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Possibilities and prospects of bioplastics production from agri-waste using bacterial communities: Finding a silver-lining in waste management

Mamun Mandal [a], Anamika Roy [a], Debasis Mitra [b], Abhijit Sarkar [a,*]

[a] Laboratory of Applied Stress Biology, Department of Botany, University of Gour Banga, Malda – 732 103, West Bengal, India
[b] Department of Microbiology, Graphic Era (Deemed to be University), 566/6, Bell Road, Clement Town, Dehradun, Uttarakhand 248002 India

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ABSTRACT

To meet the need of the growing global population, the modern agriculture faces tremendous challenges to produce more food as well as fiber, timber, biofuels, etc.; hence generates more waste. This continuous growth of agricultural waste (agri-waste) and its management strategies have drawn the attention worldwide because of its severe environmental impacts including air, soil and water pollution. Similarly, growing concerns about the sustainable future have fuelled the development of biopolymers, substances occurring in and/or produced by living organisms, as substitute for different synthetic and harmful polymers, especially petroleum-based plastics. Now, the components of agri-waste offer encouraging opportunities for the production of bioplastics through mechanical and microbial procedures. Even the microbial, both bacterial and fungal, system results in lower energy consumption and better eco-friendly alternatives. The review mainly concentrates on cataloging and understanding the bacterial 'input' in developing bioplastics from diverse agri-waste. Especially, the bacteria like *Cupriavidus necator, Chromatium vinosum*, and *Pseudomonas aeruginosa* produce short- and medium-chain length poly(3-hydroxyalkanote) (P3HB) polymers using starch (from corn and potato waste), and cellulose (from sugarcane bagasse, corn husks waste). Similarly, *C. necator*, and transformant *Wautersia eutropha* produce P3HB polymer using lipid-based components (such as palm oil waste). Important to note that, the synthesis of these polymers are interconnected with the bacterial general metabolic activities, for example Krebs cycle, glycolysis cycle, β-oxidation, calvin cycle, *de novo* fatty acid syntheses, etc. Altogether, the agri-waste is reasonably low-cost feed for the production of bioplastics using bacterial communities; and the whole process certainly provide an opportunity towards sustainable waste management strategy.

1. Introduction

Petroleum-based synthetic plastics have become widely used manufacturing materials, with uses ranging from packaging to toy manufacture, supermarket polybags to plastic cutlery, and straws to 3D printed - rocket engine nozzle (Pilapitiya and Ratnayake, 2024). The first plastic material was developed in 1860, and the worldwide plastic industry started in 1907. Nevertheless, industrial development occurred in the 1920s, and plastic manufacturing widened in the 1940s. In 1950, the global production of plastic was approximately 2 million tonnes (MT), which increased to 400.3 MT in 2022 (Garside, 2024); it is used once and then discarded (Müller et al., 2012). Discarded waste made of plastic can take 10–1000 years to degrade due to its durability and limited degradability (Mandal et al., 2024a). Furthermore, only 9 % of total plastic production is recycled, around 12 % is burnt, and the remaining 79 % is landfilled or dumped (Curia et al., 2019). In reality, approximately 10 MT of plastic garbage are thrown in the oceans alone annually, accounting for the vast bulk of manmade debris in the oceans. According to reports, plastics may now be used to determine the geological stratigraphy of the Anthropocene period (Hopewell et al., 2009; Weber and Lechthaler, 2021). This anthropogenic debris endangers land and marine safety, sustainability, and integrity (Ritchie and Roser, 2018; Ivar do Sul and Labrenz, 2020). This plastic debris in the environment has begun to degrade over time (a slow process) owing to abiotic (thermo-oxidative, photo-oxidative, and chemical degradation) and biotic forces (bacteria, fungi, and archaea). However, this conversion generates hazardous chemicals and greenhouse gases (GHGs), contributing to ecosystem contamination and global warming (Gilani et al., 2023). Furthermore, some petrochemical-based synthetic plastics are nonbiodegradable, resulting in their persistence as meso-, micro-,

* Corresponding author.
E-mail addresses: abbhijitbot@ugb.ac.in, abhijitbhu@gmail.com (A. Sarkar).

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and nano-sized particles at the disposal site, harming the environment (Dey et al., 2024). In summary, plastic trash contributes to a critical environmental problem that has yet to be solved. To address this issue, an alternate method must be developed, such as the manufacturing of "Biodegradable Plastic" or "Bioplastics" (Han et al., 2022).

Bioplastics have received a lot of interest because of their potential usage as a green alternative to petroleum-based synthetic plastics. Global demand for bioplastics has increased due to its benign nature, biocompatibility, and ability to degrade quickly without harming the environment (Atiwesh et al., 2021). Bioplastics are described as plastic that decomposes spontaneously and fully to CO_2 and H_2O in the environment through the activity of microorganisms. It is an environmentally friendly plastic created from potentially affordable raw materials like agricultural waste (agri-waste) (Nalini and Sathiyamurthi, 2023). Furthermore, bioplastic production from renewable sources has lower costs (1–1.5 times) than traditional petroleum-based synthetic plastic (Ezeoha and Ezenwanne, 2013). Bioplastics can be utilized in medical applications as bio-implants and to encapsulate pharmaceuticals for controlled release. It can also be used in bottles, bags, personal hygiene products, disposable goods, films, and food packaging (Narancic et al., 2020). Alarfaj et al. (2015) demonstrated the potential of *Bacillus thuringiensis*, isolated from Saudi Arabia's mangrove environment, to make biodegradable plastic poly(3-hydroxyalkanote) (P3HA). P3HA, and their derivatives are the most widely used microbial bioplastics (Sudesh et al., 2000) (Table 1). Belal and Farid (2016) identified *B. cereus* from Egypt and found that it can generate P3HB when inoculated in a medium containing 2 % whey, xylose, glucose, bagasse, lactose, molasses, sugarcane, and rice straw as a sole source of carbon. Rice bran, bagasse, wheat bran, potato starch, cassava powder, copra oil cake, corn waste, toor powder, jack fruit powder, whey wastewater and other wasted products from the food proceed industry and many different types of agri-waste were used as carbon sources to grow *B. cereus* to form a low-cost substrate for P3HB production; it can tremendously increase rate of production (Paul et al., 2017). So, using these agri-waste generations of bioplastics is a good strategy because agri-waste or organic waste is a significant part of solid waste, globally. Conversion of agri-waste into value-added products will solve two significant pollution problems: petroleum-based synthetic plastic pollution and agri-waste pollution.

Keeping all these in mind, the present review has been designed to catalogue the possibilities and prospects of major bacterial communities and their inputs to convert agri-waste to bioplastic. We believe that the summarization of the available literature on the potential threats of agri-waste and their eco-friendly management to bioplastic production might encourage future researchers to get engaged in this domain; hence, propose the road map towards a sustainable and healthy future.

2. Waste management and sustainable developmental goals

Waste management (WM) remains an essential socioeconomic and governmental concern, particularly in cities overburdened by rapid population expansion and waste production (Abubakar et al., 2022). Several worldwide development goals, agreements, and visions emphasize the importance of WM in obtaining the United Nations' Sustainable Development Goals (SDGs). For instance, sustainable WM can assist in accomplishing numerous SDGs, such as ensuring clean water and sanitation (SDG 6), municipal solid waste management (SWM) (SDG 11.6.1), food loss and waste (SDG 12.3.1), information transmitted under chemicals and waste conventions (SDG 12.4.1), hazardous waste generated and treated (SDG 12.4.2), national recycling rate (SDG 12.5.1), mitigating climate change (SDG 13), and protecting life on land (SDG 15) (Ghafari, 2022). It additionally supports a circular urban economic performance, encouraging recycling and the reuse of limited materials and resources to eliminate waste, reduce pollution, save money, and promote green development (Arya et al., 2022).

However, with economic growth, upgraded lifestyles, and materialism, urban areas around the world will continue confronting a massive WM challenge. The global population is projected to grow to 8 billion by 2025, as well as 9.3 billion by 2050, with approximately 70 % of the worldwide population inhabiting urban areas (Abubakar et al., 2022). In underdeveloped nations, most cities collect just 50–80 % of produced trash despite investing 20–50 % of their annual budgets, with 80–95 % used for collection and transportation (Guerrero et al., 2013; World Bank Solid Waste Management, 2018). Furthermore, numerous low-income developing nations collect only 10 percent of the trash produced in suburban regions, contributing to public environmental and health hazards such as increased incidences of diarrhoea and serious respiratory illnesses among individuals living near trash dumps, especially children (UN-Habitat, 2010; Hettiarachchi et al., 2018). Lack of knowledge, technology, money, and good governance are all obstacles to efficient municipal waste management (Abubakar et al., 2022).

SWM is difficult because it consists of a wide range of materials, including organic waste, metals, plastics, papers, textile waste, inserts, and so on. Organic waste creation is an important solid waste component that provides considerable advantages when properly handled (Panpatte and Jhala, 2019). The agri-industrial sectors are one of the largest contributors to organic waste generation (Elsheekh et al., 2021). The high moisture content of organic waste hinders its handling, necessitating sustainable and affordable recycling technologies. According to reports, the majority of developing countries, particularly those in Asia, generate massive amounts of organic waste (Arya et al., 2022). As a result, waste with high levels of organic content and moisture percentage may be handled using appropriate technology for its composition. The chemical and physical properties of the waste composition must be considered when determining the most effective treatment procedures (Elsheekh et al., 2021). By adopting a circular economy method to reuse and repurpose waste, it is feasible to minimize the amount of garbage that ends up in landfills and extract benefits from waste (Castellani et al., 2022).

3. Agricultural and agri-waste: the inseparable duo

3.1. Agri-waste generation: global trends and statistics

Globally, agricultural activities generate roughly $\sim 5 \times 10^9$ tonnes of waste annually (Bharti et al., 2024), occupy around 28 % of the global land used for agriculture, corresponding to 1.4 billion hectare of useable cultivated area (Sharma et al., 2021; Sahoo et al., 2024). According to Heredia-Guerrero et al. (2017), the FAO stated in 2013 that around $\sim 2.5 \times 10^8$ tonnes of non-edible agri-waste are produced during agricultural processing. In 2013, China was the globally highest producer of grain, generating $\sim 1.75 \times 10^9$ tonnes of agri-waste, including $\sim 9.93 \times 10^8$ tonnes of crop straws, $\sim 4.52 \times 10^8$ tonnes of manure from poultry and livestock, and $\sim 3.03 \times 10^8$ tonnes of forest waste (Dai et al., 2018). According to Madurwar et al. (2013), India generates around $\sim 3.5 \times 10^8$ tonnes of agri-waste annually from numerous sources. In 2016, $\sim 2.07 \times 10^7$ tonnes of waste were generated from the agri-sector in the European Union (EU), representing 0.82 % of total waste produced in EU countries (Komor and Bujanowicz-Haraś, 2019).

Cereal grain, fruits and vegetables, seafood, dairy products, beverages, poultry, meat, egg processing, and edible oil are all examples of food processing sectors. Several nations generate fruit and vegetable waste; for example, Central de Abasto produces 895 tonnes, and the produces United Kingdom 5.5×10^6 tonnes (FAO, 2014). According to Kiran et al. (2014), the beverage industry produced around 105 kilotonnes of trash, which included damaged packaging and spilled drinks. Every year, 50–70 % of raw materials are squandered in the preparation of seafood as well as marine biotic life (Kumar et al., 2018). Seafood waste, primarily produces from crabs, prawns and lobster shells, accounts for around 6×10^6–8×10^6 tonnes globally, with Southeast Asia contributing 1.5×10^6 tonnes. The edible oil business generates waste through several processing processes (Okino-Delgado et al., 2017).

Table 1
Different types of microbe-based bioplastics and their structures and monomers.

Name of the polymer		Monomer name	Percussor (conversion rates)	Production volume in tonnes (year)	Reference
Bio-based polyesters[#]	Poly(3-hydroxyalkanoates) (P3HA) a) Poly(3-hydroxybutyrate) (P3HB) b) Poly(4-hydroxybutyrate) (P4HB) c) Poly(3-hydroxyvalerate) (P3HV) d) Poly(3-hydroxyhexanoate) (P3HHx) e) Poly(3-hydroxyheptanoate) (P3HP) f) Poly(3-hydroxyoctanoate) (P3HO) g) Poly(3-hydroxynonanoate) (P3HN) h) Poly(3-hydroxydecanoate) (P3HD) i) Poly(3-hydroxyundecanoate) (P3HUD) j) Poly(3-hydroxydodecanoate) (P3HDD) k) Poly(3-hydroxytridecanoate) (P3HTD) l) Poly(3-hydroxytetradecanoate) (P3HTTD) m) Poly(3-hydroxypentadecanoate) (P3HPD) n) Poly(3-hydroxyhexadecanoate) (P3HHD)	3-(*R*)-hydroxybutyric acid	Starch → Glucose (88 %) Fermt. Sugar → PHB (35 %)	1,04,640 (2023)[$]	Tan et al., 2014
	Polylactic acid (PLA)	Lactic acid Cyclic di-ester lactide	Fermt. Sugar → Lactic acid (85 %) Starch → Glucose (88 %)	6,75,800 (2023)[$]	Masutani and Kimura, 2014
	Polybutylene succinate (PBS)	Succinic acid 1,4-butanediol	Starch → Glucose (88 %) Fermt. Sugar → Succinic acid (80 %)	19,620 (2023)[$]	Thakur et al., 2022
	Polyethylene 2,5-furandicarboxylate (PEF)	Ethylene glycol* 2,5-Furandicarboxylic acid*	Starch → Sugar (88 %) Glucose → Ethanol (48 %) Ethanol → Ethene (48 %) Ethene → Ethene oxide (85 %) HMF → FDCA (80 %) Sugar (Fructose) → HMF (63 %)	–	Andreeßen and Steinbüchel, 2019; Loos et al., 2020
	Polyethylene terephthalate (Bio-PET)	Ethylene glycol* Terephthalic acid*	Starch → Glucose (88 %) Glucose → Ethanol (48 %), Isobutanol (39 %) Ethanol → Ethene (48 %) Ethene → Ethene oxide (85 %)	47,960 (2023)[$]	Andreeßen and Steinbüchel, 2019
	Polybutylene succinate adipate (PBSA)	1,4-butanediol Succinic acid Adipic acid	Starch → Glucose (88 %) Fermt. Sugar → Succinic acid (80 %)	–	Shah et al., 2013
	Polytrimethylene terephthalate (PTT)	1,3-Propanediol* Terephthalic acid*	Starch → Glucose (88 %) Fermt. Sugar → 1,3-Propanediol (40 %), Glucose → Isobutanol (39 %)	2,94,300 (2023)[$]	Andreeßen and Steinbüchel, 2019
	Polybutylene terephthalate (Bio-PBT)	Butanediol Terephthalic acid	Starch → Glucose (88 %) Glucose → Isobutanol (39 %) Isobutanol → p-Xylene (68 %) Sugar→ Succinic acid (80 %) Succinic acid → 1,4 Butanediol (77 %)	–	Pascault et al., 2012
	Polybutylene adipate terephthalate (Bio-PBAT)	Adipic acid 1,4-butane diol Terephthalic acid	Starch → Glucose (88 %) Glucose → Isobutanol (39 %) Isobutanol→ p-Xylene (68 %) Sugar→ Succinic acid (80 %) Succinic acid → 1,4 Butanediol (77 %)	1,00,280 (2023)[$]	Yang et al., 2023
Bio-based polyolefins[#]	Polyethylene (Bio-PE)	Ethylene*	Starch → Glucose (88 %) Fermt. Sugar → Ethanol (48	2,68,140 (2023)[$]	Andreeßen and Steinbüchel, 2019

(continued on next page)

Table 1 (*continued*)

Name of the polymer		Monomer name	Percussor (conversion rates)	Production volume in tonnes (year)	Reference
			%) Ethanol → Ethene 48 (%)		
	Polypropylene (Bio-PP)	Propylene*	Starch → Glucose (88 %) Glucose → Ethanol (48 %) Ethanol → Ethene (48 %) Butene → Propylene (68 %)	10,900 (2023)$	
Bio-based polyamides (Bio-PAs)#	Homopolyamides a) Bio-PA 6 b) Bio-PA 11	1,4-Butanediamine (succinic acid) 1,6-Hexanediamine (propylene, butadiene) 1,10-Decanediamine* (castor oil) Adipic acid (cyclohexane) Sebacic acid* (castor oil) 11-Aminoundecanoic acid* (castor oil)	Starch → Glucose (88 %) Fermt. Sugar → Lysine (70 %) Lysine → Caprolactam (47 %) Ricinoleic acid → Undecane acid (50 %)	3,98,940 (2023)$	Andreeßen and Steinbüchel, 2019
	Copolyamides a) Bio-PA 4.10 b) Bio-PA 5.10 c) Bio-PA 6.10 d) Bio-PA 10.10		Ricinoleic acid → Sebacic acid 60 %)		
Polysaccharide polymers#	Cellulose-based polymers (Cellulosics) a) Regenerated cellulose b) Cellulose diacetate	Cellobiose	Wood → Cellulose (90 %) Wood → Cellulose (50 %)	91,560 (2023)$	Nath et al., 2023
	Starch-based polymers a) Thermoplastic starch (TPS) b) Starch blends	Amylose Amylopectin	Potato, corn, wheat → Starch content (75 %)	–	
Bio-based polyacrylates#	Poly(methyl methacrylate) (Bio-PMMA)	Methyl methacrylate	Starch → Glucose (88 %) Glucose → Ethanol (48 %) Ethanol → Ethene (48 %)	–	Gilsdorf et al., 2024
Others	Polyvinyl chloride (Bio-PVC) #	Vinyl chloride	Starch → Glucose (88 %) Glucose → Ethanol (48 %) Ethanol → Ethene (48 %)	–	Singh and Devi, 2019
	Polyurethanes (PURs)	Polyols* Isocyanates	Natural oil polyols (castor oil), sugars Toluene, methylenedianiline	1714,000 (2016)†	Andreeßen and Steinbüchel, 2019
	Polythioester (PTE)	Mercaptoalkanoic acids	Acrylic acid, H_2S	–	Andreeßen and Steinbüchel, 2019
	Polytrimethylene 2,5-furandicarboxylate (PTF)	1,3-Propanediol* 2,5-Furandicarboxylic acid dimethyl ester*	Sugars Fructose	–	Papageorgiou et al., 2016

Fermt.: Fermented; HMF: 5-hydroxymethyl furfural; FDCA: 2,5-Furandicarboxylic acid. *Monomer produced from biomass or biomass-derived compound. #Biopolymers facts and statistics, 2023. $EuropeanBioplastics: Bioplastics Market Development Update (2023). †EuropeanBioplastics: nova Institute 2017.

According to Chang et al. (2018), the edible oil-industry produces 3.5 × 10^8 tonnes of de-oiled cakes and oil flour as an unwanted byproduct per year.

3.2. Types of agri-waste

Agri-waste generated during the cultivation and processing of agricultural goods such as crops, fruits, dairy products, and vegetables. The waste produced by different stages of agri-industrial activity is mainly divided into two categories: agri-waste at the field level and at the industry level (time of food processing) (Nath et al., 2023). Every process of farming, from land clearance to harvesting, results in the production of agri-waste. Agri-waste may be further categorized into two types based on the production stage: field leftovers and process leftovers (Sadh et al., 2018; Nath et al., 2023). Field leftovers are agricultural harvesting and treatment remnants that stay on the field. Field leftovers include seed pods, leaves, stems, stalks, fruits, dairy, vegetables, grains, meat, poultry, and crops; process leftovers remain after the crop has been processed into another usable resource. The leftovers are husks, stubble, seeds, leaves, stems, roots, stalks, straw, bagasse, shells, peel, pulp, and molasses (Adetunji et al., 2023; Mandal et al., 2024b). Agri-waste at the industry level includes tea, oil cake (from groundnut, canola, sunflower, soybean, coconut, sesame, mustard, etc.), sugarcane, cotton, coffee, cereal, chocolate, fruit peels (from bananas, oranges, mangoes, pawpaws, pineapples, etc.), and vegetable peels (from potato, cassava, etc.), etc., contributing significantly to waste (Sadh et al., 2018). Such fruit and vegetable waste are converted into animal feed (Kumar et al., 2020). Agri-waste also includes animal waste (dead animals, excreta), processing waste (fertilizer cans, packaging material), and hazardous waste (herbicides, pesticides, and insecticides) (Yaashikaa et al., 2020). Moreover, inappropriate disposal of these wastes can result in catastrophic financial losses, estimated at $300 billion per year, and severe environmental damage, posing significant health risks (Bharti et al., 2024).

3.3. Environmental impacts of agri-waste

Traditionally, agri-waste is burnt or allowed to decompose in open dumping sites, producing major air pollution and increasing soil degradation, water pollution, and food poisoning. There are other difficulties related to this practice that contribute to climate change.

3.3.1. Impacts on air quality

Wastes generated by agricultural operations on farms/fields may have an impact on global air quality, either favourably or adversely. Farmers often use various inorganic fertilizers, insecticides, herbicides, and pesticides to increase productivity and defend against weeds, pests, and insects (Mandal and Sarkar, 2024a). These synthetic chemicals contain variety of hazardous toxic compounds (such as aromatic hydrocarbons and chlorofluorocarbons), these are absorbed by agri-crops. When these crops undergo burning in the open environment, they emit various gases and components into the atmosphere, such as carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), carbon monoxide (CO), chlorine (Cl) ammonia (NH_3), particulate matter (PM_{10}, $PM_{2.5}$, and PM_1), and non-methane hydrocarbons (Mandal et al., 2023; Roy et al., 2024). One molecule of nascent $Cl^{—}$ destroys 100,000 ozone molecules until it is eliminated from the hydrosphere's stratospheric zone (Khan et al., 2024). Similarly, improper dumping of agri-waste also releases CH_4 under anaerobic conditions, another toxic GHGs that largely contributes to global warming. Additionally, the making of animal feed increased the release of organic acid compounds and trace gases into the atmosphere (Aneja et al., 2009). Around the world, the cattle industry emits 18 % of total GHGs, with anthropogenic NOx, CH_4, and NH_3 accounting for 65 %, 37 %, and 64 %, respectively (Esparza et al., 2020). Animal production produces hundreds of volatile organic carbons (VOCs), including hydrocarbons, acids, alcohols, esters, aldehydes, amides, ketones, aromatics, and other sulphur and nitrogen compounds. Among them, some compounds have undesirable odours, such as H_2S, which is mostly released by swine dung (Khan et al., 2024).

3.3.2. Impacts on soil quality

The wastewater from agri-industrial facilities contains many harmful substances, including inorganic and organic compounds, suspended matter, nutrients, and heavy metals (Khan et al., 2024). When sewage sludge and wastewater are put into agricultural land, it decreases soil quality, reduces microbiological activity, and severely affects the soil's physico-chemical attributes. These wastes' breakdown and biological degradation differ depending on the biological and physico-chemical interactions that form liquid type component known as "leachate". This leachate is comprised of various inorganic and organic substances, harming both agri- and natural environments. The leachate produced by the biodegradation of various waste materials contains 1000–3000 mg/L of NH_3—N in different regions of the world, but in the United States, it contains 21–1500 mg kg^{-1} of Cr, 0.2–41 mg kg^{-1} of Cd, and 16–1300 mg kg^{-1} of Ni (Kafei et al., 2023). The burning of agricultural leftovers on farms damages soil quality. Additionally, it decreases residue volume, causes nutritional loss, and eliminates several beneficial microorganisms (Sial et al., 2019). Agricultural activities also significantly contribute to global plastic pollution (packaging materials and agrochemical containers), using MT of plastic yearly discharged into agri-soil that reaches into marine ecosystems (Lakhiar et al., 2024).

3.3.3. Impacts on the water quality

Water pollution driven by agri-wastes predominantly comes from the release of carcinogens and toxic agrochemicals (such as insecticides, pesticides, and fungicides) from the farms' irrigation systems that drain into the underground water. This significantly affects the aquatic system (wetlands, rivers, streams, and lakes) and human health. Agrochemicals also harm biodiversity in marine systems by killing insects and weeds as well as disrupting the aquatic ecosystem's food cycle (Mateo-Sagasta et al., 2017; Schreinemachers and Tipraqsa, 2012). The fruit and vegetable processing and juice sector discharges a large amount of sewage system directly into the water environment, significantly impacting aquatic biodiversity (Mateo-Sagasta et al., 2017). In both developed and developing nations, agriculture pollution is mostly caused by the leaching of various nutrients (nitrate, phosphate, and heavy metals). The leaching of these nutrients causes eutrophication, especially nitrates, into subsurface water bodies. Likewise, more or $<$38 % of water bodies are contaminated by agricultural activities in the European Union and the United States (Edition, 2016; Paquin and Cosgrove, 2016). Waste material from the animal-processing industries is a major source of water pollution. The total biological oxygen demand (BOD) of residential sewage and pig manure was 200–500 mg/L and 30,000–80, 000 mg/L, respectively, resulting in hypoxia in water bodies since organic matter breakdown requires oxygen to dissolve (Khan et al., 2024).

As a result, this waste must be appropriately disposed of, recycled, or used to provide value for the environment and agriculture (Mandal et al., 2024b). "Reducing", "recycling", and "reusing" field waste may significantly decrease the environmental impact of agricultural activities, potentially cutting GHGs emissions by up to 25 % and saving water resources by 15 % (Bharti et al., 2024).

3.4. Diverse management practices of agri-waste

The five most common food waste disposal methods utilized worldwide are animal feeding, landfills/dumping, incineration, and organic fertilizer production through composting/anaerobic digestion. The various management practices of agri-waste are discussed below.

3.4.1. Animal feeding

South Korea, Japan, and Taiwan have legislation that encourages using agricultural waste to feed animals, accounting for 81 %, 33 %, and 72.1 % of total agri-waste produced, respectively (Gen et al., 2006; Kim et al., 2011). In developing nations, agri-waste collection and segregation are not done appropriately. As a result, practically all the agri-waste produced is combined with municipal solid waste (MSW), which cannot be cleaned or used for animal feed (Sahoo et al., 2024).

3.4.2. Landfills/dumping

In developing countries, the majority of agri-waste management approaches utilized are open dumping sites and landfills, accounting for 90 % of the total. Many modern-day landfills convert potentially dangerous landfill gas emissions into powerhouses to generate electricity (USEPA, 2020). Many countries, including Brazil, Turkey, Mexico, Malaysia, Romania, Costa Rica, Belarus, South Africa, Jamaica, China, Nigeria, Vietnam, and Ukraine, now dispose of unorganized foreign trash in landfills. It is predicted that 20 to 80 % of all foreign garbage in the globe has yet to be segregated from agricultural waste (Adhikari et al. 2006). Landfills are not presently regarded as a viable alternative for processing agri-waste due to their biodegradability and potential for attracting disease-causing vectors (Louis, 2004). Furthermore, landfilling agricultural waste might result in an 8 % increase in GHGs (Sahoo et al., 2024).

3.4.3. Incineration

Effective incineration of agri-waste can decrease trash volume and landfill space requirements. Many countries, notably Singapore and the United States, have embraced this strategy (Khoo et al., 2010). Incineration is more expensive than other methods (high capital and maintenance costs), and costly equipment and highly sophisticated procedures are required to limit gas emission residues. Yates and Gutberlet (2011) deliberated that incineration is not widely employed for agri-waste management in developing nations like Brazil and Ukraine.

3.4.4. Recycling of agri-waste and value-added products

Landfilling and incineration are the most common disposal methods for agri-waste. Agri-waste is biodegradable and organic, including nutrients such as polysaccharides (10–25 % starch, 35–50 % cellulose, and 25–30 % hemicellulose), lignins, proteins, minerals, fibers, vitamins, and others (Mandal et al., 2022a; Adetunji et al., 2023). Instead of dumping/burning, the chemical composition of agri-waste makes it a versatile candidate with the potential to produce a variety of valuable products such as organic fertilizers, bioethanol, biodiesel, biohydrogen, methane, butanol, syngas, biochar, bio-oil, bioplastics, biosurfactants, organic acids bioenzymes, and electricity generation (Nalini and Sathiyamurthi, 2023; Osman et al., 2023). Similarly, animal manures are used to make fertilizer because they contain 19 % nitrogen, 38 % phosphorus, and 61 % potassium. On the other hand, after the production of biogas, the leftovers can be used as biofertilizers or conditioners for the soil due to the presence of its nutritional and carbon properties as well as macronutrients (K, N, P, Mg, Ca) and microelements (Cu, Zn, Fe, and Al) that promote plant growth (Mandal et al., 2022a; Mandal and Sarkar, 2024b). So, it can reduce the environmental burden and modify the soil microbial community. Agri-waste can be converted into bio-fertilizers through various processes, including aerobic composting with microbes, anaerobic digestion, vermicomposting, chemical hydrolysis via acidic or alkaline treatment (at 600–1000 °C), and in-situ decomposition of organic matter (Cerda et al., 2018; Ayilara et al., 2020). Anaerobic digestion (AD) process is the most common biological process; it involves the decomposing of organic agri-waste through four phases: hydrolysis, acetogenesis, acidogenesis, and methanogenesis, that can be carried through by different kinds of microbes (Saravanan et al., 2023). Some abandoned agri-based foodstuffs are used to make food products like cereal bars and cookies. As an example, the core portion of pineapple waste was combined with other components, such as soybean extracts and crushed rice, to produce novel cereal bars that are low in calories but high in protein, minerals, and dietary fiber (Aparecida Damasceno et al., 2016).

4. Bioplastics: a futuristic solution

Bioplastic refers to a group of biopolymers derived from renewable sources (like plants, animals, etc.) or through the biosynthesis of microorganisms (Bilo et al., 2018). Generally, it should be biocompatible and biodegradable in the environment and should not generate any toxicity (Rosenboom et al., 2022). Nevertheless, it is important to understand that not all types of bioplastics are biologically degradable. As an example to follow, bio-based polypropylene (bio-PP), polyethylene (bio-PE), polyamides (bio-PA), polyethylene terephthalate (bio-PET) and poly-(trimethylene terephthalate) (bio-PTMT) are chemically comparable to petroleum-based polymers but non-degradable, also known as bio-based non-degradable polymers. On the contrary, P3HAs, polylactic acid (PLA) and some polyesters (such as PCL and PBS) are bio-based biodegradable polymers (Thakur et al., 2018). Additionally, several biodegradable polymers generated from nonrenewable resources, such as poly(trimethylene carbonate) (PTMC), polycaprolactone (PCL), polyethylene glycol (PEG), and polybutylene adipate-co-terephthalate (PBAT), are also started to increasing attention and gain some value of the market share, they are known as fossil-based biodegradable polymers. So, these polymers are mainly classified into three categories: (a) bio-based non-degradable polymers, (b) bio-based biodegradable polymers, and (c) fossil-based biodegradable polymers (Rosenboom et al., 2022).

The earliest manufactured plastic was a cellulose-based bioplastic invented in 1856. Eventually, different types of bioplastics made from renewable sources in 1920s, including carbohydrates, proteins, lipids, and cellulose, were investigated (Melchor-Martínez et al., 2022). Moreover, these early initiatives were hampered by restricted technology (high starting costs) and the availability of less expensive fossil-based polymers. In the 1990s, technological advances in polymer synthesis, such as starch blends and P3HAs (Lisec, 2017; Cooke and Pomeroy, 2023). At the beginning of the 2000s, fascination with bioplastics increased due to a trend towards sustainable products, including ecosystem issues related to synthetic plastics. Investigators focused on PLA, bioplastic derived from sugars fermentation from plants (Dash et al., 2024). Bioplastics have grown significantly in the last ten years, with companies investing in development and research to improve qualities such as thermal insulation, durability, and processing ability (Ahmad et al., 2020). Bioplastics are currently utilized extensively in various fields, such as the packaging industry, goods for consumers, automotive components, and the textile industry. The recent study focuses on managing end-of-life waste (EoL) by enhancing the ability to degrade and composting of bioplastics (Rosenboom et al., 2022). Overall, the background of bioplastics has seen amazing advancements in materials research, industry expansion, and ecosystem concerns. With a growing emphasis on circularity and sustainability, consumer interest in bioplastics will rise, supporting more research and technical advances in this area (Gahlawat et al., 2017).

4.1. Comparison of synthetic plastics versus bioplastics

Petroleum-based synthetic plastics are high molecular mass polymers that generally contain 1000–10,000 monomeric repeating units (Dash et al., 2024). Traditional petroleum-based synthetic plastics are manufactured in a sequence of stages, the first of which is the distillation of crude oil in an oil refinery. This method separates and fractionates the heavy type of crude oil into smaller groupings of lighter materials known as segments. Each segment comprises polymeric hydrocarbon chains of varying sizes and structures. One of these fractions, naphtha, is essential for producing monomers such as propylene, ethylene, and styrene, which are used to make synthetic plastics. All of these monomers are associated with making polymers by polyaddition and/or polycondensation facilitated by particular catalysts (Danial et al., 2021). Some regularly used synthetic plastics in our daily lives include PE, PP, PET, polyester, and polyvinyl chloride (PVC) (Mandal et al., 2024a).

Bioplastics are bio-based polymers produced in the presence of microbes using renewable resources such as carbohydrate and plant-based oils (Adetunji et al., 2023). They are alternative polymers that have physical qualities similar to synthetic plastics. Microbes may degrade bioplastics, producing water, CO_2, and biomass under aerobic as well as anaerobic environments (Ru et al., 2020). Because of their solid physico-chemical and biological qualities, bioplastics, as well as biopolymers, are used in producing paints and disposable packaging ingredients and in producing engineered chemicals applications and bio-fertilizer production (Liu et al., 2020). They are also employed in releasing drug-carriers, dental therapy, medical devices, and many other industrial purposes due to their bio-compatibility, non-cytotoxicity, wear resistance, elasticity and bio-degradability (de Castro et al., 2022). P3HA is one of the most well-known examples of bioplastics derived from bacterial metabolic processes. This polymer group includes P3HB, polyhydroxyoctanoate (PHO), poly(3-hydroxyhexanoate) (P3HHx), poly(3-hydroxyvalerate) (P3HV), and poly(3-hydroxybutyrate-*co*-3-hydroxyhexanoate) (PHBH), among others (de Souza and Gupta, 2024).

5. Agri-waste to bioplastics: the bacterial 'input'

Previous bioplastic research revealed many scientific approaches to synthesizing these ecologically friendly bio-based polymers, such as direct biomass extraction of bacteria-based monomers/polymers production. This section explains commonly used bacteria-based monomers and polymers synthesis methods at the industrial-scale that use agri-waste materials as the starting source. Figs. 1 and 2 exhibit detailed approaches for converting agri-waste streams into bioplastics, while Table 2 presents some of the most current findings on bioplastics synthesis via these pathways.

5.1. Synthesis of 'monomer'

Raw materials are fermented to form monomers, which are then polymerized to yield PLA and PGA (polyglycolic acid). At first, PLAs are made by transforming the carbohydrates into dextrose, which is subsequently fermented into lactic acid before being polymerized (Mandal et al., 2022b). However, several bacteria can generate lactic acid (Fahim et al., 2019). For example, *Lactobacillus* sp. and genetically modified *E. coli* are being commercialized because of their fast-growing capacity, strong, as well as high-yielding potentiality with minimal nutritional conditions (Choi et al., 2002; Jung et al., 2010). The fermentation stage is followed by purification and recovery to ensure compliance with the necessary specifications. However, further polymerization can occur by either a ring-open reaction of lactide or direct-polycondensation of lactic acid (Jem and Tan, 2020). Yang et al. (2010) reported the generation of

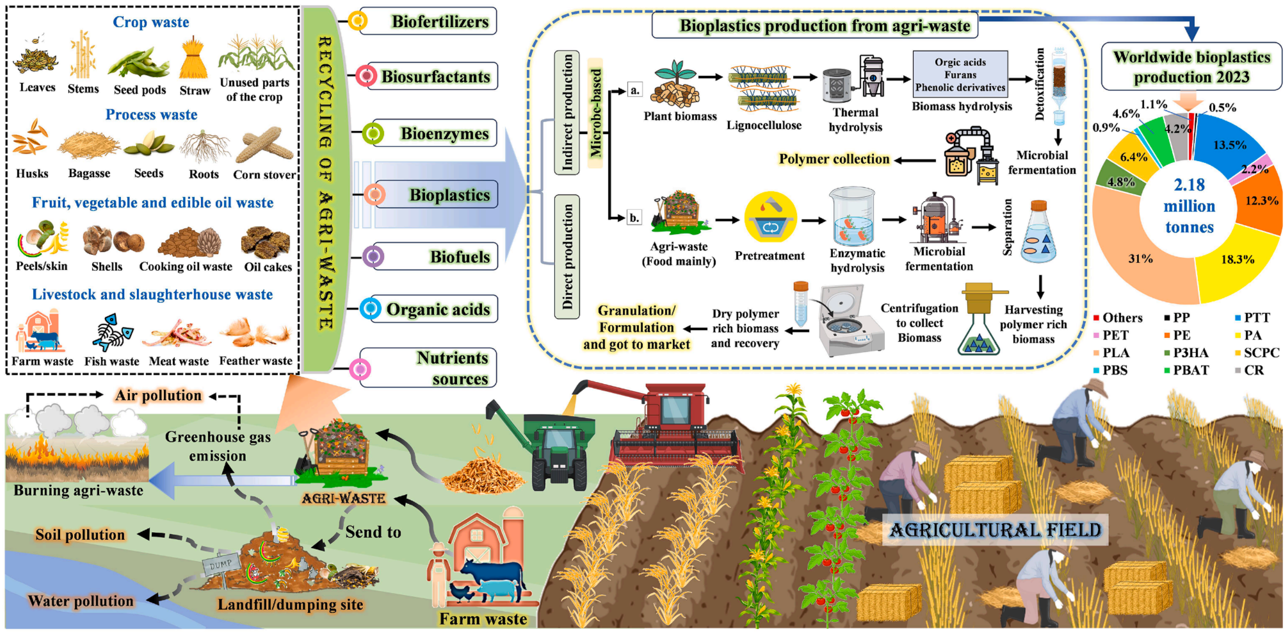

Fig. 1. Different types of agri-waste and their recycling procedure. Two procedures generally produce bioplastics production from agri-waste: one is direct production, and the other is indirect production. Indirect production is one type of microbe-based approach (de Souza and Gupta, 2024). Worldwide bioplastics production of 2.18 million tonnes crossed in 2023 (Data accessed from europeanbioplastics; https://www.european-bioplastics.org/bioplastics-market-development-update-2023–2/#; Date of accession: 01.08.2024). Biobased-nonbiodegradable bioplastics (such as PP: Polypropylene; PTT: Polytrimethylene terephthalate; PET: Polyethylene terephthalate; PE: Polyethylene; PA: Polyamide) produced 47.9 %, and biobased-biodegradable bioplastics (such as PLA: Polylactic acid; P3HA: Poly-3-hydroxyalkanoates; SCPC: Starch-containing polymer compounds; PBS: Polybutylene succinate; PBAT: Poly(butylene adipate-co-terephthalate); CR: Cellulose regenerates) produced 52.1 % of total bioplastics production in 2023.

PLA and related co-polymers with varying lactate proportions using genetically modified *E. coli* derived from renewable sources. Another group of researchers developed a more efficient manufacturing approach for Poly(D-lactate-co-glycolate-co-4-hydroxybutyrate) utilizing metabolically modified *E. coli* (Choi et al., 2002). Researchers also observed that the polymers had varying properties depending on the proportions of the monomers contained. Rajendran and Han (2022) conducted an economic and technological assessment for the sustainable production of PLA from food waste, utilizing the *Lactobacillus casei*. The generated lactic acid was separated from the fermented medium using a membrane-integrated-separation technique and then polymerized in a ring-open reaction to get PLA. The authors obtained food waste from four different nations (India, China, the United States, and Brazil) with differing protein, fat, carbohydrate, and water content. They reported that PLAs manufacturing rate is proportional to the percentage of sugars in food waste. The PLA-based biological materials have the same type of elongation capacity, tensile modulus as well as rip resistance as traditional polymers such as PP, nylons and PET. As a result, this is one of the most abundant bioplastics following starch blends (Table 2).

5.2. Synthesis of 'polymer'

Microorganisms utilizing various renewable sources is critical as a profitable strategy for large scale biopolymer manufacturing (Verdini et al., 2022; Martínez-Burgos et al., 2023). Pretreatment is required for the bioconversion of agri-waste to plastics in order to convert its compound organic components (viz. cellulose, lignin, starch, lipid) into simple sugars that are then subjected to bacteria-based fermentation for the production of polymer (Naik et al., 2021). Pretreatment methods include physical followed by chemical, and biological, as well as enzymatic hydrolysis. In the physical treatment procedure, agri-waste materials are turned into fermented organic compounds through thermal-based and physical pretreatments such as grinding, heating, microwaves, and ultrasound (Tsang et al., 2019). After that, the fermentable sugars are generated through chemical pretreatment that may involve alkali or acid treatment. And finally, the biological treatment uses bacteria to convert agri-waste into a fermentable substrate, which produces the bioplastics. For example, *Pseudomonas resinovorans* generated medium chain-length-P3HA (mcl-P3HA) of 21.3 g/L from the grapefruit waste (Follonier et al., 2014). *Bacillus sphaericus* NCIM 5149 secreted 19 % P3HB from jackfruit seed powder, an inexpensive feedstock (Ramadas et al., 2009). Furthermore, sugars extracted from agri-waste of maize straw were fermented through mixed microbial culture (MMC) derived from dairy waste, yielding 41.4 % poly (hydroxybutyrate-3-*co*-hydroxyvaleate) (PHBV) after 72 h of incubation. A stirred-tank bioreactor scale-up yielded 76.3 % after 96 h (Verdini et al., 2022).

Lipid waste (including cooking oil wastes, lipids, plant oils from palm oil, and animal meats) is also accessible for conversion in bioplastics production. For example, triacylglycerides can be used directly as a sole source of carbon or hydrolyzed to glycerol as well as fatty acids before usage. Oils provide more P3HA than carbohydrates; however, palm oil generates less P3HA while having the greatest saturated fatty acid concentration (Naheed and Jamil, 2014). The most frequent remnants from sugarcane processing are molasses and sweetwater, both of which have significant carbohydrate content and nutritional value. According to Zhang et al. (1994), molasses often sells for 30 to 55 % of the price of glucose, which is one of the essential carbon sources typically used to produce P3HA. Page reported a type of P3HA synthesized for the first time by *Azobobactor vinelandii* utilizing molasses as carbon sources in 1992, with a yield of roughly 19 to 22 g/L (Page, 1992). The use of a two-stage fermenting method with the same isolate substantially enhanced P3HB production (Chen and Page, 1997). A substantial oxygenation rate was employed in the first stage to enhance cell formation, but it was lowered in the second stage to boost P3HB production to approximately 36 g/L. *Pseudomonas corrugate* produces P3HA utilizing soy molasses as a substrate and accumulates 5–17 % mcl-P3HA concentration at 1.5–3.6 g/L of dry cell weight (Solaiman et al., 2005). *Bacillus* sp. was also shown to accumulate ~25–35 % of P3HB using sugarcane molasses as the carbon substrate in a fed-batch

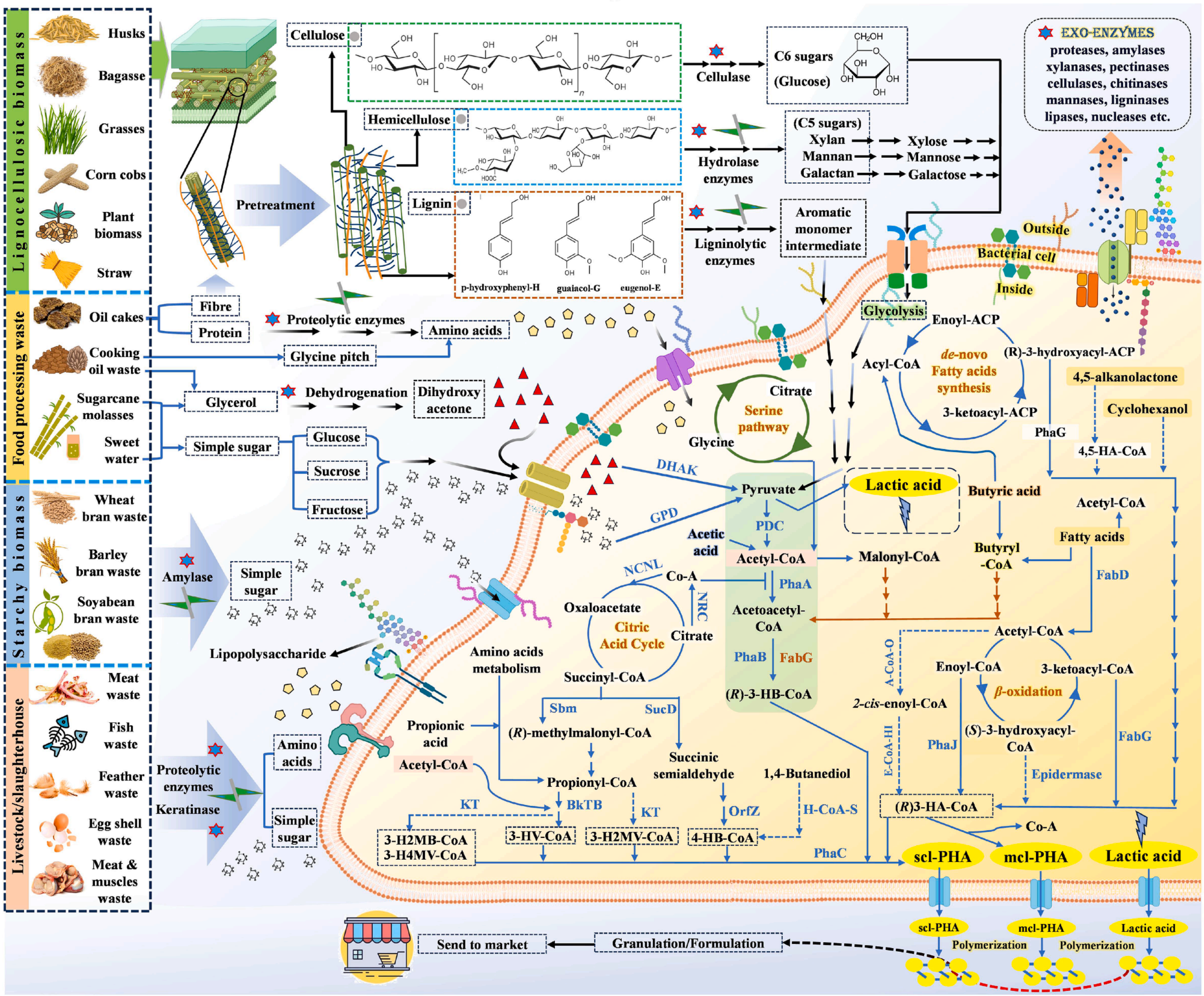

Fig. 2. Different types of agri-waste materials are produced in different stages of agricultural activities. Out of these materials, which contain complex structures, those materials are pretreated (chemically, physically, biologically, enzymatically, and microbes can be digested through exo-enzymes) before bacterial utilization to produce biopolymers (Madison and Huisman, 1999; Lu et al., 2009). Contradictally, those components contain simple sugars, amino acids, etc., which are directly used by microbes as carbon sources to synthesize biopolymers (Chen, 2010; Khosravi-Darani et al., 2013). P3HAs' microbial biosynthetic pathways are represented here and have been extensively studied (adopted from Tan et al., 2014). Lines with dots indicate putative pathways. More than one arrow represented the steps of the pathway jumped from the precursor to the final product to avoid the complexity of the overall diagram. 3-H2MB-CoA: 3-hydroxy-2-methylbutyryl-CoA; 3-H4MV-CoA: 3-hydroxy-4-methylvaleryl-CoA; 3-HV-CoA: 3-hydroxyvaleryl-CoA; 3-H2MV-CoA: 3-hydroxy-2-methylvaleryl-CoA; 4-HB-CoA: 4-hydroxybutyryl-CoA; (*R*)3-HB-CoA: 3-hydroxybutyryl-CoA; (*R*)-3-HA-CoA: (*R*)-3-hydroxyacyl-CoA; 4,5-HA-CoA: 4,5-hydroxyacyl-CoA. KT: Ketothiolase, putative; NRC: nutrient-rich conditions; NCNL: non-carbon nutrient limitation; Sbm: Methylmalonyl-CoA mutase; SucD: Succinic semialdehyde dehydrogenase; BktB: 3-Ketothiolase; OrfZ: 4-Hydroxybutyrate-CoA:CoA transferase; H—CoA-S: Hydroxyacyl-CoA synthase, putative; GPD: Glyceraldehyde-3-phosphate dehydrogenase; PDC: pyruvate dehydrogenase complex; PhaA: 3-Ketothiolase; PhaB: NADPH-dependent acetoacetyl-CoA reductase; PhaC: PHA synthase; E-CoA-HI: Enoyl-CoA hydratase I, putative; A-CoA-O: Acyl-CoA oxidase, putative; PhaJ: (*R*)-Enoyl-CoA hydratase; FabD: Malonyl-CoA:ACP transacylase; FabG: NADPH-dependent 3-Ketoacyl reductase; FadD: Acyl-CoA synthetase; PhaG: 3-Hydroxyacyl-ACP:CoA transacylase; DHAK: Dihydroxyacetone kinase; Co-A: Coenzyme-A.

fermentation procedure ((Wu et al., 2001); Elumalai et al., 2020). A higher quantity (up to 40 g/L) of sugarcane molasses greatly enhances cell biomass and P3HB production. This is linked to the nutritional composition of vitamins (biotin and riboflavin) contained in sugarcane molasses, which are needed for bacterial cell development (Tripathi et al., 2019). *Alcaligenes* sp. used molasses in an optimized fermentation method (7.5 g/L), producing 70.89 % higher molecular mass P3HB at 0.312 g/L productivity after one hour of incubation (Tripathi and Narayanan, 2019; Tripathi et al., 2019). Another isolate, *Halomonas campaniensis*, thrived on starch, cellulose, lipids, fatty acids, and protein-rich food waste and generated 70 % P3HB at 37 °C (Yue et al., 2014; Mihajlovski et al., 2021). *B. megaterium* converted dairy waste into P3HB (Tsang et al., 2019; Seo et al., 2022). Mostafa et al. (2020) isolated new strains of P3HB-producing bacteria (*Bacillus aquimaris, Tamlana crocina, Halomonas halophila*, and *Erythrobacter aquimaris*) from the mangrove rhizosphere of the Red Sea in Saudi Arabia. Felix et al. (2017) described the generation of bioplastics from the waste material of red swamp crayfish. According to the United States Department of Agriculture, approximately 45 % of crayfish that enter the United States food market end up being wasted. The European Union's guidelines urged the preferred use of garbage as animal feed, but disease control concerns rendered it illegal. Thus, an optimal end-use technique valorises agri-waste by transforming it into value-added goods.

5.2.1. *Synthesis of P3HAs*

P3HA is a kind of polymer that spontaneously accumulates in

Table 2
The examples of numerous types of microbes producing bioplastics using agri-waste.

Substrate	Biological process	Microbes	Type of bioplastic obtained	References
Food waste	Hydrolysis, fermentation, and biosynthesis	*Halomonas hydrothermalis, Halomonas campaniensis*	P3HB	Tsang et al., 2019
Sugarcane bagasse, teff straw (Eragrostis tef), corn cob, and banana peel	Hydrolysis and biosynthesis	*Bacillus* spp, *Micrococcus* sp., *Staphylococcus* sp.	P3HB	Gasser et al., 2014
Food waste	Enzyme hydrolysis, fermentation, purification, separation, and polymerization	*Lactobacillus casei*	PLA	Rajendran and Han, 2022
Food waste	Acid hydrolysis, fermentation	*E. coli*	Lactic acid	(Santos-Corona et al., 2022)
Barley straw and pumpkin residues	Fermentation and biosynthesis	*Bacillus aryabhatti, Bacillus filamentosus*	P3HB	Poyraz et al., 2022
Orange, onion peels, banana, mango, and rice straw	Fermentation and biosynthesis	*Bacillus wiedmannii*	P3HB	Danial et al., 2021
Starch extracted form cassava pulp and oil palm trunk	Fermentation and biosynthesis	*Bacillus aryabhattai*	P3HB	(Bomrungnok et al., 2020)
Sheep cheese whey	Fermentation and biosynthesis	MMC	P3HA	(Asunis et al., 2020)
Sugarcane molasses and residues	Fermentation and biosynthesis	*Bacillus subtilis*	P3HA	(Rathika et al., 2019)
Cheese whey mother liquor	Fermentation, pretreatment and biosynthesis	*Paracoccus homiensis, Lysinibacillus* sp.	P3HA	(Mozejko-Ciesielska et al., 2022)
Rice straw	Fermentation, and biosynthesis	*Bacillus megaterium*	P3HA	(Li et al., 2021)
Waste activated sludge	Fermentation and biosynthesis	MMC	P3HA	(Lorini et al., 2022)
Rice husk	Fermentation and biosynthesis	*Azospirillum brasilense*	Poly(butylene succinate adipate)	(Wu, 2012)
Sugarcane molasses	Fermentation and biosynthesis	*Bacillus megaterium*	P3HB	Yatim et al., 2017
Dairy waste	Fermentation, biosynthesis and extraction	*Bacillus megaterium*	P3HB	Tsang et al., 2019
Sweetwater	Fermentation and biosynthesis	*Bacillus megaterium*	P3HB	Yatim et al., 2017
Palm oil empty fruit bunch	Fermentation and biosynthesis	*Bacillus cereus suaeda*	P3HB	(Hidayat et al., 2019)
Sugarcane molasses	Fermentation, biosynthesis and extraction	*Alcaligenes* sp., *Bacillus megaterium, Pseudomonas aeruginosa*	P3HB	Geethu et al., 2019
	Fermentation and biosynthesis	*Alcaligenes* sp.	P3HB	Tripathi et al., 2019
Sludge palm oil	Fermentation and biosynthesis	*Cupriavidus necator*	PHBH	(Thinagaran and Sudesh, 2019)
Palm oil waste	Fermentation and biosynthesis	Transformant *Wautersia eutropha*	PHBV	Loo et al. 2005
Food waste	Blended, anaerobic fermentation, extraction	*Haloferax mediterranei*	P3HA	(Wang and Zhang, 2021)
Pulp waste, palm jaggery, tamarind kernel powder, and green gram	Synthesis, isolation, purification	*Bacillus subtilis*	P3HB	Sathiyanarayanan et al., 2013
Sugarcane bagasse, corn cob, teff (Eragrostisi teff) straw and banana peel	Salt hydrolysis, biosynthesis, extraction and purification	*Bacillus* sp.	P3HB	Getachew and Woldesenbet, 2016
Paddy straw, oil cake, rice bran, wheat bran, and sugarcane molasses	Blended, biosynthesis, purification, and quantification	*Streptomyces* sp.	P3HB	Krishnan et al., 2017
Date syrup	Biosynthesis and extraction	*Pseudodonghicola xiamenesis*	P3HB	Mostafa et al., 2020
Rice husk, sugarcane molasses, fruit wastes, vegetable wastes, whey, sugarcane bagasse, wheat husk, potato starch, and jackfruit seed powder	Biosynthesis, extraction, and purification	*Wickerhamomyces anomalus*	Poly(3HB-Co-3HV)	Ojha and Das, 2018
Mustard oil, soya bean oil, castor seed oil, vegetable oil, corn oil, palm oil, crude glycerol, coconut oil, rapeseed oil, sunflower oil and jatropha oil				
Wheat bran hydrolysate	Enzymatic hydrolysis, biosynthesis, extraction	*Ralstonia eutropha*	P3HB	Annamalai and Sivakumar, 2016
Jack fruit seed hydrolysate	Fementation and extraction	*Bacillus sparecius*	P3HB	Ramadas et al., 2010
Pineapple peel	Fementation and extraction	*Bacillus drentensis*	P3HB	Penkhrue et al., 2020
Molasses	Biosynthesis and extraction	*Exiguobacterium* sp., *Klebsiella* sp.	P3HA	Sadaat and Jamil, 2020
Ragi husk and sesame oil cake	Submerged fermentations and extraction	*Bacillis megterium*	P3HA	Israni and Shivakumar, 2020

bacterial cells and is increasingly used to replace chemically synthesized bioplastic. P3HA is a bacterial secondary metabolic product that does not play an important function in organism development (Muhammadi et al., 2015). The P3HA polymer, which is composed of oxygen, hydrogen, and carbon, is a complex family of polyesters synthesized by various bacteria and stored in the cytoplasm of cells as energy storage and intracellular carbon molecules (Wu et al., 2003; Palmeri et al., 2012). The molecule is normally made up of 600–35,000 repeating (*R*)-hydroxy fatty acid monomer units, each with an *R*-group side chain. Approximately 150 hydroxy alkanoic acids and over 90 bacterial taxa have been found to produce these polyester-based materials (Zinn et al., 2001; Kee et al., 2022). P3HAs are characterized according to their branch-type monomers, with short chain-length-P3HA (scl-P3HA) containing 3–5 carbon atoms (Table 1). P3HV, P3HB, and poly (4-hydroxybutyrate) (P4HB) are three frequently occurring forms of scl-P3HA. P3HHx and poly(3-hydroxydecanoate) (P3HD) are examples of mcl-P3HA molecules with 6 or more atoms of carbon (Steinbüchel et al., 1992; Wu et al., 2003). P3HA homopolymers contain only one monomer, whereas heteropolymers contain many monomers. The characteristics of homopolymers and heteropolymers diverge, which has become the primary trait contributing to P3HA variation, both in biosynthesis and in applications spanning from the packaging sector to the pharmaceuticals industry. The most commonly recognized polymer members of the P3HA group are PHBV and P3HB (Kee et al., 2022).

P3HA plays an important function in preparing bacteria for stress survival. P3HA enhances the long-term survival of bacteria in nutrient-limited environments by serving as carbon and energy stores for both sporulating and non-sporulating bacteria. Furthermore, bacteria with P3HA have shown improved stress tolerance to brief environmental stressors such as heat, ultraviolet (UV) radiation exposure, and osmotic stress (Kadouri et al., 2005). The P3HA biosynthesis pathway is linked to bacterial major metabolic processes, including amino acid catabolism, glycolysis, Calvin cycle, Krebs cycle, serine pathway, β-oxidation and de novo fatty acid syntheses (Fig. 2) (Tan et al., 2014; Kee et al., 2022). P3HA and related metabolic pathways have several common intermediates, the most notable of which is acetyl CoA. In several P3HA-producing bacteria, such as *Cupriavidus necator, Chromatium vinosum*, and *Pseudomonas aeruginosa*, the metabolic flow from acetyl-CoA to P3HA is highly reliant on nutrition factors (Steinbüchel and Hein, 2001). Under the nutrient-rich circumstances, high Co-A production from the Krebs cycle inhibits P3HA production by suppressing 3-ketothiolase (PhaA), allowing acetyl-CoA to be channelled into the Krebs cycle for energy generation and cell development (Ratledge, 2001). In contrast, Under nutrient-insufficient conditions (when a key nutrient, such as nitrogen or phosphorus, is restricted in the presence of an excessive carbon source), Co-A concentrations are not inhibitory, permitting acetyl-CoA to be induced toward P3HA synthesis routes for P3HA formation (Jung and Lee, 2000; Ratledge, 2001). This metabolic regulatory method allows P3HA-accumulating bacteria to optimize nutritional sources while adapting to changing environmental conditions. Additionally, P3HA synthase (PhaC) is a main metabolic enzyme that defines the kind of P3HA produced by bacterial strains. For example, *Cupriavidus necator* generates only scl-P3HA monomers through the PhaC, whereas *Pseudomonas aeruginosa* prefers mcl-P3HA because of its substrate specificity. Furthermore, the PhaC from another strain of *Pseudomonas* sp. generates 6–13 repeating units of scl-P3HA as well as mcl-P3HA monomers (Sudesh et al., 2000; Nomura and Taguchi, 2007). However, the production of P3HA through (*R*)-hydroxyalkyl-CoA (*R*-3-HA-CoA) substrates has been most widely described, the broad range of P3HA precursors is not limited to (*R*)-3-HA-CoA (Lu et al., 2009). Tan et al. (2014) presented putative potential metabolic pathways (Fig. 2) for the conversion of 4,5-alkanolactone to 4,5-hydroxyacyl-CoA (4,5-HA-CoA) and cyclohexanol to 6-hydroxyhexanoyl-CoA. Nonetheless, the present understanding of biosynthetic routes is mostly limited to (*R*)-3-HA-CoA precursors and does not account for the chemically varied P3HA monomers and long-chain-length (lcl-) P3HA monomers. A lot of knowledge gaps are still present, and the depth of ideas about biosynthetic pathways is yet to be unknown. Further research to validate suspected routes and uncover novel biosynthetic pathways is expected to aid in developing P3HA materials that may be customized to specific application requirements.

6. Biotechnological interventions to enhance bacterial potentials for bioplastics productions

For adaptation to the diverse and changing environment, microbes have evolved a range of both beneficial and adverse feedback regulation networks. As an outcome, rational metabolic engineering frequently fails to produce effective cell factories of bacteria. To address this issue, (i) comprehensive data from omics studies, such as transcriptomic, genomic sequencing, and fluxomic with modern molecular techniques and tools, and (ii) the development of screening libraries, can be used to detect engineering targets for improved bio-based monomer and polymer manufacturing (Chen et al., 2023). Large DNA, amino acid, and protein databases, in addition to in silico techniques, give information about biosynthesis routes as well as the structure and function of essential biosynthesis proteins. Furthermore, new bio- chemical and physical methodologies help us comprehend the production of bacterial monomers and polymers (Moradali and Rehm, 2020). All of these improvements have laid a solid foundation for the development of cell factories for increased monomer and polymer production, as well as the production of customizable polymers. Modern synthetic biology technologies utilizing DNA factories are next-generation techniques for cell factory design and precise strain engineering (Rehm, 2015). Despite a deeper knowledge of biosynthesis routes and enzymes, understanding the molecular processes of synthesis, alterations, as well as if necessary, release aids the development of novel-designed polymers. Several bacterial polysaccharides, for example, are enzymatically changed at the polymer level, such as deacetylated, acetylated, epimerized, and phosphoethanolaminated, which alter property characteristics including as gel-forming and visco-elasticity ability (Moradali et al., 2015).

Genes that encode enzymes involved in polymerization and polysaccharide modification are often grouped in a single operon. The potent specialized promoters frequently regulate the transcription of these operons as well as the complete biosynthetic gene clusters (Schmid et al., 2015). As an example, a genomic study of *Corynebacterium glutamicum* identified 11 essential genes involved in glutaric acid production. Combining these genes results in strains capable of producing glutaric acid at a titration of ~106 g/L (Han et al., 2020). To identify the essential genes involved in cadaverine synthesis, 67 gene-repressing sRNAs were generated and evaluated in Escherichia coli. The most potent anti-serA isolates can generate cadaverine at a titration of ~14 g/L (Noh et al., 2019). Additionally, using the adaptation laboratory evolution (ALE) of *Pseudomonas puticosa* in xylose substrates medium and subsequently genomics evaluation, the altered targets of aroB and Xyle genes alterations were determined, which was favourable for the strain's growth, and yield of muconate exceeded 33 g/L (Ling et al., 2022).

The CRISPR/Cas9 gene editing approach was recently used to knock out of the 2-methylcitrate synthase genes, that are encoded by the gene prpC, in order to increase PHBV synthesis. CRISPR/Cas9 genome editing has increased synthesis up to 16-fold (Qin et al. 2018). The recombinant *E. coli* isolate was changed by inserting the P3HB-generating gene operon phaCAB from the *Ralstonia eutropha*, and then the recombinant bacterium was transformed using many single-guide RNAs (sgRNAs). They efficiently connect to numerous PhaC sites. The number of binding sgRNAs influenced PhaC's functionality. PhaC activity impacts the yield and molecular properties of P3HB, which are directly proportional to its activity. Highly effective PhaC increases P3HB accumulation. Thus, the adoption of the CRISPRi genome editing technique significantly improves recombinant P3HB production. This is a significant success in P3HA production since we can increase P3HA synthesis by altering the sgRNA sequence and its interaction with PhaC (Li et al., 2017).

Ralstonia eutropha now has a highly competent type of strain in the production of P3HB that has been introduced based on the optimization of the Ribosome Binding Site (RBS). RBS libraries containing all of the phbCAB genes have been developed using oligo-linker-mediated technology. These optimised RBS enhanced P3HB synthesis by 0- 92 % of recombinant *E. coli*, demonstrating the efficiency of the semi-rational RBS library optimization approach (Li et al., 2016).

Bacillus sp. synthesizes γ-PGA (poly(γ-glutamic acid)) from glutamate using the enzyme known as PGS (γ-PGA synthetase). After the modification at transcriptional level of γ-PGA, synthetase can improve γ-PGA synthesis. *Bacillus amyloliquefaciens* and *B. licheniformis* include four genes that encode γ-PGA synthetase (PGS): PGSB-A, PGSB-B, PGSB-C, and PGSB-E. In *B. anthracis*, their equivalents are cap- A, B, C, and E, whereas in *B. subtilis*, they are ywtABC and ywsC. PGS-BCA genes, after the transcription, disrupt the production of γ-PGA. However, recombinant production of γ-PGA synthetase was achieved by introducing the xylose-inducing plasmid pWH1520 incorporation in *Bacillus*, which contains PGS-BCA build, into a γ-PGA knock-out isolate of *B. subtilis* MA41 by heterologous gene expression (Li et al., 2022).

Several tactics were used to improve the manufacturing and monomer composition of P(LA-co-3HB). One such approach was the elimination of 's' factors, which control global gene transcriptions. The four regulatory factors were deleted from *E. coli*, including RpoN, RpoS, FecI, and FliA (Kadoya et al., 2015a); the mutants were utilized to produce P(LA-co-3HB). The results indicated that the RpoN excision mutant produced more polymer than the wild-type *E. coli*. Another work used genome wide transposon mutation to develop PLA synthesizing *E. coli* mutants with high yields (Kadoya et al., 2015b).

7. Future prospects

The bacterial use of agri-wastes to create any valuable goods is difficult. The research indicates that creating such items is viable, and there is a global push to adopt a circular-economy perception. Investigators, companies, and stockholders have been researching methods to mass-produce these bio-based products. The feasibility of mass manufacturing of bioplastics can be realized if the following conditions are encountered: 1) determining the best type of raw ingredients required; 2) constant facility of low-cost agri-wastes as the sole source of carbon; 3) bacteria types and compatibility; 4) suitable industrial-scale fermentation systems; 5) the financial expenditures; 6) suitable purification process; 7) optimized production levels; 8) optimized production yields capacity; 9) properties of bioplastics; and 10) the targeting the marketing strategies to promote the products; 11) . The targeted market determines the success of a product's commercialization, and industrial scale fermentation is critical. In terms of bioplastics, crude biopolymer may be made and delivered to the handbags, medical sectors, cosmetics, and agri-industries, each of which can modify the bioplastics to their own demands. Membrane enrichment, nanoenzyme application in the digestion process, cryogenic and hydrate separation, multiple-stage, and high-pressure anaerobic digestion are some examples of sophisticated current upgrading procedures that can help improve bioplastic productivity (Capanoglu et al., 2022). As next-generation biotechnology emerges, such as nanotechnological approaches, including encapsulation/nanoemulsion, appropriate methods may be designed to maximize production. Bioengineering may be used in bacterial fermentation to increase product output by selecting and identifying bacterial strains that efficiently use carbon substrates for high-performance fermentation. Efficient extraction and purification methods might be improved to increase biomaterial production. Furthermore, the treatment methods for agri-wastes should be investigated to encourage less chemical-intensive treatment. Bioengineered bacteria that consume raw, untreated waste would eradicate the treatment stages. The most common novel techniques to overcome these limitations are applied by nanotechnological approaches such as, and biotechnological processes such as fermentation and enzyme use.

Researchers are also actively working on technical advances in sustainable raw resources, cleaner manufacturing, and biopolymer applications to build commercial-scale production more profitable and ecologically benign. These developments may boost the global market contribution of bioplastics in the next decades. Additionally, worldwide scientific collaboration is required to combat plastic pollution. The word "microplastics" has surfaced in bioplastics-related papers recently. Moreover, the influence of these types of microplastics on the ecosystem is little known. Additional research is needed to assess bioplastics breakdown mechanisms and possible toxicity. Although, further research is required to increase biorefinery processes' performance while adhering to green chemistry principles to maintain a consistent market supply of biopolymers sustainably and cost-effectively.

8. Conclusion

The adverse effects of synthetic plastic materials in the natural environment have drawn the scientific community's considerable attention to the cost-effective manufacture of bioplastics. Agri-waste is a vital product that accounts for a significant portion of worldwide organic waste. Improper agri-waste management causes environmental dangers by releasing harmful components such as GHGs. The bacterial processing of agri-waste now provides environmental protection and is a long-term source of billions of dollars in revenue. Advances in bioplastics manufacturing technology continue to improve the practicality and scalability of employing agri-waste as a feedstock. The synthesis technique is determined by the type of agri-waste, its content, and the result of the intended bioplastics. This analysis concludes that, among the many production strategies, microbial fermentation may be effectively used for bio-transforming agri-waste into complex bioplastics, an active research and development field.

Declarations

Ethics approval: Not applicable.
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CRediT authorship contribution statement

Mamun Mandal: Conceptualization, Resources, Investigation, Writing – original draft. **Anamika Roy:** Writing – review & editing. **Debasis Mitra:** Writing – review & editing. **Abhijit Sarkar:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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