible, and possess mechanical properties akin to polypropylene[4]. PHAs are produced by bacteria naturally as intracellular carbon and energy storage materials under carbon-rich but nutrient-limiting conditions, and provide functional and environmental benefits[5,6]. Conventional PHA production has typically relied on pure carbon substrates such as glucose, sucrose, maltose, starch, fatty acids, methanol, and alkanes[7]. However, carbon feedstocks alone account for nearly 50% of total production costs[8], making economical alternatives essential for industrial-scale feasibility. First-generation sugar-based feedstocks such as sugarcane, corn sugar, whey, palm oil, and vegetable oils have been extensively studied but are problematic for food security and food and energy market competition[9]. While potent as substrates, their congruence with world food demands makes large-scale utilization not sustainable. On the other hand, sugar-based agro-industrial residues present a more promising avenue. Waste streams like sugarcane bagasse, molasses of cane and beet, corn steep liquor, and fruit peels carry high concentrations of fermentable sugars that are compatible for microbial conversion into PHAs by organisms like *Cupriavidus*

necator and *Bacillus megaterium*[10,11]. This use of by-products minimizes reliance on food crops, reduces substrate expense, and supports circular economy principles through valorizing waste. In addition, their structural variability allows them to have extensive applications, from packaging, textiles, and animal feed supplements to biomedical applications such as implants and drug delivery. Generally, renewable waste feedstocks are economically and environmentally friendly, facilitating sustainable PHAs production. Their incorporation not only enhances degradable plastics but also helps in conserving resources and minimizing environmental deterioration[12,13].

This review aims to highlight the application of sugar-rich feedstocks in the sustainable production of PHAs as biobased plastics.

Sugar-rich feedstocks for PHAs production

Biosynthesis using sugar-rich feedstocks for PHAs production

Efficiency in PHAs biosynthesis varies with feedstock content, sugar type, and conditions of fermentation. Conveniently metabolizable substrates such as molasses, fruit juices, and corn steep liquor result in high yields in *Cupriavidus necator* and *Bacillus megaterium*. Lignocellulosic residues, however, need to be pre-treated, and results are determined by microbial tolerance to degradation by-products[12]. Furthermore, several studies revealed that pre-treatment is considered as an energy-sensitive and costly step as it converts lignocellulosic biomass into fermentable sugars. The recalcitrant nature of biomass, having tough lignin, requires significant

energy to break it down[14,15]. Microbial metabolism and biosynthesis of PHAs are highly dependent on sugar composition. Strains capable of utilizing mixed sugars broadly ferment well, while limited strains are poor. Inhibitory substances like organic acids, phenolics, and salts found in molasses or fruit waste can inhibit growth, and detoxification or microbial acclimation is needed. Optimal sugar concentration is crucial—suboptimal levels limit biomass, while excess may lead to osmotic stress or catabolite repression. Fermentation conditions such as pH, aeration, temperature, oxygen transfer, and C/N ratio control polymer accumulation, with nitrogen deficiency and carbon excess favouring PHAs storage. Fed-batch operations are frequently employed to maintain maximum sugar concentration[16,17]. Strain choice also matters. Effective strains degrade several sugars, are resistant to inhibitors, and store high levels of PHAs. *Bacillus subtilis*, *B. cereus*, *Alcaligenes* sp., and *Pseudomonas aeruginosa* break down sucrose, glucose, and fructose, while *B. megaterium* can accommodate molasses variation. Tolerant strains such as *Bacillus* sp. BM37, *Paracoccus* sp., *Halomonas*, and *C. necator* perform well on sugar-rich residues[18–21].

Conversion of substrates through three sequential enzyme-catalyzed reactions

This pathway entails the conversion of substrates such as sugars or amino acids into acetyl-CoA, which is then followed by three consecutive enzyme-catalyzed reactions. The reversible condensation of acetyl CoA into acetoacetyl-CoA is catalyzed by B -Ketothiolase (PhbA). The intermediate is subsequently reduced by acetoacetyl-CoA reductase (PhbB) into d-(-)-3-hydroxybutyryl-CoA, which requires NADPH. The polymerization is then catalyzed by P(3-HB) synthase (PhbC)[22]. Later on, the cycle is closed by acetoacetyl-CoA synthetase (AACS), which reconstitutes acetoacetyl-CoA and converts to acetyl-CoA, which then can feed into the citric acid cycle[23].

Conversion of substrates through β-oxidation intermediates produced from fatty acids

Bacteria such as *Ralstonia eutropha* (also known as *Cupriavidus necator*) have extracellular lipases and possibly extracellular polysaccharides that help in the formation of stable emulsions when cultivated on plant oils, thus making fatty acids more bioavailable[24,25]. During β-oxidation, enoyl-CoA molecules are either directed towards the PHAs precursor (R)-3-hydroxyacyl-CoA through an (R)-specific enoyl-CoA hydratase (PhaJ), or 3-ketoacyl-CoA molecules are converted to (R)-3-hydroxyacyl-CoA via a β-ketoacyl-ACP reductase (FabG).

Conversion of substrates through other pathways

The second route is through the 3-hydroxyacyl-ACP-CoA transferase (PhaG) enzyme conversion of the fatty acid biosynthesis intermediate (R)-3-hydroxyacyl-ACP into (R)-3-hydroxyacyl-CoA[26]. Another well studied route is the utilization of propionic acid to produce (R)-3-hydroxyvaleryl-CoA. After the uptake of propionic acid, acyl-CoA synthetase catalyzes its conversion to propionyl-CoA. Aside from two molecules of acetyl-CoA, PhaA can also condense acetyl-CoA with propionyl-CoA to give ketovaleryl-CoA (Fig. 1). However, this reaction is mainly performed by two other 3-ketothiolase named BktB[27]. Ketovaleryl-CoA is eventually reduced to (R)-3-hydroxyvaleryl-CoA by PhaB.

Pre-treatment process of bagasse and molasses from sugar-based cultivated crops for PHAs production

Lignocellulosic biomass, which consists of cellulose, hemicellulose, and lignin, is inherently resistant to microbial breakdown and, therefore, pre-treatment is an essential process for effective sugar production and subsequent PHAs production (Fig. 2). Efficient
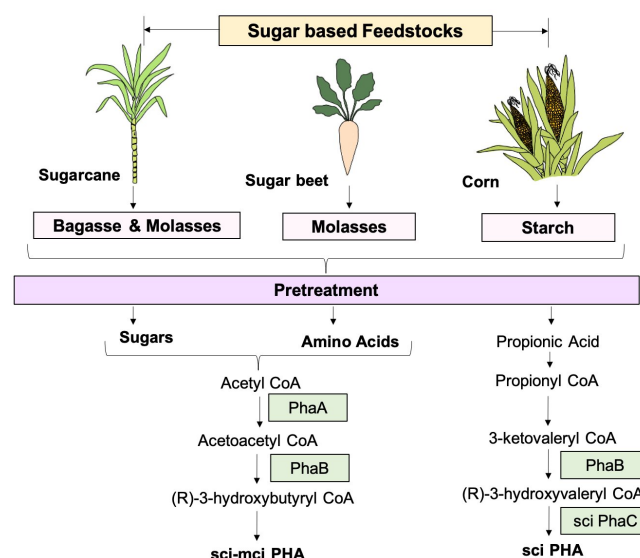

Fig. 1 PHAs production from sugar based feedstocks.

pre-treatment increases cellulose exposure, allowing as much as 90% of reducing sugars to be liberated for fermentation[28]. This mechanism is central to reducing production costs by maximizing sugar release, consequently enhancing yield, and economic viability of PHAs[29,30]. The increased fermentability of sugar-containing feedstocks is a result of their sucrose, glucose, and fructose, which are easily metabolized by PHAs-producing microorganisms like *Cupriavidus necator* and *Bacillus megaterium* with very high productivities[29,31,32]. For agro-industrial residues like sugarcane bagasse, pre-treatment plays a significant role in lignin removal, cellulose decrystallization, and solubilization of hemicellulose, enhancing porosity and enzymatic accessibility[33,34]. In contrast, sugarcane molasses, even if sucrose-rich, contains phenolics, heavy metals, and nitrogenous compounds that repress microbial growth, and PHA biosynthesis. Additionally, the majority of PHAs-producing strains do not have glycosyl hydrolases to metabolize sucrose directly, necessitating hydrolysis into glucose and fructose, and minimizing inhibitory compounds[35,36]. Depending on the application of acidic, alkaline, or enzymatic hydrolysis, additional impurities can occur, which have a detrimental effect on microbial efficiency[32]. Parallel challenges are found in beet molasses and fruit peels, whose pre-treatment guarantees the release of fermentable sugars, a balance of nutrients, and neutralization of inhibitors[37]. Generally, tailoring pre-treatment to the characteristics of each feedstock is required for the development of low-cost agro-industrial residues into consistent, sustainable substrates for industrially scaled PHAs production.

Acid pre-treatment

Acid pre-treatment is one of the most common approaches to enhance the hydrolysis efficiency of lignocellulosic biomass (Fig. 2). Dilute acid pre-treatment, in general carried out with 0.05%–5% acid solutions at 160–220 °C, for time periods ranging from seconds to several hours, solubilizes mainly hemicellulose and breaks lignin–polysaccharide bonds, thus increasing cellulose access to hydrolytic enzymes. It is a process of breakage of hemicellulose and amorphous cellulose into fermentable sugars, and optimization of process parameters needs to be carried out with care to achieve a high sugar yield while limiting the formation of inhibitory by-products. Acid hydrolysis is a conventional method of releasing fermentable sugars from the lignocellulosic structure in sugarcane bagasse processing, which is followed by mechanical washing and water
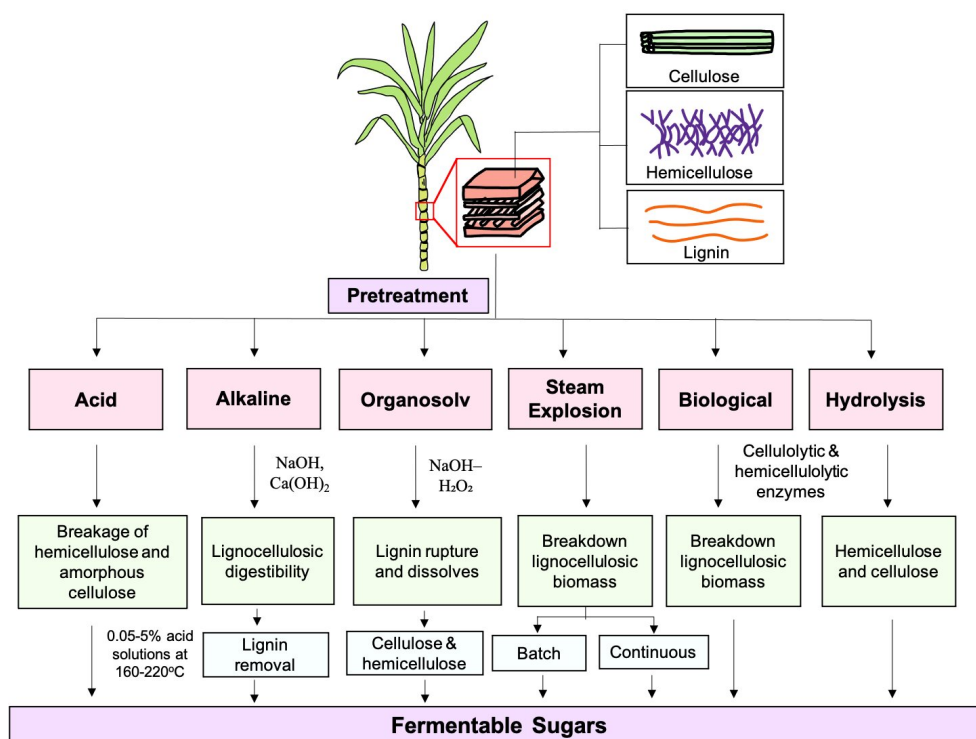
Fig. 2 Different types of pre-treatment of lignocellulosic biomass.

leaching, for the removal of fine debris and surface waxes. Further staged dehydration reduces impurities before fermentation[38]. Unless efficiently removed, such impurities inhibit microbial metabolism and polymer biosynthesis, eventually lowering PHAs yield and overall process performance. Therefore, efficient substrate purification is of great importance in valorizing agro-industrial residues. Bagasse possesses the greatest promise, yielding 5.86 mg/mL PHAs[39]. Feedstock properties also determine treatment severity. Sugar-dominant, lignin-deficient feedstocks can tolerate mild conditions, whereas lignin-dominant materials are treated with severe conditions. Oladzad et al.[40] illustrated that DPC structural recalcitrance drives bioprocess yields. Hydrothermal and dilute acid pretreatment (0.5% v/v H_2SO_4) at 80–140 °C for 60–90 min enhanced carbohydrate accessibility, and enzymatic hydrolysis was best performed at 120 °C for 90 min. This treatment enhanced total sugars by 55.02% with less inhibitors, and follow-up anaerobic digestion enhanced hydrogen, ethanol, and volatile fatty acids production by 59.75%, reiterating the significance of pre-treatment in bioprocessing efficacy. Concentrated acid pre-treatment, though efficient at milder conditions, is constrained by equipment corrosion and inhibitory lignin precipitates. The most common chemical used is sulfuric acid, whereas hydrochloric, phosphoric, and nitric acids are alternatives. Zhao et al.[34] described that 2% H_2SO_4 at 121 °C for 2 h obtained 85% solubilization of hemicellulose, and 16% lignin reduction. Dilute acid procedures are still favoured due to ease and economy[41,42], even though they create inhibitors like furfural, HMF, acetic acid, and phenolics, which negatively impact microbial fermentation as well as PHAs productivity[43,44]. Generally, dilute acid pre-treatment is seen to be the most efficient and scalable process of bagasse pre-treatment for PHAs production.

Alkaline pre-treatment

Alkaline pre-treatment, typically utilizing sodium hydroxide (NaOH), calcium hydroxide (Ca(OH)$_2$), potassium hydroxide (KOH), or ammonia (NH$_3$) is prevalently applied to enhance the digestibility of lignocellulosic biomass through selective lignin removal (Fig. 2). Adjustments of process conditions, such as alkali concentration, temperature (generally below 100 °C), and incubation time, can be made depending on feedstock composition and lignin levels. Low-lignin biomass is subjected to milder treatment, whereas high-lignin feedstocks need more concentrated alkali, or increased exposure time for effective delignification[45,46]. The pre-treatment has the added advantage of increasing the accessibility of cellulose while retaining fermentable sugars and generating fewer inhibitors than acid-based methods[47]. Some recent developments include oxidative alkaline systems, e.g., NaOH with hydrogen peroxide (H_2O_2), which enhance lignin degradation and efficiency in sugar conversion[48,49]. Yu et al.[50], for instance, indicated that treatment with 1% NaOH at 120 °C for 10 min eliminated 67.5% of the lignin in sugarcane bagasse, and NaOH–H_2O_2 blends further improved enzymatic digestibility. Whilst these benefits exist, one serious disadvantage of alkaline pre-treatment is that a considerable proportion of hemicellulose is still bound in the residual solids, and so is less available for sugar release than with dilute acid treatments. As a result, additional hemicellulolytic enzymes such as xylanase are usually added during subsequent hydrolysis to maximise overall carbohydrate recovery[51]. Generally, alkaline pre-treatment is still an economical and effective method for bagasse valorization, especially with the addition of enzymatic means for total carbohydrate utilization.

Organosolv pre-treatment

Organosolv pre-treatment utilizes organic solvents, with or without water and catalysts, to break down lignocellulosic biomass by splitting α- and β-aryl ether cross-linkages in lignin. Organosolv pre-treatment dissolves and ruptures lignin (Fig. 2), hence enhancing cellulose and hemicellulose susceptibility to enzymatic hydrolysis and, ultimately, sugar release for PHAs production[52]. Though water-soluble lignin residues are inhibitors of enzymes, the process considerably enhances biomass digestibility and enables one to recover lignin of high purity for industrial uses. Solvents can vary

from the low-boiling alcohols (methanol, ethanol), to boiling components like ethylene glycol, glycerol, dimethyl sulfoxide, and phenolics[53]. Reactions are commonly at 100–250 °C, with increased temperatures (185–210 °C) producing organic acids that decrease the requirement for external catalysts, although mineral or organic acids might be added to further promote delignification and xylose recovery[54]. Organosolv divides biomass into three streams: purified cellulose, aqueous hemicellulose, and dry lignin[55]. Experiments validate its efficacy for sugarcane bagasse, with 45.3% lignin and 72.5% hemicellulose removal with 50% ethanol at 121 °C[56], and 75.5% lignin removal with 60% ethanol, and 5% NaOH at 180 °C[57]. Effective recovery of solvent is necessary for economic feasibility[58].

Steam explosion

Steam explosion is a green pre-treatment (Fig. 2) that utilizes high-pressure saturated steam (160–260 °C), and subsequent depression to break-down lignocellulosic biomass structure and enhance digestibility[59]. Two modes are predominant: batch, in which biomass is subjected to instant depressurization into a discharge vessel; and continuous, in which it is sent into a pressurized reactor through periodic opening of valves resulting in tiny explosions[60]. Whereas the operations vary, the two methods are based on explosive decompression with similar results. This process works best for sugarcane bagasse, allowing for fractionation and recovery of lignin, cellulose, and hemicellulose[61]. Silveira et al.[62] recorded 85% solubilization of hemicellulose in a 65 L reactor, whereas Zhang et al.[63] released 9.8 g/L xylose under hot water pre-treatment with acetyl support at 160 °C for 70 min. Moreover, steam explosion causes autohydrolysis, changing bagasse surface morphology and also enhancing enzymatic saccharification efficiency[64].

Biological pre-treatment

Biological pre-treatment is an eco-friendly process (Fig. 2) that employs certain cellulolytic and hemicellulolytic enzymes or microorganisms to break down lignocellulosic biomass[65]. This approach is less energy-intensive, and generates fewer inhibitory by-products than chemical and physical pre-treatment methods. However, its application in industries is constrained by the extended duration of biodegradation. Different microorganisms, such as fungi and bacteria, recovered from sources like soil and lignocellulosic residues, can be employed for the biological pre-treatment of feedstocks rich in sugars (Tables 1 & 2).

Hydrolysis pre-treatment

Hydrolysis pre-treatment of lignocellulosic biomass hydrolyzes hemicellulose and cellulose into fermentable sugar, and thereby enhances carbon supply for PHAs production. The enzymatic hydrolysis technique is used over acid treatment since it is eco-friendly, less inhibitor is produced, avoids corrosion issues, and provides near complete cellulose conversion with higher PHAs yield[66]. Enzymatic pre-treatment processes are tailored for sugar-rich feedstocks by adapting enzyme cocktails to the targeted carbohydrate content and accessibility of the substrate. In the case of sugarcane bagasse, molasses, or comparable feedstocks, the enzyme blend is designed to maximize fermentable sugar release while reducing inhibitory by-products[67]. Cellulase, composed of endoglucanases, exocellobiohydrolyases, and β-glucosidase, hydrolyzes cellulose to glucose[68]. Hemicellulose, being branched in nature, is hydrolyzed by enzymes like xylanases, arabinofuranosidase, and glucuronidase, releasing xylose, galactose, and arabinose[69]. Hydrolytic cellulases are formed by both bacteria (*Streptomyces, Bacillus, Clostridium*), and fungi (*Trichoderma, Penicillium, Aspergillus*)[70,71]. But due to slow microbial activity, commercial enzymes are normally employed for efficient hydrolysis.

Application of sugarcane, bagasse, and molasses for PHAs production

Sugarcane, a tropical perennial grass, ranks among the most cultivated plants in the world for sugar production, and constitutes a very good feedstock for microbial fermentation as it contains a high amount of sucrose combined with fermentable sugars like glucose and fructose. Due to these properties, it presents a promising raw material to produce PHAs (Table 1). Its benefits are in the form of high hectare yields, low culture costs, and rich by-products like molasses and bagasse, which improve the feasibility for large-scale synthesis of PHAs. Sugarcane molasses, being a sugar-refining by-product consisting of almost 50% sugars along with growth-promoting nutrients, is universally known to be a low-cost substrate and is also focused on improving sustainability through waste valorization. Chaudhry et al.[72] showed that *Pseudomonas* species were able to accumulate 20%–36% PHAs from molasses, whereas *Bacillus megaterium* produced 72.7 g/L cell mass with 42% PHAs content when grown on molasses[73]. *Cupriavidus necator* (DSM 545) and *Burkholderia sacchari* strains have also been effectively used utilizing molasses or sugarcane juice[74,75]. As *C. necator* cannot directly ferment sucrose, molasses hydrolysis by chemical, enzymatic, or mixed treatments is necessary. The efficiency of fermentation is subject to optimized conditions such as temperature, pH, and nutrient levels that have a substantial impact on yields. Albuquerque et al.[76], for instance, documented that reactor pH changes volatile fatty acid composition, with impacts on PHAs copolymer ratios. Strain variation also has its importance, and *Bacillus subtilis* and *Escherichia coli* yield 54% and 47% PHAs, respectively, from molasses fermentation under pH 7 and 35 °C[77]. *Bacillus cereus*, *Alcaligenes* sp., and *Pseudomonas aeruginosa* are also commonly employed due to their high sucrose, glucose, and fructose fermentation in minimal medium conditions[18].

Bioprocess advancements have enabled the use of sugar industry by-products, particularly molasses, for PHAs production. Low-grade molasses, a sucrose-rich syrup unsuitable for food, has shown promise as a cost-effective substrate[79]. Although production levels are not always competitive, several studies highlight its potential. Chaudhry et al.[72] documented *Pseudomonas* species utilizing molasses to produce PHAs with dry cell weight in the range of 7.02–12.53 g/L and with 20.63%–35.63% polymer content. Likewise, Kulpreecha et al.[73] showed *Bacillus megaterium* BA-019 grown on sugarcane molasses yielded 72.7 g/L cell weight with 42% PHB (the most common and well-characterized PHA), showing its potential for industrial-scale usage.

Albuquerque et al.[76] introduced a three-step procedure through molasses fermentation to organic acids, PHAs accumulation, and batch fermentation and obtained 30% PHAs of cell dry weight (CDW). *Enterobacter cloacae* also used molasses efficiently by reducing production costs[78]. Recombinant approaches broadened molasses' versatility, such as *Ralstonia eutropha* recombinantly engineered with *Mannheimia succiniciproducens* sucrose genes, which promoted sucrose growth but with low yield[80], while Jo et al.[81] improved poly(3-hydroxybutyrate) [P(3HB)] and poly(3HB-co-lactate) production by recombinant *R. eutropha* expressing β-fructofuranosidase. Fermentations in the laboratory validated high yields, with *Bacillus cereus* SPV yielding 61% PHAs in flasks, and 51% in a 2 L fermenter[82], and *Pseudomonas fluorescens* A2a5 yielding 68.7% PHAs with 32 g/L biomass in a 5 L reactor[83]. Analogously, genetically engineered Klebsiella aerogenes containing *R. eutropha* genes had yields similar to wild strains, albeit with stability constraints[84].

Vinasse, another acidic pH and high-organic load by-product of the sugar industry, also favours PHAs production if pre-treated to

remove polyphenolic inhibitors. Haloarchaea like *Haloarcula marismortui* and *H. mediterranei* effectively converted vinasse into 4.5–19.7 g/L PHAs[85,86], with mixing vinasse and molasses favouring PHB accumulation up to 56%[32]. Strain and substrate concentration have a significant effect on yields, varying from 0.60 g/L PHB in *Bacillus megaterium* using 4% molasses[87] to 59% PHB in *Azotobacter vinelandii* UWD using 5% molasses[88]. Halophiles eschew sterile conditions and produce PHBV without precursors, and discharge of saline effluent is an issue, partially resolved by desalination measures[89].

Sugarcane bagasse, a lignocellulosic sugar-processing by-product, is a rich feedstock for PHAs but must be pre-treated to release fermentable sugars and minimize inhibitors like furfural and acetic acid. Acid hydrolysis of bagasse at 120 °C allowed *Burkholderia* sp. to produce 3.26 g/L PHB[90], whereas *Burkholderia cepacia* grown on bagasse hydrolysate produced 53% CDW with 2.3 g/L 3HB[91]. In the same vein, *Cupriavidus necator* survived acid/heat-pretreated bagasse hydrolysates upon inoculation at high density, yielding PHB at 57% CDW[92]. Tyagi et al.[38] proved that residual sugars in bagasse filtrate, optimally at 60% with yeast extract and salts at pH 7.0 ± 0.5, yielded 55% PHAs, proving the worth of non-lignocellulosic bagasse-derived media. Apart from PHB, co-polymer production has also been investigated; Lopes et al.[90] reported PHBV production when levulinic acid was supplemented during *Burkholderia* fermentations. Yu & Stahl[92] also demonstrated that toxicity in hydrolysates could be alleviated by dilution as well as inoculation with tolerant strains of *C. necator*. Bengtsson et al.[93] further reported a Tg of −10.3 and −14 °C for the PHAs produced from 53%–63% mol 3HV from molasses and synthetic VFA solutions, respectively. Taken together, these results establish that sugarcane bagasse, besides its traditional applications as fuel for boilers and raw material for papermaking, can be used as a cheap carbon source for sustainable PHAs production.

Application of sugar beet and sugar beet molasses for PHAs production

Sugar beet, a temperate root crop, is one of the most concentrated sources of sucrose that can be tapped for microbial fermentation and production of PHAs[102]. The juice of sugar beet has been utilized as a substrate for *Azotobacter lactus*, resulting in a 66% yield of PHAs against 80% using pure sucrose[103]. Sugar beet pulp has also been used as a carbon source, with pulp sugars sustaining *Paraburkholderia sacchari* to yield 62.2 g/L PHB with 53.1% content, a yield of 0.27 g/g, and productivity of 1.7 g/(L·h)[104]. Like sugarcane, sugar beet molasses, a residual effluent of processing with 50%–60% fermentable sugars, and other organics, is nutrient-dense and inexpensive for PHAs production (Table 2)[88]. Microorganisms like *Pseudomonas putida*, *Bacillus megaterium*, and *Cupriavidus necator* B-10646 utilize beet-derived substrates effectively[37]. Molasses hydrolysis with β-fructofuranosidase supported *C. necator* in converting 88.9% sucrose to hexoses, which resulted in 80–85 g/L biomass and polymer compositions close to 80%, while copolymer P(3HB-co-3HV) was formed from precursors such as propionate and valerate. *Azotobacter vinelandii* UWD produced copolymers having β-hydroxyvalerate through β-oxidation processes. Beet molasses has stimulatory compounds, presumably amino-N compounds, that enhance PHAs accumulation over biomass growth, with trace peptone addition further enhancing yields[37,105]. Sugar beet wastewater has also been used as an inexpensive medium, with 4.05 g/L PHAs (41.79% biomass) production with 6% molasses and ammonium oxalate, illustrating dual advantage of polymer production and COD elimination[106]. Together, sugar beet and residues offer an environmentally friendly, economically feasible pathway towards industrial PHAs production.

Table 1. Production of PHAs from sugarcane by-products.

By-product	Concentration of raw material	Initial treatment of raw material	Microbe utilized with inoculum concentration	PHAs yield (%)	Ref.
Molasses	80 g/L	Acidic treatment	*Cupriavidus necator* 11599	75.64	[35]
Molasses	2–10	Not mentioned	*Enterobacter* sp. SEL2	47.4–92.1	[36]
Cane molasses + ammonium sulphate	20 g/L	Not mentioned	*Bacillus megaterium* BA-019	49.9–55.5	[73]
Cane molasses + urea	20 g/L	Not mentioned	*Bacillus megaterium* BA-019	49.9–55.5	[73]
Molasses	1%	Alkaline/acidic pre-treatment; Hydrothermal pre-treatment	*Cupriavidus necator* (DSM 545 strain); 40 mL	27.20	[75]
Molasses	Not mentioned	Not mentioned	*Bacillus subtilis*	62.2	[77]
Molasses	Not mentioned	Not mentioned	*Escherichia coli*	58.7	[77]
Molasses	2%–10% (at even intervals)	Sulfuric acid treatment and Tricalcium phosphate treatment	*B. subtilis* (2 mL)	21.09–54.1	[77]
Molasses	2–10	Tricalcium phosphate treatment	*B. subtilis* (2 mL)	21.1–54.1	[77]
Molasses	2–10	Tricalcium phosphate treatment	*E. coli*	21.1–54.1	[77]
Molasses	0–8	Acidic treatment	*Enterobacter cloacae*	36.0–51.8	[78]
Molasses	–	Acidic treatment	*Enterobacter cloacae* (2–16)	44.2–53.7	[78]
Molasses	2–10	Not mentioned	*Bacillus cereus* SPV	61.1	[82]
Molasses + corn steep liquor	2%–5%	Not mentioned	*Bacillus megaterium*	18.3–49.12	[87]
Molasses + corn steep liquor	4 or 1%–6%, 0%–6%	Pretreated with activated charcoal (1:1) for 2 h	*Bacillus megaterium* ATCC 6748	35	[93]
Molasses + corn steep liquor	4% (w/w); 4% (v/v)			43	
Molasses	1%	Not mentioned	*Bacillus thuringiensis* IAM12077	23.81	[95]
Bagasse	1%		*Bacillus thuringiensis* IAM12077	9.68	[95]
Molasses	10 and 40.0 g/L	Acidic treatment	*Pseudomonases aregunoisa* NCIM No. 2948	62.44	[96]
Molasses	–	Sulfuric acid treatment	*Bacillus thurigenisis* HA1	61.6	[97]
	–	–	*Cupriavidus necator* DSM 428	24.33	[98]
	–	–	Mixed microbial culture	57.5	[99]
Molasses	0.0–0.5 g/L	Not mentioned	*Alcaligenes eutrophus* DSM 545	18–26	[100]
Molasses	2–10	Not mentioned	*Bacillus flexus* strain AZU-A2	88.0	[101]

Table 2. Production of PHAs from sugar beet by-products.

By-product	Concentration of raw material	Initial treatment of raw material	Microbe utilized with inoculum concentration	PHA yield (%)	Ref.
Beet molasses	40%	Acid and enzymatic hydrolysis	*Cupriavidus necator* B-10646 wild strain	80	[37]
Beet molasses	5% w/v	Not mentioned	*Azotobacter cinelandii* UWD	75–85	[88]
Beet juice	1 L	Not mentioned	*Alcaligenes latus* (ATCC 29714)	38.66	[103]
Cane molasses + beet molasses	3%	Not mentioned	*Bacillus megaterium* strain L9	41	[105]
Beet molasses + sugar beet waste water	1%–15% (with odd intervals)	Not mentioned	*Bacillus megaterium* AUMC b 272	27.20–32.92	[106]
Beet molasses	5% w/v	Not mentioned	*Azotobacter vinelandii* UWD (4% w/v)	65–73	[107]
Sugar beet pulp	6%	Recombinant endoglucanase (rCKT3eng)	*Haloarcula* sp. TG1	17.8	[108]
Pressed sugar beet pulp	Not mentioned	Acidification	*Pseudomonas citronellolis*	38	[109]
			Pseudomonas putida KT2440	31	

Application of corn grain, stover, and steep liquor for PHAs production

Corn and its derivatives are cheap and available feedstocks for the production of PHAs (Table 3). Corn syrup, obtained as a result of starch hydrolysis, is mostly glucose, offering an inexpensive and reliable source of carbon for microbial fermentation, whereas corn steep liquor (CSL), a wet-milled by-product, is rich in nutrients and increases polymer yields[110]. Other corn-derived substrates, such as grain, stover, oil, and gluten, have also been tested for the synthesis of PHAs[111]. While dextrose from corn grain is available as a reliable feedstock, its utilization competes with use in foods. Microbial fermentations via strains like *Bacillus megaterium* convert corn syrup sugars to PHAs effectively, and yields can be enhanced by optimizing aeration, temperature, and nutrient ratios. de Mello et al.[112] obtained 62% PHB accumulation (11.64 g/L, 0.162 g/L·h), which was raised to 70% (14.17 g/L, 0.197 g/L·h) in an 8-L bioreactor with milled corn hydrolysate and crude glycerol using *Cupriavidus necator*. Chaijamrus & Udpuay[94] produced 43% PHB with 4% molasses and 4% CSL. Recombinant *E. coli* carrying PHAs synthase genes stored PHAs from hydrolyzed corn starch, soybean oil, and cheese whey by using β-oxidation inhibitors such as acrylic acid[113]. *Photobacterium* sp. TLY01 gave 53.89 g/L PHB on corn starch and glycerol[114] and *Bacillus* sp. CFR 256 on CSL 8.20 g/L PHAs (51.2% biomass) in 72 h[115]. Acid-hydrolyzed corn cobs yielded 35.84 g/L reducing sugars, sustaining *Bacillus* sp. BM 37 to yield 36.2% PHB[116], although *Pseudomonas aeruginosa* resulted in only 0.38% PHB[117]. Moreover, *Halomonas mediterranei* produced PHAs from extruded corn starch and rice bran[118].

Corn stover hydrolysates also worked well, with *Paracoccus* sp. LL1 producing 9.71 g/L with 72.4% PHAs accumulation[119]. Corn bran hydrolysates were poor performers[120]. CSL and milk whey were used as co-substrates by *E. coli* strains that exhibited good P(3HB) yields, with K1060 performing the best. Commercially, Metabolix Inc. opened a 50,000-ton/yr PHAs plant in Iowa in 2010 from corn syrup[121]. However, extensive dependence on first-generation corn feedstocks is not sustainable. Farming of corn is costly from an environmental viewpoint, and life-cycle analyses indicate PHAs from corn do not lessen eutrophication or smog impacts compared to petrochemical plastics[122,111]. Future sustainability is contingent on combining enhanced PHAs fermentation technologies with sustainable production of corn.

Application of fruit waste and juices for PHAs production

Fruit and juice processing wastes are plentiful sugar-containing feedstocks ideal for the production of PHAs[132]. They harbour fermentable sugars like glucose, fructose, and sucrose[133,134], and comprise apple pomace, grape must, orange peels, mango pulp, and pineapple juice. Their valorization not only solves waste issues but also minimizes the environmental impact of fruit processing operations. Microorganisms like *Haloferax mediterranei* and *Pseudomonas aeruginosa* are shown to be able to produce PHAs from such wastes[135,136]. The operation generally includes pre-treatment and hydrolysis to break down fermentable sugars for easy microbial accessibility[137]. Despite this, inhibitory metabolites like phenolics can prevent growth and biosynthesis, the effects of which can be

Table 3. Comparison of PHAs yield through different sugar rich feedstocks utilizing various microbial strains.

Other sugar rich feedstocks	Concentration/weight of raw material	Initial treatment of raw material	Microbe utilized with inoculum concentration	PHA yield (%)	Ref.
Hydrolyzed citrus pulp	Not mentioned	Dilute acid hydrolysis	*Bacillus sp.* strain COL1/A6	54.6	[2]
Corn cob hydrolyzate	0.2, 0.5, and 1 g	Acid hydrolysis	*Bacillus* spp. BM 37	36.16	[119]
Apple pulp waste	1:3 v/v deionized water	Not mentioned	*Pseudomonas citronellolis* NRRL B-2504	30	[123]
Apple pulp waste	1:3 v/v deionized water	Not mentioned	Co-culture of *Cupriavidus necator* DSM 428 and *Pseudomonas citronellolis* NRRL B-2504	52	[124]
Apple pulp waste	1:3 v/v deionized water	Not mentioned	Co-culture of *Cupriavidus necator* DSM 428 and *Pseudomonas citronellolis* NRRL B-2504	48	[124]
Banana peels	20 g	Not mentioned	*Zobellella* sp. DD5	34.38	[125]
Corn oil waste	20–50 mg	Acidic treatment	*Pseudomonas* sp. strain DR2	Up to 37.34	[126]
Coir pith	3%	Hydrolysis	*Azotobacter beijerinickii*	48.9	[127]
Ground orange juicing waste	10 mL	Gas chromatography	*Cupriavidus necator* H16	73	[128]
Jackfruit seed hydrolysate	0.2 mL	Enzymatic hydrolysis	*Bacillus sphaericus* NCIM 5149	49	[129]
Oil palm empty fruit bunch	Not mentioned	Enzymatic hydrolysis	*B. megaterium* R11	51.6	[130]
Apricots	10 g	Enzymatic hydrolysis	*Pseudomonas resinovorans*	1.4	[131]

reversed by detoxification or microbial consortia[138]. Solid-state and submerged fermentation are both viable, although better yields are typically obtained under submerged systems[139]. Record yields are 56% PHB from pineapple juice[140], and 75% PHAs from oil palm frond juice[141] (Table 3). Pre-treatment processes like enzymatic hydrolysis or acid treatment enhances yields[142,143]. Seasonal and spatial availability of fruits guarantees a renewable feedstock, while waste conversion to resource supports circular economy principles and sustainable development objectives[144].

Application of sugar maple sap and syrup for PHAs production

Sugar maple syrup and sap, as unconventional ones, are promising sugar-dense feedstocks for PHAs production. Maple sap has high sucrose content, while syrup, its concentration, has even higher sugar content, which makes both candidates for microbial fermentation[145]. Although less is known about them, their high concentration, and purity of sugars offer potential for effective PHAs synthesis. Yezza et al.[145] used maple sap and *Alcaligenes latus* to synthesize poly-β-hydroxybutyrate (PHB) to attain yields of up to 78% dry weight of cells. The PHB produced had chemical, thermal, and spectroscopic properties that were similar to commercial sucrose-derived PHB. Lokesh et al.[146] also found that sap from felled oil palm trunks (OPT), which contained 5.5% w/v fermentable sugar, was a cheap renewable source of carbon. With a termite gut isolate, *Bacillus megaterium* MC1 yielded 3.28 g/L of P(3HB), which is equivalent to 30 wt% of cell dry weight. Talebian-Kiakalaieh et al.[147] showed that *Burkholderia cepacia* ATCC 17759 was able to grow on sugar maple hydrolysate and produce 51% 3-hydroxybutyrate. The seasonal nature of maple sap and syrup availability brings with it opportunities and challenges for PHAs production. Utilizing these substrates can increase the economic worth of the maple industry, and offer renewable substitutes to traditional sugar feedstocks for bioplastic production.

Challenges associated with scaling lab results for PHAs production

Scaling up laboratory results in the production of PHAs to industrial processes encounters serious economic, technical, and regulatory challenges. The cost-determining carbon substrates still contribute 30%–67% of the costs of production, and whereas laboratory work frequently employs pure glucose or sucrose, industrial viability hinges on the incorporation of low-cost, waste-derived feedstocks[30,148]. These residues are however accompanied by variability in sugar content, inhibitory substances, and nutrient imbalance, all contributing to decreased microbial efficiency and process stability. Industrial fermentation poses an added problem, where aeration, pH, temperature, and agitation are difficult to maintain uniformly in large-scale bioreactors, tending to result in metabolic diversion and decreased yields. Cost-saving measures like mixed microbial cultures, or open fermentation systems invite competition from unwanted microbes and degradation of PHAs. Sugar feedstocks such as molasses, bagasse, and vinasse have inconsistent composition and inhibitors and need uniform, low-cost pre-treatment to deliver consistent quality (Fig. 3). Non-optimized processes lower sugar yield and increase expense. Scale-up is confronted by oxygen transfer, mixing, and heat issues in achieving high-cell-density titres. Feedstock availability, waste valorization, regulation, and supply-chain integration complicate matters. PHA recovery is energy- and solvent-hungry, usually offsetting upstream expense, although new greener processes are untested at scale[149].

Downstream recovery exacerbates these problems; whereas solvent-based extraction is effective on a small scale, it is expensive,
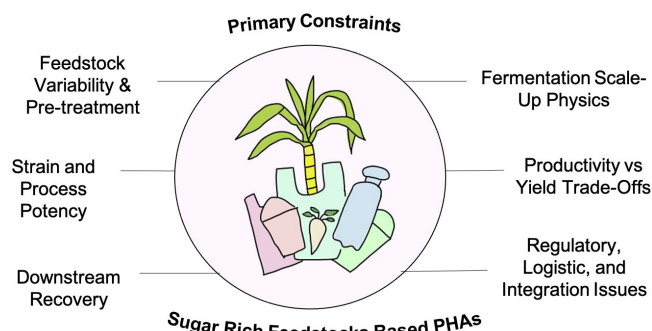

Fig. 3 Primary bottlenecks in PHAs production from sugar rich feedstocks.

environmentally stressful, and less effective in bulk. Industrial purification hence requires new solutions that reconcile efficiency with sustainability. Lastly, ensuring product quality, safety, and environmental compliance is more challenging in the case of non-food-grade waste-based substrates. The elimination of such obstacles is critical for the commercialization of PHAs from potential laboratory materials to practicable industrial bioplastics[17,30].

Environmental and economic benefits of PHAs from sugar-rich feedstocks

PHAs have attracted considerable interest as eco-friendly substitutes for petrochemical plastics based on their similar material properties as well as their important environmental advantages[150]. Derived from sugar-based biomass, PHAs are biodegradable and can be degraded by microbes to water and carbon dioxide without leaving toxic residues[151,152]. In contrast to traditional plastics that last for centuries and result in plastic and microplastic pollution, PHAs biodegrade innocuously, lessening long-term environmental risks. Their application lowers landfilling, water pollution, and environmental persistence[153]. In addition, PHAs are not toxic and do not release toxic chemicals or microplastics upon decomposition[154]. Life-cycle analyses reveal that PHAs require lower energy and lower greenhouse gas emissions than traditional plastics. For example, the substitution of an equal weight of high-density polyethylene with PHA can save 2.9 kg of CO_2 emissions, and 15 kg of emissions relative to polystyrene[155]. Such properties render PHAs an eco-friendly option for bioplastic manufacture and green material uses.

The sustainable source of PHAs from sugarcane, corn syrup, and similar carbohydrate-based feedstocks enhances the environmental status of PHAs by minimizing fossil fuel use and carbon footprints. Governments and industries seeking sustainable alternatives acknowledge PHAs as aligned with the principles of the circular economy, promoting resource efficiency and environmental care[156,157,13]. These benefits (Fig. 4) notwithstanding, economic limitations restrict their global adoption. High production expense, dictated in part by feedstock cost and accessibility, continues to be a stumbling block. Though sugarcane, corn syrup, and crop residues can be used as carbon substrates for microbial fermentation[152], challenges with food–feed competition, yield stability, and transport economics raise the cost of operations. Large-scale production entails technical limitations, especially fermentation and downstream processing, where big bioreactors need optimal oxygenation, pH regulation, and stable microbial growth to ensure productivity[158]. Downstream purification and separation are still costly, ranging from 30%–50% of overall costs[159]. Even though PHA prices have fallen from USD$9.50/kg in 2002, to USD$2.62/kg in
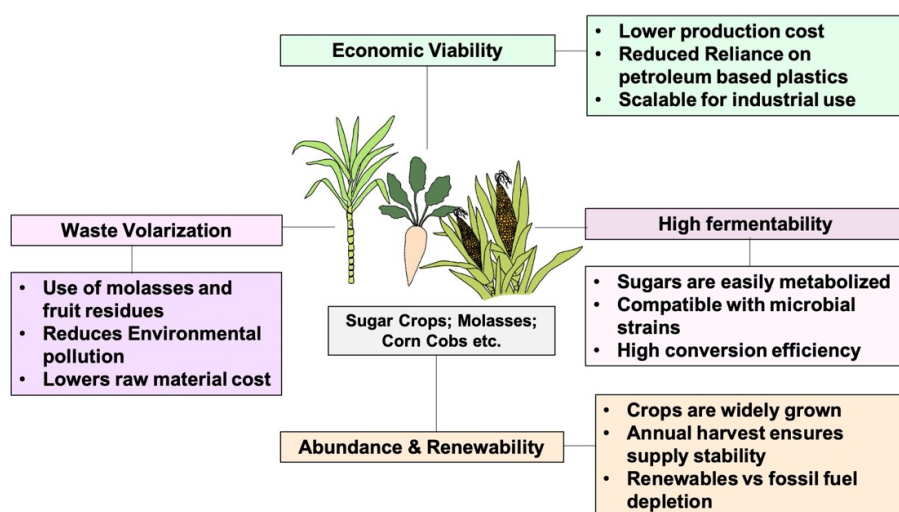
Fig. 4 Advantages of sugar based feedstocks for PHAs production.

2019[160], petroplastics are still cheaper and prevalent. Using sugar-derived by-products, like molasses and fruit waste from processing, provides cost-saving opportunities, and reduces environmental pollution[161,162,136]. Technological innovation, such as engineered microbial hosts, increased intracellular storage, and valorization of non-traditional waste-derived feeds, further enhances economic viability[163,164]. Therefore, although PHAs pose an environmental necessity, cost issues remain but regulatory demands and growing demands in packaging, agriculture, and in biomedical applications highlight their promise as renewable bioplastics[8,165,156].

Role of PHAs produced from sugar-rich feedstocks in a circular economy

The conversion of agricultural residues and waste to value is increasingly being recognized (Fig. 5), as it de-prioritizes waste management infrastructure while recovering by-products as valuable resources in a closed loop[166]. PHAs play an important role by reducing plastic litter, improving resource efficiency, preventing climate change, and promoting circular economy measures[149]. Feedstocks like sugarcane bagasse, fruit peels, and molasses contribute carbon sources for microbial fermentation, lowering the dependence on virgin raw materials. Organic content in these wastes can be transformed into sugars and volatile fatty acids (VFAs) by anaerobic treatments[167]. But pre-treatment processes, although required to enhance accessibility, may increase expenditure and

produce inhibitory compounds like furfural that lower PHAs yields[168]. Process parameter optimization and prevention of acidogenic inhibition are important to successful waste-to-PHAs conversion[169,170]. The major industrial uses of PHAs are in the packaging industry; e.g., poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (BIOPOL®) was used in shampoo bottles and cups[171], while poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH, Nodax™) is used in carpets and biodegradable bags[172]. Blending PHAs with natural fibres, such as sugarcane bagasse-reinforced PHB and PHBV composites, also found to have good mechanical and biodegradable properties[173,174]. In biomedical applications, PHAs find applications in drug delivery, implants, and tissue engineering[174,175]. PHB also possesses antimicrobial activity, inhibiting Vibrio infection in shrimp[176]. Some commercial activities involve Bio-on in Italy, which synthesizes PHAs polymers from sugar beet[177,155], and Bioextrax, which is producing PHAs from sugar beet feedstocks[178].

Agriculture is another prospective area. PHAs as mulches also help to improve water retention in the soil, minimize contamination, and increase yield[179]. In contrast to polluting polyethylene mulches that end up in landfills[180], degradable PHAs offer sustainable options[181]. They are best suited for films and coatings due to their low oxygen permeability, but their potential future applications can be PHAs-based growth bags. These bags reduce toxicity, minimize root deformities, and stimulate healthier plant development[182,183]. Due to their biodegradability and environmental friendliness, PHAs are suitable candidates for industrial and agricultural uses[149].
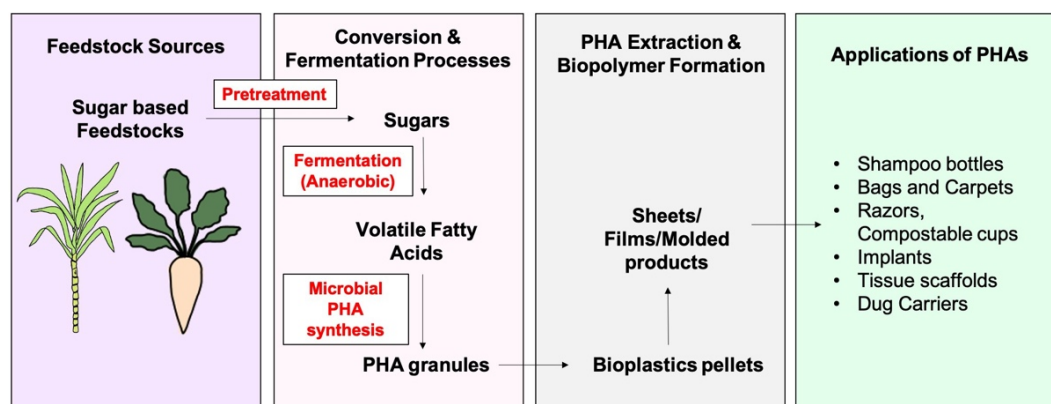

Fig. 5 Circular route of PHAs bioplastic production from sugar based feedstocks and its applications.

Techno-economic and life cycle assessment (LCA)

LCA is an extensive approach employed to assess the environmental effects of products, materials, or services throughout their life cycle, from the acquisition of raw materials to production, transportation, use, and waste. LCA is essential in researching PHAs, which are finding their way as eco-friendly substitutes to traditional plastics that remain in the environment as they are non-biodegradable[184]. PHAs, with origins in renewable sugar-based feedstocks, provide biodegradability, diversity, and lower dependence on fossil fuels, becoming central to sustainable material manufacture[22]. The majority of LCAs have turned their attention to the first-generation sugar feedstocks of corn glucose, sugarcane molasses, and sugar beet residues, considering environmental benefits and process hotspots, such as the energy-hungry chloroform-based extraction of PHAs. Interest is increasingly developing in second-generation waste-derived sugar substrates such as lignocellulosic hydrolysates, residues of food processing, and organic materials from wastewater, although few reports exist[185]. PHAs production from sugar sources continues to be expensive (USD$3–12/kg), with the feedstock contributing to about 50% of expenses[30]. Sugarcane sucrose is very promising, with prices ranging as low as USD$3.02/kg, 22.56 MJ/kg energy requirement, and a conversion rate of 0.2–0.4 g PHAs/g sugar, less than PLA (0.5 g/g). Sugar-derived PHAs have carbon intensities of 1.5–3.0 kg CO_2-eq/kg, less than PLA (2.0–3.5) and PE (2.5–6.0), but land use is still an issue[184].

Comparison of the mechanical properties of PHAs with petrochemical plastics

PHAs produced from sugar feedstocks have adjustable mechanical properties, however these properties tend to vary from typical petrochemical plastics such as polyethylene (PE) and polypropylene (PP)[186]. Homopolymers like PHB have high crystallinity (40%–70%), are rigid and brittle, with tensile strengths of 15 to 43 MPa, Young's modulus of 1–3.5 GPa, and elongation at break of 1%–15%, being susceptible to cracking when subjected to stress. Their hardness and restricted ductility are different from those of PE, PP, and other petroplastics. Monomer structure, chain length, and crystallinity are the factors controlling mechanical response, and these factors are further influenced by copolymerization or microbial fermentation to create medium-chain-length PHAs with softer and more flexible properties. Though less durable and thermally stable than high-performance petroplastics, these PHAs can retain favourable barrier properties, processability, and biodegradability. Thus playing a role in packaging, disposable items, and biomedical devices. Though copolymerization or blending strategies can enhance the flexibility and lower brittleness in sugar-rich feedstock-based PHA, the level of mechanical reliability as achieved in traditional plastics has not yet been attained. Since PHAs offer multifunctional biodegradable substitutes with added advantage towards eco-friendly product but its mechanical profiles need to be considered while using for specific applications[186].

Novel sugar-based polymers beyond PHAs

Polymers from sugar are a new generation of bioplastics with performance and environmental benefits compared to petroleum-based plastics[187]. Polyethylene furanoate (PEF), a product of 2,5-furandicarboxylic acid (FDCA) derived from sugar, has a thermal behaviour comparable to polyethylene terephthalate (PET) but with ~10-fold reduced oxygen permeability (~0.0107 vs 0.114 barrer), thus best suited for food packaging[188]. Nonetheless, its application under pressurized conditions is limited by such disadvantages as brittleness and poor strain-hardening[189,190]. Sugars from biomass comprise of monosaccharides, disaccharides, and sugar alcohols, which are renewable, biodegradable, and versatile platforms for recyclable, high-performance polymers (Fig. 6) that overcome fossil-plastic limitations such as depletion of resources, environmental pollution, and carbon emissions[191,192].

Polyamides from diaminosugars, aldaric acids, and aminoaldonic acids have superior thermal and mechanical properties[191]. Polyamides from isosorbide possess tensile strength and thermal stability equivalent to or superior to typical nylons[193]. EPFL scientists accomplished catalyst-free conversion of xylose dimethyl glyoxylate into polyamides with 97% atom economy without harmful additives and maintaining toughness over recycling cycles[194]. Techno-economic studies indicate production costs are competitive with conventional nylons[195]. 2,5-Furandicarboxylic acid (FDCA) from fructose is employed for the manufacture of polyethylene furanoate (PEF), having improved gas barrier properties compared to PET[196]. Sugar alcohols xylitol and sorbitol act as monomers for biodegradable polyurethanes and polycarbonates, imparting flexibility[197]. Isoidide- and isomannide-derived polymers synthesized at Duke University and the University of Birmingham exhibit tunable mechanical properties that vary from rubbery extensibility to nylon-like toughness because of stereochemical diversity[198].
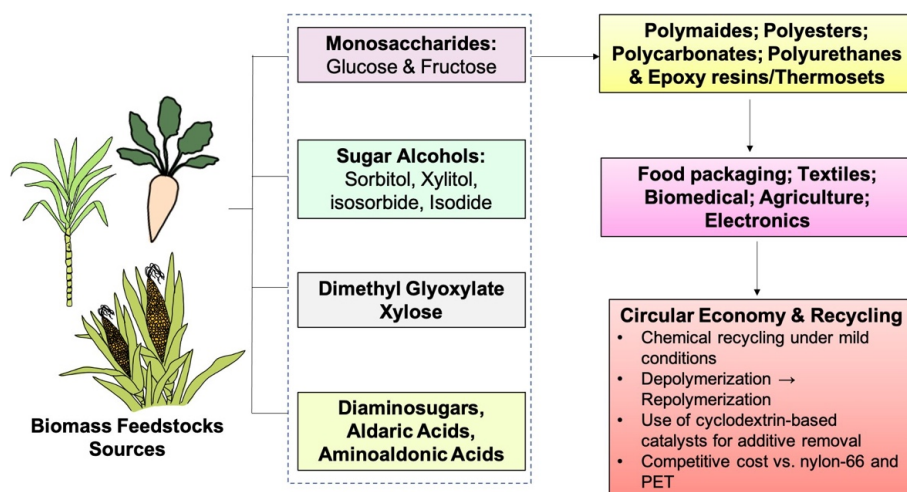

Fig. 6 Sugars based feedstock to smart materials.

Sugar monomers like sorbitol, glucose, and isosorbide have been combined with epoxy resins and thermosets to improve thermal stability and toughness[199]. Sugared furans offer petroleum-free renewable thermoset alternatives[200], and dynamic covalent chemistries allow for vitrimer-type thermosets with recyclability and re-shapability for use in the automobile and electronic industries[201,202]. Chemical modifications such as acetalization and etherification enable tuning of hydrophobicity, crystallinity, and rates of degradation. Their biocompatibility facilitates medical applications, and sugar polymers are able to condense into nanoparticles, micelles, and hydrogels for controlled drug delivery, including colon-specific release[203,204].

Cost and scalability are issues, but enzymatic and microbial production of sugar-based monomers, coupled with sugar biorefineries, increases feasibility. Recyclability tests show maintained tensile strength, and chemical recyclability under mild conditions[205]. Firms such as Bloom Biorenewables, a spin-off from EPFL, are working towards commercial-scale production. Sugar-based catalysts such as cyclodextrins improve upcycling and recycling by eliminating additives, maximizing yield and purity[206,207]. Generally, sugar-derived polymers such as polyamides, polyesters, polycarbonates, and epoxy resins provide adjustable functionality, recyclability, and compliance with circular economy doctrine, making them ideal for packaging, biomedical, and high-performance applications with prospects for sustainable reform of the plastics sector[208].

Conclusions and future perspectives

The application of PHAs have been reported in several areas, from daily use to specialized uses like in biomedicals. Research opportunities in PHAs production have been gaining speed with advancements in genome engineering techniques. Discovering alternative carbon sources is key to maintaining sustainable production methods. With the characteristics of renewability, abundance, microbial compatibility, cost-effectiveness, and eco-friendly, the sugar rich feedstock have become essential for the sustainable and efficient production of PHAs with higher yields. These sugar-based substrates can significantly reduce the carbon footprint of PHAs compared to petroleum based substrates. Moreover, these also support the circular economy perspective by the creation of value-added products. The integration of these feedstocks in PHAs production processes through biotechnological tools have also impacted the existing agricultural practices and utilization of infrastructures in such processes. This shift results in more sustainable bioplastic manufacturing, compared to traditional ones. Additionally, since these feedstocks are obtained from waste/by-products of sugar-based crops, they are easily available in sufficient quantity, thus reducing the dependency on imported raw materials and supporting local economies. PHA production from these feedstocks is a positive and practical approach for the problem of plastic pollution and resource depletion, leading towards the attainment of sustainable development goals.

Though challenges still remain, the development in science has created further opportunities for the exploration of genetically engineered microbes in tailoring the properties of PHAs properties in several different fields such as packaging, biomedical devices, and agricultural films[209]. Another opportunity will be seen in the investigation of mixed culture fermentation systems and new bioreactor designs to maximize PHAs production from different feedstocks, such as agricultural waste and food waste in favour of waste valourization and circular economy approaches[210]. PHAs blends and composites with superior mechanical, thermal, and barrier properties also provide alternatives for environmental friendly plastics against conventional plastics. This will be driven by consumer and regulatory demand[211]. Interdisciplinary interactions and positive actions among academia, industry, and policy makers towards the adoption of these PHAs through these feedstocks will help in commercializing a green alternative product, reducing plastic pollution and promoting circular economy[212].

Ethical statement

Not applicable.

Author contributions

The authors confirm their contributions to the paper as follows: conceptualization, original writing, review and editing: Misra V, Mall AK. All authors reviewed the results and approved the final version of the manuscript.

Data availability

All data and information discussed are derived from previously published literature, which has been appropriately cited within the manuscript. No new datasets were created or analyzed during the preparation of this article.

Conflict of interest

The authors declare that they have no conflict of interest.

Dates

References

1. Blettler MCM, Mitchell C. 2021. Dangerous traps: macroplastic encounters affecting freshwater and terrestrial wildlife. *Science of The Total Environment* 798:149317

2. Santimano MC, Prabhu NN, Garg S. 2009. PHA production using low-cost agro-industrial wastes by *Bacillus* sp. strain COL1/A6. *Research Journal of Microbiology* 4:89−96

3. Quintero-Silva MJ, Suárez-Rodríguez SJ, Gamboa-Suárez MA, Blanco-Tirado C, Combariza MY. 2024. Polyhydroxyalkanoates production from cacao fruit liquid residues using a native *Bacillus megaterium* strain: preliminary study. *Journal of Polymers and the Environment* 32:1289−303

4. Bhatia SK. 2025. Research progress on the synthesis, modification, and applications of microbial biopolymers. *Polymers* 17(15):2053

5. Rehm BHA. 2010. Bacterial polymers: biosynthesis, modifications and applications. *Nature Reviews Microbiology* 8:578−92

6. López-Cuellar MR, Alba-Flores J, Gracida Rodríguez JN, Pérez-Guevara F. 2011. Production of polyhydroxyalkanoates (PHAs) with canola oil as carbon source. *International Journal of Biological Macromolecules* 48:74−80

7. Shen XW, Yang Y, Jian J, Wu Q, Chen GQ. 2009. Production and characterization of homopolymer poly(3-hydroxyvalerate) (PHV) accumulated by wild type and recombinant *Aeromonas hydrophila* strain 4AK4. *Bioresource Technology* 100(18):4296−99

8. Bugnicourt E, Cinelli P, Lazzeri A, Alvarez V. 2014. Polyhydroxyalkanoate (PHA): review of synthesis, characteristics, processing and potential applications in packaging. *Express Polymer Letters* 8(11):791−808

9. Vigneswari S, Noor MSM, Amelia TSM, Balakrishnan K, Adnan A, et al. 2021. Recent advances in the biosynthesis of polyhydroxyalkanoates from lignocellulosic feedstocks. *Life* 11:807

10. Bellini S, Demichelis F, Tommasi T, Tarraran L, Fino D. 2024. Integrated biorefinery strategy for poly(3-hydroxybutyrate) accumulation in *Cupriavidus necator* DSM 545 using a sugar rich syrup from cereal waste and acetate from gas fermentation. *Journal of Environmental Chemical Engineering* 12:111661

11. Guzmán-Lagunes F, Wongsirichot P, Winterburn J, Guerrero Sanchez C, Montiel C. 2023. Polyhydroxyalkanoates production: a challenge for the plastic industry. *Industrial & Engineering Chemistry Research* 62(44):18133−58

12. Sen KY, Baidurah S. 2021. Renewable biomass feedstocks for production of sustainable biodegradable polymer. *Current Opinion in Green and Sustainable Chemistry* 27:100412

13. Rosenboom JG, Langer R, Traverso G. 2022. Bioplastics for a circular economy. *Nature Reviews Materials* 7:117−37

14. Karp SG, Woiciechowski AL, Soccol VT, Soccol CR. 2013. Pretreatment strategies for delignification of sugarcane bagasse: a review. *Brazilian Archives of Biology and Technology* 56(4):679−89

15. Andhalkar VV, Ahorsu R, de Maria PD, Winterburn J, Medina F, et al. 2022. Valorization of lignocellulose by producing polyhydroxyalkanoates under circular bioeconomy premises: facts and challenges. *ACS Sustainable Chemistry & Engineering* 10(50):16459−75

16. Mozejko-Ciesielska J, Moraczewski K, Czaplicki S, Singh V. 2023. Production and characterization of polyhydroxyalkanoates by *Halomonas alkaliantarctica* utilizing dairy waste as feedstock. *Scientific Reports* 13:22289

17. Możejko-Ciesielska J, Ray S, Sankhyan S. 2023. Recent challenges and trends of polyhydroxyalkanoate production by extremophilic bacteria using renewable feedstocks. *Polymers* 15(22):4385

18. Shin Y, Jung HJ, Oh J, Kim S, Lee Y, et al. 2024. Production of Polyhydroxybutyrate by halotolerant *Halomonas cerina* YK44 using sugarcane molasses and soybean flour in tap water. *International Journal of Biological Macromolecules* 279(4):135358

19. da Costa e Silva PE, Houllou LM. 2022. Obtainment of polyhydroxyalkanoates (PHAs) from microalgae supplemented with agro-industry residue corn steep liquor. *Journal of Botany Research* 5(1):138−40

20. Chang Y, Zhao XQ, Zhang X, Jiao Y. 2025. Corn steep liquor as an efficient bioresource for functional components production by biotransformation technology. *Foods* 14(13):2158

21. Nielsen C, Rahman A, Rehman AU, Walsh MK, Miller CD. 2017. Food waste conversion to microbial polyhydroxyalkanoates. *Microbial Biotechnology* 10(6):1338−52

22. Winnacker M. 2019. PHA production: a sustainable alternative to conventional plastics. *Macromolecular Bioscience* 19(3):1800415

23. Chen GQ, Hajnal I, Wu H, Lv L, Ye J. 2015. Engineering biosynthesis mechanisms for diversifying polyhydroxyalkanoates. *Trends in Biotechnology* 33(10):565−74

24. Gutschmann B, Bock MCE, Jahns S, Neubauer P, Brigham CJ, et al. 2021. Untargeted metabolomics analysis of *Ralstonia eutropha* during plant oil cultivations reveals the presence of a fucose salvage pathway. *Scientific Reports* 11:14267

25. Lu X, Wang L, Yang Z, Lu H. 2013. Strategies of polyhydroxyalkanoates modification for the medical application in neural regeneration/nerve tissue engineering. *Advances in Bioscience and Biotechnology* 4:731−40

26. Riedel SL, Jahns S, Koenig S, Bock MCE, Brigham CJ, et al. 2015. Polyhydroxyalkanoates production with *Ralstonia eutropha* from low quality waste animal fats. *Journal of Biotechnology* 214:119−27

27. Slater S, Houmiel KL, Tran M, Mitsky TA, Taylor NB, et al. 1998. Multiple β-ketothiolases mediate poly(β-hydroxyalkanoate) copolymer synthesis in *Ralstonia eutropha*. *Journal of Bacteriology* 180:1979−87

28. Xing Y, Bu LX, Wang K, Jiang JX. 2012. Pretreatment of furfural residues with alkaline peroxide to improve cellulose hydrolysis. Characterization of isolated lignin. *Cellulose Chemistry and Technology* 46(3−4):249−60

29. Hassan S, Ngo T, Ball AS. 2024. Valorisation of sugarcane bagasse for the sustainable production of polyhydroxyalkanoates. *Sustainability* 16(5):2200

30. Zytner P, Kumar D, Elsayed A, Mohanty A, Ramarao BV, et al. 2023. A review on polyhydroxyalkanoate (PHA) production through the use of lignocellulosic biomass. *RSC Sustainability* 1:2120−34

31. Fabbri S, Owsianiak M, Hauschild MZ. 2023. Evaluation of sugar feedstocks for bio-based chemicals: a consequential, regionalized life cycle assessment. *GCB Bioenergy* 15:72−87

32. Dalsasso RR, Pavan FA, Bordignon SE, de Aragão GMF, Poletto P. 2019. Polyhydroxybutyrate (PHB) production by *Cupriavidus necator* from sugarcane vinasse and molasses as mixed substrate. *Process Biochemistry* 85:12−18

33. Xu Z, Huang F. 2014. Pretreatment methods for bioethanol production. *Applied Biochemistry and Biotechnology* 174:43−62

34. Zhao X, Wen J, Chen H, Liu D. 2018. The fate of lignin during atmospheric acetic acid pretreatment of sugarcane bagasse and the impacts on cellulose enzymatic hydrolyzability for bioethanol production. *Renewable Energy* 128:200−9

35. Mouho OMB, Doudjo S, Yan S, Konan ATS, Yao KB, et al. 2025. Strategies to enhance polyhydroxyalkanoate production from sugarcane molasses by *Cupriavidus necator* 11599. *Open Journal of Applied Sciences* 15(3):573−96

36. Naheed N, Jamil N. 2014. Optimization of biodegradable plastic production on sugar cane molasses in *Enterobacter* sp. SEL2. *Brazilian Journal of Microbiology* 45(2):417−26

37. Kiselev EG, Demidenko AV, Zhila NO, Shishatskaya EI, Volova TG. 2022. Sugar beet molasses as a potential C-substrate for PHA production by *Cupriavidus necator*. *Bioengineering* 9(4):154

38. Tyagi P, Saxena NK, Sharma A. 2018. Production of polyhydroxyalkanoates (PHA) from a non-lignocellulosic component of sugarcane bagasse: fueling a biobased economy. *Biofuels, Bioproducts and Biorefining* 12(4):536−41

39. Oyewole OA, Abdulmalik SU, Abubakar AO, Chimbekujwo KI, Obafemi YD, et al. 2024. Production of polyhydroxyalkanoate (PHA) by *Pseudomonas aeruginosa* (OL405443) using agrowastes as carbon source. *Cleaner Materials* 11:100217

40. Oladzad S, Fallah N, Mahboubi A, Afsham N, Taherzadeh MJ, et al. 2024. Comparison of acid and hydrothermal pretreatments of date waste for value creation. *Scientific Reports* 14:18056

41. Salgaonkar BB, Mani K, Braganca JM. 2013. Characterization of polyhydroxyalkanoates accumulated by a moderately halophilic salt pan isolate *Bacillus megaterium* strain H16. *Journal of Applied Microbiology* 114:1347−56

42. Dietrich K, Dumont MJ, Del Rio LF, Orsat V. 2019. Sustainable PHA production in integrated lignocellulose biorefineries. *New Biotechnology* 49:161−68

43. Kovalcik A, Pernicova I, Obruca S, Szotkowski M, Enev V, et al. 2020. Grape winery waste as a promising feedstock for the production of polyhydroxyalkanoates and other value-added products. *Food and Bioproducts Processing* 124:1−10

44. Kumar P, Singh M, Mehariya S, Patel SKS, Lee JK, et al. 2014. Ecobiotechnological approach for exploiting the abilities of *Bacillus* to produce co-polymer of polyhydroxyalkanoate. *Indian Journal of Microbiology* 54(2):151−57

45. Kim JS, Lee YY, Kim TH. 2016. A review on alkaline pretreatment technology for bioconversion of lignocellulosic biomass. *Bioresource Technology* 199:42−48

46. Xu H, Li B, Mu X. 2016. Review of alkali-based pretreatment to enhance enzymatic saccharification for lignocellulosic biomass conversion. *Industrial & Engineering Chemistry Research* 55(32):8691−705

47. Raud M, Krennhuber K, Jäger A, Kikas T. 2019. Nitrogen explosive decompression pre-treatment: an alternative to steam explosion. *Energy* 177:175−82

48. Ayeni AO, Daramola MO. 2017. Lignocellulosic biomass waste beneficiation: evaluation of oxidative and non-oxidative pretreatment methodologies of South African corn cob. *Journal of Environmental Chemical Engineering* 5(2):1771−79

49. Zhang N, Tao P, Lu Y, Nie S. 2019. Effect of lignin on the thermal stability of cellulose nanofibrils produced from bagasse pulp. *Cellulose* 26:7823−35

50. Yu N, Tan L, Sun ZY, Nishimura H, Takei S, et al. 2018. Bioethanol from sugarcane bagasse: focused on optimum of lignin content and reduction of enzyme addition. *Waste Management* 76:404−13

51. Lee WS, Chua ASM, Yeoh HK, Nittami T, Ngoh GC. 2015. Strategy for the biotransformation of fermented palm oil mill effluent into biodegradable polyhydroxyalkanoates by activated sludge. *Chemical Engineering Journal* 269:288−97

52. Moxley K, Schmidt S. 2012. Isolation of a phenol-utilizing marine bacterium from Durban Harbour (South Africa) and its preliminary characterization as *Marinobacter* sp. KM2. *Water Science and Technology* 65(5):932−39

53. Thring RW, Chornet E, Overend RP. 1990. Recovery of a solvolytic lignin: effects of spent liquor/acid volume ratio, acid concentration and temperature. *Biomass* 23:289−305

54. Sun Y, Cheng J. 2002. Hydrolysis of lignocellulosic materials for ethanol production: a review. *Bioresource Technology* 83:1−11

55. Duff SJB, Murray WD. 1996. Bioconversion of forest products industry waste cellulosics to fuel ethanol: a review. *Bioresource Technology* 55:1−33

56. Schmatz AA, Salazar-Bryam AM, Contiero J, Sant'Anna C, Brienzo M. 2021. Pseudo-lignin content decreased with hemicellulose and lignin removal, improving cellulose accessibility, and enzymatic digestibility. *BioEnergy Research* 14:106−21

57. Zhang J, Xie J, Zhang H. 2021. Sodium hydroxide catalytic ethanol pretreatment and surfactant on the enzymatic saccharification of sugarcane bagasse. *Bioresource Technology* 319:124171

58. Taherzadeh MJ, Karimi K. 2008. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: a review. *International Journal of Molecular Sciences* 9(9):1621−51

59. Ziegler-Devin I, Chrusciel L, Brosse N. 2021. Steam explosion pretreatment of lignocellulosic biomass: a mini-review of theorical and experimental approaches. *Frontiers in Chemistry* 9:705358

60. Lam PS. 2011. *Steam explosions of biomass to produce durable wood pellets*. Thesis. University of British Columbia, Vancouver, Canada. 180 pp

61. Raud M, Olt J, Kikas T. 2016. N$_2$ explosive decompression pretreatment of biomass for lignocellulosic ethanol production. *Biomass and Bioenergy* 90:1−6

62. Silveira MHL, Chandel AK, Vanelli BA, Sacilotto KS, Cardoso EB. 2018. Production of hemicellulosic sugars from sugarcane bagasse *via* steam explosion employing industrially feasible conditions: pilot scale study. *Bioresource Technology Reports* 3:138−46

63. Zhang W, You Y, Lei F, Li P, Jiang J. 2018. Acetyl-assisted autohydrolysis of sugarcane bagasse for the production of xylo-oligosaccharides without additional chemicals. *Bioresource Technology* 265:387−93

64. Yan F, Tian S, Du K, Wang X. 2021. Effects of steam explosion pretreatment on the extraction of xylooligosaccharide from rice husk. *BioResources* 16(4):6910−20

65. Wan C, Li Y. 2012. Fungal pretreatment of lignocellulosic biomass. *Biotechnology Advances* 30(6):1447−57

66. Abu-Thabit NY, Pérez-Rivero C, Uwaezuoke OJ, Ngwuluka NC. 2022. From waste to wealth: upcycling of plastic and lignocellulosic wastes to PHAs. *Journal of Chemical Technology & Biotechnology* 97:3217−40

67. Østby H, Hansen LD, Horn SJ, Eijsink VGH, Várnai A. 2020. Enzymatic processing of lignocellulosic biomass: principles, recent advances and perspectives. *Journal of Industrial Microbiology & Biotechnology* 47(9):623−57

68. González-Rojo S, Díez-Antolínez R. 2023. Production of polyhydroxyalkanoates as a feasible alternative for an integrated multiproduct lignocellulosic biorefinery. *Bioresource Technology* 386:129493

69. Yuan Q, Liu S, Ma MG, Ji XX, Choi SE, et al. 2021. The kinetics studies on hydrolysis of hemicellulose. *Frontiers in Chemistry* 9:781291

70. Liu P, Zheng Y, Yuan Y, Han Y, Su T, et al. 2023. Upcycling of PET oligomers from chemical recycling processes to PHA by microbial co-cultivation. *Waste Management* 172:51−59

71. Sahu SS, Maiti SK. 2024. A circular economy approach to valorisation of lignocellulosic biomass-biochar and bioethanol production. In *Biomass Energy for Sustainable Development*, eds Shah MP, Kaur P. Boca Raton: CRC Press. pp. 335−54 doi: 10.1201/9781003406501-17

72. Chaudhry WN, Jamil N, Ali I, Ayaz MH, Hasnain S. 2011. Screening for polyhydroxyalkanoate (PHA)-producing bacterial strains and comparison of PHA production from various inexpensive carbon sources. *Annals of Microbiology* 61:623−29

73. Kulpreecha S, Boonruangthavorn A, Meksiriporn B, Thongchul N. 2009. Inexpensive fed-batch cultivation for high poly(3-hydroxybutyrate) production by a new isolate of *Bacillus megaterium*. *Journal of Bioscience and Bioengineering* 107(3):240−45

74. Baei MS, Najafpour GD, Younesi H, Tabandeh F, Eisazadeh H. 2009. Poly(3-hydroxybutyrate) synthesis by *Cupriavidus necator* DSMZ 545 utilizing various carbon sources. *World Applied Sciences Journal* 7:157−61

75. Sen KY, Hussin MH, Baidurah S. 2019. Biosynthesis of poly(3-hydroxybutyrate) (PHB) by *Cupriavidus necator* from various pretreated molasses as carbon source. *Biocatalysis and Agricultural Biotechnology* 17:51−59

76. Albuquerque MGE, Eiroa M, Torres C, Nunes BR, Reis MAM. 2007. Strategies for the development of a side stream process for polyhydroxyalkanoate (PHA) production from sugar cane molasses. *Journal of Biotechnology* 130:411−21

77. Gomaa EZ. 2014. Production of Polyhydroxyalkanoates (PHAs) by *Bacillus subtilis* and *Escherichia coli* grown on cane molasses fortified with ethanol. *Brazilian Archives of Biology and Technology* 57:145−54

78. Nair AM, Annamalai K, Kannan SK, Kuppusamy S. 2014. Utilization of sugarcane molasses for the production of polyhydroxyalkanoates using *Bacillus subtilis*. *Malaya Journal of Biosciences* 1(1):24−30

79. Gomez JGC, Méndez BS, Nikel PI, Pettinari MJ, Prieto MA, et al. 2012. Making green polymers even greener: towards sustainable production of polyhydroxyalkanoates from agroindustrial by-products. In *Advances in Applied Biotechnology*, ed. Petre M. UK: IntechOpen. pp. 41−62 doi: 10.5772/31847

80. Park SJ, Jang YA, Noh W, Oh YH, Lee H, et al. 2015. Metabolic engineering of *Ralstonia eutropha* for the production of polyhydroxyalkanoates from sucrose. *Biotechnology and Bioengineering* 112:638−43

81. Jo SY, Sohn YJ, Park SY, Son J, Yoo JI, et al. 2021. Biosynthesis of polyhydroxyalkanoates from sugarcane molasses by recombinant *Ralstonia eutropha* strains. *Korean Journal of Chemical Engineering* 38:1452−59

82. Akaraonye E, Moreno C, Knowles JC, Keshavarz T, Roy I. 2012. Poly(3-hydroxybutyrate) production by *Bacillus cereus* SPV using sugarcane molasses as the main carbon source. *Biotechnology Journal* 7:293−303

83. Jiang Y, Song X, Gong L, Li P, Dai C, et al. 2008. High poly(β-hydroxybutyrate) production by *Pseudomonas fluorescens* A2a5 from inexpensive substrates. *Enzyme and Microbial Technology* 42(2):167−72

84. Zhang H, Obias V, Gonyer K, Dennis D. 1994. Production of polyhydroxyalkanoates in sucrose-utilizing recombinant *Escherichia coli* and *Klebsiella* strains. *Applied and Environmental Microbiology* 60:1198−205

85. Bhattacharyya A, Pramanik A, Maji SK, Haldar S, Mukhopadhyay UK, et al. 2012. Utilization of vinasse for production of poly-3-(hydroxybutyrate-co-hydroxyvalerate) by *Haloferax mediterranei*. *AMB Express* 2:34

86. Pramanik A, Mitra A, Arumugam M, Bhattacharyya A, Sadhukhan S, et al. 2012. Utilization of vinasse for the production of polyhydroxybutyrate by *Haloarcula marismortui*. *Folia Microbiologica* 57:71−79

87. Gouda MK, Swellam AE, Omar SH. 2001. Production of PHB by a *Bacillus megaterium* strain using sugarcane molasses and corn steep liquor as sole carbon and nitrogen sources. *Microbiology Research* 156:201−7

88. Page WJ. 1992. Production of polyhydroxyalkanoates by *Azotobacter vinelandii* UWD in beet molasses culture. *FEMS Microbiology Reviews* 9:149−57

89. Bhattacharyya A, Saha J, Haldar S, Bhowmic A, Mukhopadhyay UK, et al. 2014. Production of poly-3-(hydroxybutyrate-co-hydroxyvalerate) by *Haloferax mediterranei* using rice-based ethanol stillage with simultaneous recovery and re-use of medium salts. *Extremophiles* 18:463−70

90. Lopes MSG, Gomez JGC, Taciro MK, Mendonça TT, Silva LF. 2014. Polyhydroxyalkanoate biosynthesis and simultaneous remotion of organic inhibitors from sugarcane bagasse hydrolysate by *Burkholderia* sp. *Journal of Industrial Microbiology & Biotechnology* 41:1353−63

91. Favaro L, Marina B, Rodriguez JEG, Morelli A, Ibraheem I, et al. 2019. Bacterial production of PHAs from lipid rich by-products. *Applied Food Biotechnology* 6:45−52

92. Yu J, Stahl H. 2008. Microbial utilization and biopolyester synthesis of bagasse hydrolysates. *Bioresource Technology* 99(17):8042−48

93. Bengtsson S, Pisco AR, Reis MAM, Lemos PC. 2010. Production of poly-hydroxyalkanoates from fermented sugar cane molasses by a mixed culture enriched in glycogen accumulating organisms. *Journal of Biotechnology* 145:253–63

94. Chaijamrus S, Udpuay N. 2008. Production and characterization of polyhydroxybutyrate from molasses and corn steep liquor produced by *Bacillus megaterium* ATCC 6748. *Agricultural Engineering International: CIGR Journal* 10:1–12

95. Shivakumar S. 2012. Polyhydroxybutyrate (PHB) production using agro-industrial residue as substrate by *Bacillus thuringiensis* IAM 12077. *International Journal of ChemTech Research* 4(3):1158–62

96. Tripathi AD, Yadav A, Jha A, Srivastava SK. 2012. Utilizing of sugar refinery waste (cane molasses) for production of bio-plastic under sub-merged fermentation process. *Journal of Polymers and the Environment* 20:446–53

97. Castilla-Marroquí JD, Pacheco N, Herrera-Corredor JA, Hernández-Rosas F, Jiménez-Morales K, et al. 2024. Polyhydroxyalkanoates production by *Bacillus thuringiensis* HA1 using sugarcane molasses as carbon source. *Revista Mexicana de Ingeniería Química* 23:Bio24352

98. Razzaq S, Shahid S, Farooq R, Noreen S, Perveen S, et al. 2024. Sustainable Bioconversion of agricultural waste substrates into poly(3-Hydroxyhexanoate) (mcl-PHA) by *Cupriavidus necator* DSM 428. *Biomass Conversion and Biorefinery* 14:9429–39

99. Oehmen A, Pinto FV, Silva V, Albuquerque MGE, Reis MAM. 2014. The impact of pH control on the volumetric productivity of mixed culture PHA production from fermented molasses. *Engineering in Life Sciences* 14:143–52

100. Beaulieu M, Beaulieu Y, Melinard J, Pandian S, Goulet J. 1995. Influence of ammonium salts and cane molasses on growth of *Alcaligenes* eutrophus and production of polyhydroxybutyrate. *Applied and Environmental Microbiology* 61:165–69

101. Desouky SES, Ali Abdel-Rahman M, Azab MS, Esmael ME. 2017. Batch and fed batch production of polyhydroxyalkanoates from sugarcane molasses by *Bacillus flexus* Azu-A2. *Journal of Innovations in Pharmaceutical and Biological Sciences* 4(3):55–66

102. Misra V, Srivastava S, Mall AK. 2022. *Sugar beet cultivation, management and processing.* Singapore: Springer. xlvi, 1005 pp doi: 10.1007/978-981-19-2730-0

103. Wang B, Sharma-Shivappa RR, Olson JW, Khan SA. 2013. Production of polyhydroxybutyrate (PHB) by *Alcaligenes latus* using sugarbeet juice. *Industrial Crops and Products* 43:802–11

104. Sarafidou M, Vittou O, Psaki O, Filippi K, Tsouko E, et al. 2024. Evaluation of alternative sugar beet pulp refining strategies for efficient pectin extraction and poly(3-hydroxybutyrate) production. *Biochemical Engineering Journal* 208:109368

105. Medjeber N, Abbouni B, Menasria T, Beddal A, Cherif N. 2015. Screening and production of polyhydroxyalcanoates by *Bacillus megaterium* by the using cane and beet molasses as carbon sources. *Der Pharmacia Lettre* 7(6):102–9

106. Zohri AE, Kamal El-Dean A, Abuo-Dobara M, Ali M, Bakr M, et al. 2019. Production of polyhydroxyalkanoate by local strain of *Bacillus megaterium* AUMC b 272 utilizing sugar beet waste water and molasses. *Egyptian Sugar Journal* 13:45–70

107. Chen GQ, Page WJ. 1994. The effect of substrate on the molecular weight of poly-*β*-hydroxybutyrate produced by *Azotobacter vinelandii* UWD. *Biotechnology Letters* 16:155–60

108. Kurt-Kızıldoğan A, Türe E, Okay S, Otur Ç. 2023. Improved production of poly(3-hydroxybutyrate) by extremely halophilic archaeon *Haloarcula* sp. TG1 by utilization of rCKT3eng-treated sugar beet pulp. *Biomass Conversion and Biorefinery* 13:10911–21

109. Kacanski M, Knoll L, Nussbaumer M, Neureiter M, Drosg B. 2023. Anaerobic acidification of pressed sugar beet pulp for mcl-polyhydroxyalkanoates fermentation. *Process Biochemistry* 131:235–43

110. Zhou K, Yu J, Ma Y, Cai L, Zheng L, et al. 2022. Corn steep liquor: green biological resources for bioindustry. *Applied Biochemistry and Biotechnology* 194:3280–95

111. Kim S, Dale B. 2005. Life cycle assessment study of biopolymers (poly-hydroxyalkanoates) - derived from No-tilled corn (11 pp). *The International Journal of Life Cycle Assessment* 10:200–10

112. de Mello AFM, de Souza Vandenberghe LP, Machado CMB, Valladares-Diestra KK, de Carvalho JC, et al. 2023. Polyhydroxybutyrate production by *Cupriavidus necator* in a corn biorefinery concept. *Bioresource Technology* 370:128537

113. Fonseca GG, Antonio RV. 2006. Polyhydroxyalkanoates production by recombinant *Escherichia coli* using low cost substrate. *American Journal of Food Technology* 2:12–20

114. Tian L, Li H, Song X, Ma L, Li ZJ. 2022. Production of polyhydroxyalkanoates by a novel strain of *Photobacterium* using soybean oil and corn starch. *Journal of Environmental Chemical Engineering* 10:108342

115. Vijayendra SVN, Rastogi NK, Shamala TR, Anil Kumar PK, Kshama L, et al. 2007. Optimization of polyhydroxybutyrate production by *Bacillus* sp. CFR 256 with corn steep liquor as a nitrogen source. *Indian Journal of Microbiology* 47:170–75

116. Stoica I, Petrovici AR, Silion M, Varganici CD, Dinica RO, et al. 2018. Corn cob hydrolyzates used for microbial biosynthesis of polyhydroxybutyrate. *Cellulose Chemistry and Technology* 52:65–67

117. Patel SS. 2014. Production of Polyhydroxybutyrate using agro-industrial waste by *Psuedomonas aeruginosa*. *International Journal of Innovation of Scientific Research* 3:107–10

118. Huang TY, Duan KJ, Huang SY, Chen CW. 2006. Production of polyhydroxyalkanoates from inexpensive extruded rice bran and starch by *Haloferax mediterranei*. *Journal of Industrial Microbiology and Biotechnology* 33:701–6

119. Sawant SS, Salunke BK, Kim BS. 2015. Degradation of corn stover by fungal cellulase cocktail for production of polyhydroxyalkanoates by moderate halophile *Paracoccus* sp. LL1. *Bioresource Technology* 194:247–55

120. Odeniyi OA, Adeola OJ. 2017. Production and characterization of polyhydroxyalkanoic acid from *Bacillus thuringiensis* using different carbon substrates. *International Journal of Biological Macromolecules* 104:407–13

121. Chanprateep S. 2010. Current trends in biodegradable polyhydroxyalkanoates. *Journal of Bioscience and Bioengineering* 110:621–32

122. Gerngross TU. 1999. Can biotechnology move us toward a sustainable society? *Nature Biotechnology* 17:541–44

123. Rebocho AT, Pereira JR, Freitas F, Neves L, Alves VD, et al. 2019. Production of medium-chain length polyhydroxyalkanoates by *Pseudomonas citronellolis* grown in apple pulp waste. *Applied Food Biotechnology* 6:71–82

124. Rebocho AT, Pereira JR, Neves LA, Alves VD, Sevrin C, et al. 2020. Preparation and characterization of films based on a natural P(3HB)/mcl-PHA blend obtained through the co-culture of *Cupriavidus necator* and *Pseudomonas citronellolis* in apple pulp waste. *Bioengineering* 7:34

125. Maity S, Das S, Mohapatra S, Tripathi AD, Akthar J, et al. 2020. Growth associated polyhydroxybutyrate production by the novel *Zobellellae tiwanensis* strain DD5 from banana peels under submerged fermentation. *International Journal of Biological Macromolecules* 153:461–69

126. Song JH, Jeon CO, Choi MH, Yoon SC, Park W. 2008. Polyhydroxyalkanoate (PHA) production using waste vegetable oil by *Pseudomonas* sp. strain DR2. *Journal of Microbiology and Biotechnology* 18(8):1408–15

127. Sathesh Prabu C, Murugesan AG. 2010. Effective utilization and management of coir industrial waste for the production of poly-*β*-hydroxybutyrate (PHB) using the bacterium *Azotobacter beijerinickii*. *International Journal of Environmental Research* 4(3):519–24

128. Lagunes FG. 2016. Synthesis of polyhydroxyalkanoates using orange juicing waste as feedstock. Thesis. The University of Manchester, UK. pp. 158

129. Ramadas NV, Soccol CR, Pandey A. 2010. A statistical approach for optimization of polyhydroxybutyrate production by *Bacillus sphaericus* NCIM 5149 under submerged fermentation using central composite design. *Applied Biochemistry and Biotechnology* 162:996–1007

130. Zhang Y, Sun W, Wang H, Geng A. 2013. Polyhydroxybutyrate production from oil palm empty fruit bunch using *Bacillus megaterium* R11. *Bioresource Technology* 147:307–14

131. Follonier S, Goyder MS, Silvestri AC, Crelier S, Kalman F, et al. 2014. Fruit pomace and waste frying oil as sustainable resources for the

bioproduction of medium-chain-length polyhydroxyalkanoates. *International Journal of Biological Macromolecules* 71:42–52

132. Umesh M, Sankar SA, Thazeem B. 2021. Fruit waste as sustainable resources for polyhydroxyalkanoate (PHA) production. In *Bioplastics for Sustainable Development*, eds Kuddus M, Roohi. Singapore: Springer. pp. 205–29 doi: 10.1007/978-981-16-1823-9_7

133. Qureshi AS, Khushk I, Naqvi SR, Simiar AA, Ali CH, et al. 2017. Fruit waste to energy through open fermentation. *Energy Procedia* 142:904–9

134. Choi IS, Lee YG, Khanal SK, Park BJ, Bae HJ. 2015. A low-energy, cost-effective approach to fruit and *Citrus* peel waste processing for bioethanol production. *Applied Energy* 140:65–74

135. Longo A, Fanelli F, Villano M, Montemurro M, Rizzello CG. 2024. Bioplastic production from agri-food waste through the use of *Haloferax mediterranei*: a comprehensive initial overview. *Microorganisms* 12:1038

136. Atarés L, Chiralt A, González-Martínez C, Vargas M. 2024. Production of polyhydroxyalkanoates for biodegradable food packaging applications using *Haloferax mediterranei* and agrifood wastes. *Foods* 13(6):950

137. Preethi K, Lakshmi M, Umesh M, Priynaka K, Thazeem B. 2017. Fruit peels: a potential substrate for acetic acid using *Acetobacter aceti*. *International Journal of Applied Research* 3(4):286–91

138. Umesh M, Basheer T. 2018. Microbe mediated bioconversion of fruit waste into value added products: microbes in fruit waste management. In *Research Anthology on Food Waste Reduction and Alternative Diets for Food and Nutrition Security*, eds Pathak VM, Navneet. 1st Edition. PA: IGI Global Hershey. pp. 57–78 doi: 10.4018/978-1-7998-5354-1.ch031

139. Castilho LR, Mitchell DA, Freire DMG. 2009. Production of polyhydroxyalkanoates (PHAs) from waste materials and by-products by submerged and solid-state fermentation. *Bioresource Technology* 100:5996–6009

140. Suwannasing W, Imai T, Kaewkannetra P. 2015. Potential utilization of pineapple waste streams for polyhydroxyalkanoates (PHAs) production *via* batch fermentation. *Journal of Water and Environment Technology* 13:335–47

141. Zahari MAKM, Abdullah SSS, Roslan AM, Ariffin H, Shirai Y, et al. 2014. Efficient utilization of oil palm frond for bio-based products and biorefinery. *Journal of Cleaner Production* 65:252–60

142. Hafid HS, Nor'Aini AR, Mokhtar MN, Talib AT, Baharuddin AS, et al. 2017. Over production of fermentable sugar for bioethanol production from carbohydrate-rich Malaysian food waste via sequential acid-enzymatic hydrolysis pretreatment. *Waste Management* 67:95–105

143. Favaretto DPC, Rempel A, Lanzini JR, Silva ACM, Lazzari T, et al. 2023. Fruit residues as biomass for bioethanol production using enzymatic hydrolysis as pretreatment. *World Journal of Microbiology and Biotechnology* 39:144

144. Bhat R. 2021. *Valorization of agri-food wastes and by-products: recent trends, innovations and sustainability challenges*. Amsterdam: Elsevier. doi: 10.1016/C2020-0-01248-X

145. Yezza A, Halasz A, Levadoux W, Hawari J. 2007. Production of poly-β-hydroxybutyrate (PHB) by *Alcaligenes latus* from maple sap. *Applied Microbiology and Biotechnology* 77:269–74

146. Lokesh BE, Hamid ZAA, Arai T, Kosugi A, Murata Y, et al. 2012. Potential of oil palm trunk sap as a novel inexpensive renewable carbon feedstock for polyhydroxyalkanoate biosynthesis and as a bacterial growth medium. *CLEAN – Soil, Air, Water* 40(3):310–17

147. Talebian-Kiakalaieh A, Amin NAS, Mazaheri H. 2013. A review on novel processes of biodiesel production from waste cooking oil. *Applied Energy* 104:683–710

148. Gundlapalli M, Ganesan S. 2025. Polyhydroxyalkanoates (PHAs): key challenges in production and sustainable strategies for cost reduction within a circular economy framework. *Results in Engineering* 26:105345

149. Zhou W, Bergsma S, Colpa DI, Euverink GW, Krooneman J. 2023. Polyhydroxyalkanoates (PHAs) synthesis and degradation by microbes and applications towards a circular economy. *Journal of Environmental Management* 341:118033

150. Sabapathy PC, Devaraj S, Meixner K, Anburajan P, Kathirvel P, et al. 2020. Recent developments in Polyhydroxyalkanoates (PHAs) production –a review. *Bioresource Technology* 306:123132

151. Koller M, Maršálek L, de Sousa Dias MM, Braunegg G. 2017. Producing microbial polyhydroxyalkanoate (PHA) biopolyesters in a sustainable manner. *New Biotechnology* 37:24–38

152. Koller M. 2018. A review on established and emerging fermentation schemes for microbial production of polyhydroxyalkanoate (PHA) biopolyesters. *Fermentation* 4:30

153. Kourmentza C, Koutra E, Venetsaneas N, Kornaros M. 2017. Integrated biorefinery approach for the valorization of olive mill waste streams towards sustainable biofuels and bio-based products. In *Microbial Applications*, eds Kalia V, Kumar P. Vol. 1. Cham: Springer. pp. 211–38 doi: 10.1007/978-3-319-52666-9_10

154. Acharjee SA, Bharali P, Gogoi B, Sorhie V, Walling B, et al. 2023. PHA-based bioplastic: a potential alternative to address microplastic pollution. *Water, Air, & Soil Pollution* 234:21

155. Dietrich K, Dumont MJ, Del Rio LF, Orsat V. 2017. Producing PHAs in the bioeconomy—towards a sustainable bioplastic. *Sustainable Production and Consumption* 9:58–70

156. Vidal F, van der Marel ER, Kerr RWF, McElroy C, Schroeder N, et al. 2024. Designing a circular carbon and plastics economy for a sustainable future. *Nature* 626:45–57

157. Iles A, Martin AN. 2013. Expanding bioplastics production: sustainable business innovation in the chemical industry. *Journal of Cleaner Production* 45:38–49

158. Jayalath SU, de Alwis AP. 2025. PHA, the greenest plastic so far: advancing microbial synthesis, recovery, and sustainable applications for circularity. *ACS Omega* 10(30):32564–86

159. Marciniak P, Możejko-Ciesielska J. 2021. What is new in the field of industrial wastes conversion into polyhydroxyalkanoates by bacteria? *Polymers* 13:1731

160. Gomes Gradíssimo D, Pereira Xavier L, Valadares Santos A. 2020. Cyanobacterial polyhydroxyalkanoates: a sustainable alternative in circular economy. *Molecules* 25:4331

161. Singh SP, Jawaid M, Chandrasekar M, Senthilkumar K, Yadav B, et al. 2021. Sugarcane wastes into commercial products: processing methods, production optimization and challenges. *Journal of Cleaner Production* 328:129453

162. Khatami K, Perez-Zabaleta M, Owusu-Agyeman I, Cetecioglu Z. 2021. Waste to bioplastics: how close are we to sustainable polyhydroxyalkanoates production? *Waste Management* 119:374–88

163. Mohandessi M, Bandara K, Wan C. 2024. Green technologies for recovery of polyhydroxyalkanoates: opportunities and perspectives. *Advances in Bioenergy* 9:335–81

164. Shen MY, Souvannasouk V, Saipa S, Chu CY, Tantranont N, et al. 2023. PHA Production from molasses using mixed microbial cultures: techno-economic feasibility analysis. *Research Square*:Preprint

165. Elmowafy E, Abdal-Hay A, Skouras A, Tiboni M, Casettari L, et al. 2019. Polyhydroxyalkanoate (PHA): applications in drug delivery and tissue engineering. *Expert Review of Medical Devices* 16(6):467–82

166. Harrison STL, van Coller C, Smart M, Broadhurst J, Kotsiopoulos T, et al. 2023. Integrating ARD prevention and mine waste minimisation: soil fabrication from coal waste. *Water Research Commission Report No. 2844/1/23*. 140 pp

167. Lu J, Tappel RC, Nomura CT. 2009. Mini-review: biosynthesis of poly(hydroxyalkanoates). *Polymer Reviews* 49:226–48

168. Berson RE, Young JS, Kamer SN, Hanley TR. 2005. Detoxification of actual pretreated corn stover hydrolysate using activated carbon powder. *Applied Biochemistry and Biotechnology* 124:923–34

169. Jankowska E, Duber A, Chwialkowska J, Stodolny M, Oleskowicz-Popiel P. 2018. Conversion of organic waste into volatile fatty acids – The influence of process operating parameters. *Chemical Engineering Journal* 345:395–403

170. Zhou M, Yan B, Wong JWC, Zhang Y. 2018. Enhanced volatile fatty acids production from anaerobic fermentation of food waste: a mini-review focusing on acidogenic metabolic pathways. *Bioresource Technology* 248:68–78

171. Koller M, Mukherjee A. 2022. Polyhydroxyalkanoates (PHAs) – production, properties and biodegradable. In *Biodegradable polymers in the circular plastics economy*, eds Dusselier M, Lange JP. US: Wiley. doi: 10.1002/9783527827589.ch6

172. Anjum A, Zuber M, Zia KM, Noreen A, Anjum MN, et al. 2016. Microbial production of polyhydroxyalkanoates (PHAs) and its copolymers: a review of recent advancements. *International Journal of Biological Macromolecules* 89:161−74

173. Camargo FA, Innocentini-Mei LH, Lemes AP, Moraes SG, Durán N. 2012. Processing and characterization of composites of poly(3-hydroxybutyrate-co-hydroxyvalerate) and lignin from sugar cane bagasse. *Journal of Composite Materials* 46:417−25

174. Sabapathy PC, Devaraj S, Anburajan P, Parvez A, Kathirvel P, et al. 2023. Active polyhydroxybutyrate (PHB)/sugarcane bagasse fiber-based antimicrobial green composite: material characterization and degradation studies. *Applied Nanoscience* 13:1187−99

175. Moshood TD, Nawanir G, Mahmud F, Mohamad F, Ahmad MH, et al. 2022. Green product innovation: a means towards achieving global sustainable product within biodegradable plastic industry. *Journal of Cleaner Production* 363:132506

176. Kiran GS, Lipton AN, Priyadharshini S, Anitha K, Suárez LEC, et al. 2014. Antiadhesive activity of poly-hydroxy butyrate biopolymer from a marine *Brevibacterium casei* MSI04 against shrimp pathogenic vibrios. *Microbial Cell Factories* 13:114

177. Babu PK, Maruthi Y, Pratao SV, Sudhakar K, Sadiku R, et al. 2013. Development and characterisation of polycaprolactone (pcl)/poly ((r)-3-hydroxybutyric acid) (PHB) blend microspheres for tamoxifen drug release studies. *International Journal of Pharmacy and Pharmaceutical Sciences* 7(9):95−100

178. Bioextrax. 2014. *Cost-competitive and sustainable replacements for a circular future.* https://bioextrax.com/ (Accessed on September 20, 2025)

179. Sintim HY, Bandopadhyay S, English ME, Bary A, Liquet y González JE, et al. 2021. Four years of continuous use of soil-biodegradable plastic mulch: impact on soil and groundwater quality. *Geoderma* 381:114665

180. Tocchetto RS, Benson RS, Dever M. 2001. Outdoor weathering evaluation of carbon-black-filled, biodegradable copolyester as substitute for traditionally used, carbon-black-filled, nonbiodegradable, high-density polyethylene mulch films. *Journal of Polymers and the Environment* 9:57−62

181. Kasirajan S, Ngouajio M. 2012. Polyethylene and biodegradable mulches for agricultural applications: a review. *Agronomy for Sustainable Development* 32:501−29

182. Rekhi P, Goswami M, Ramakrishna S, Debnath M. 2022. Polyhydroxyalkanoates biopolymers toward decarbonizing economy and sustainable future. *Critical Reviews in Biotechnology* 42:668−92

183. El-malek FA, Farag A, Omar S, Khairy H. 2020. Polyhydroxyalkanoates (PHA) from *Halomonas pacifica* ASL10 and *Halomonas salifodiane* ASL11 isolated from Mariout salt lakes. *International Journal of Biological Macromolecules* 161:1318−28

184. Oviyya KR, Nithyalkshmi B. 2024. Polyhroxyalkanoates (PHAs): a comprehensive review of life cycle assessment, environmental impacts, and satiable development. *International Journal of Research Publication and Reviews* 5(10):3061−67

185. Koch M, Spierling S, Venkatachalam V, Endres HJ, Owsianiak M, et al. 2023. Comparative assessment of environmental impacts of 1st generation (corn feedstock) and 3rd generation (carbon dioxide feedstock) PHA production pathways using life cycle assessment. *Science of The Total Environment* 863:160991

186. Lorini L, Martinelli A, Capuani G, Frison N, Reis M, et al. 2021. Characterization of polyhydroxyalkanoates produced at pilot scale from different organic wastes. *Frontiers in Bioengineering and Biotechnology* 9:628719

187. Cywar RM, Rorrer NA, Hoyt CB, Beckham GT, Chen EYX. 2022. Biobased polymers with performance-advantaged properties. *Nature Reviews Materials* 7:83−103

188. Burgess SK, Leisen JE, Kraftschik BE, Mubarak CR, Kriegel RM, et al. 2014. Chain mobility, thermal, and mechanical properties of poly (ethylene furanoate) compared to poly(ethylene terephthalate). *Macromolecules* 47(4):1383−91

189. Eerhart AJJE, Faaij APC, Patel MK. 2012. Replacing fossil based PET with biobased PEF; process analysis, energy and GHG balance. *Energy & Environmental Science* 5:6407−22

190. Knoop RJI, Vogelzang W, van Haveren J, van Es DS. 2013. High molecular weight poly(ethylene-2,5-furanoate); critical aspects in synthesis and mechanical property determination. *Journal of Polymer Science Part A: Polymer Chemistry* 51:4191−99

191. Galbis JA, de Gracia García-Martín M, de Paz MV, Galbis E. 2016. Synthetic polymers from sugar-based monomers. *Chemical Reviews* 116(3):1600−36

192. Gregory GL, López-Vidal EM, Buchard A. 2017. Polymers from sugars: cyclic monomer synthesis, ring-opening polymerisation, material properties and applications. *Chemical Communications* 53:2198−217

193. Guo M, Wang Y, Li Z, Xu J, Chen Q, et al. 2024. Influence of polyol impurities on the transesterification kinetics, molecular structures and properties of isosorbide polycarbonate. *Polymer Chemistry* 15(15):4204−20

194. Manker LP, Hedou MA, Broggi C, Jones MJ, Kortsen K, et al. 2024. Performance polyamides built on a sustainable carbohydrate core. *Nature Sustainability* 7:640−51

195. Ecole Polytechnique Fédérale de Lausanne. 2024. *Revolutionizing plastics: How sugar based polyamides could save our planet.* https://scitech-daily.com/revolutionizing-plastics-how-sugar-based-polyamides-could-save-our-planet/

196. Sanders JH, Cunniffe J, Carrejo E, Burke C, Reynolds AM, et al. 2024. Biobased polyethylene furanoate: production processes, sustainability, and techno-economics. *Advanced Sustainable Systems* 8(11):2400074

197. Desai Y, Jariwala S, Gupta RK. 2023. Bio-based polyurethanes and their applications. *Polyurethanes: Preparation, Properties, and Applications*, ed. Gupta RK. Volume 2. US: American Chemical Society. pp. 1−14 doi: 10.1021/bk-2023-1453.ch001

198. Stubbs CJ, Worch JC, Prydderch H, Wang Z, Mathers RT, et al. 2022. Sugar-based polymers with stereochemistry-dependent degradability and mechanical properties. *Journal of the American Chemical Society* 144:1243−50

199. Shibata M, Ishigami N, Shibita A. 2017. Synthesis of sugar alcohol-derived water-soluble polyamines by the thiol-ene reaction and their utilization as hardeners of water-soluble bio-based epoxy resins. *Reactive and Functional Polymers* 118:35−41

200. Marotta A, Ambrogi V, Cerruti P, Mija A. 2018. Green approaches in the synthesis of furan-based diepoxy monomers. *RSC Advances* 8(29):16330−35

201. Gonçalves FAMM, Santos M, Cernadas T, Ferreira P, Alves P. 2022. Advances in the development of biobased epoxy resins: insight into more sustainable materials and future applications. *International Materials Reviews* 67(2):119−49

202. Capretti M, Giammaria V, Santulli C, Boria S, Del Bianco G. 2023. Use of bio-epoxies and their effect on the performance of polymer composites: a critical review. *Polymers* 15(24):4733

203. Eroglu MS, Oner ET, Mutlu EC, Bostan MS. 2017. Sugar based biopolymers in nanomedicine; new emerging era for cancer imaging and therapy. *Current Topics in Medicinal Chemistry* 17:1507−20

204. Wang J, Wang D, Zhang Y, Dong J. 2021. Synthesis and biopharmaceutical applications of sugar-based polymers: new advances and future prospects. *ACS Biomaterials Science & Engineering* 7(3):963−82

205. Wroblewska A, Zych A, Thiyagarajan S, Dudenko D, van Es D, et al. 2015. Towards sugar-derived polyamides as environmentally friendly materials. *Polymer Chemistry* 6(22):4133−43

206. Bu SH, Cho W, Lee C, Ham G, Yang B, et al. 2024. Mechanochemical engineering and supramolecular reconstruction of MoS_2 nanosheets with C60-γCD complexes for enhanced photocatalytic and piezoelectric performances. *Chemical Engineering Journal* 502:157688

207. Gyeonbuk D. 2025. *Sugar derived catalyst boosts plastic recycling and hydrogen production.* https://techxplore.com/news/2025-02-sugar-derived-catalyst-boosts-plastic.html

208. Wang H, Xu F, Zhang Z, Feng M, Jiang M, et al. 2023. Bio-based poly-carbonates: progress and prospects. *RSC Sustainability* 1:2162−79

209. Vicente D, Proença DN, Morais PV. 2023. The role of bacterial polyhy-droalkanoate (PHA) in a sustainable future: a review on the biological diversity. *International Journal of Environmental Research and Public Health* 20(4):2959

210. Werker A, Lorini L, Villano M, Valentino F, Majone M. 2022. Modelling mixed microbial culture polyhydroxyalkanoate accumulation biopro-cess towards novel methods for polymer production using dilute volatile fatty acid rich feedstocks. *Bioengineering* 9:125

211. Emaimo AJ, Olkhov AA, Iordanskii AL, Vetcher AA. 2022. Polyhydrox-yalkanoates composites and blends: improved properties and new applications. *Journal of Composites Science* 6(7):206

212. Kumar R, Verma A, Shome A, Sinha R, Sinha S, et al. 2021. Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability* 13(17):9963