# Chapter 15
# Biotechnology and Microbial Genomics for Circular Bioeconomy

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## 15.1 Circular Bioeconomy

Worldwide industrialization is linked with an increasing demand for energy and natural resources, the consumption of fossil fuels, high pollution, and greenhouse gas (GHG) emissions, which are associated with climate change. The circular economy emerges in response to the traditional linear economy, which extracts raw materials from nature, manufactures products, and finally throws them away as waste. The circular economy improves the sustainability of goods and services and minimizes waste (Stahel, 2016; Ubando et al., 2020). Furthermore, a study indicates that a transition of a European nation to a circular economy could decrease up to 70% greenhouse gas (GHG) emissions and increase by 4% its

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workforce (Stahel, 2016). In this century, biomass has been promoted as an alternative to fossil fuels to fulfill the requirements of society. The biorefinery of biomass, which generates multiple products from biological feedstocks, resembling the refinery of petroleum in the fossil-fuel-based economy, is of increasing application toward the bioeconomy (Ubando et al., 2020). The term bioeconomy has

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been defined as “the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes, and services across all economic sectors aiming toward a sustainable economy” (International Advisory Council of the Global Bioeconomy Summit (IACGBS), 2018). The bioeconomy is growing worldwide, generating in 2019/2020 more than 17.5 million direct jobs in the European Union and >2.5 million direct jobs in Argentina (Trigo et al., 2023). Bioeconomy is strongly associated with the United Nations (UN) Sustainable Development Goals (SDGs). The circular bioeconomy is based on biological resources that are transformed into services, processes, and products, which are later recycled with minimal waste accumulation and environmental impact (Fig. 15.1). The feasibility of the circular bioeconomy relies on the available resources, ecosystems, and socioeconomic aspects (e.g., sustainable production

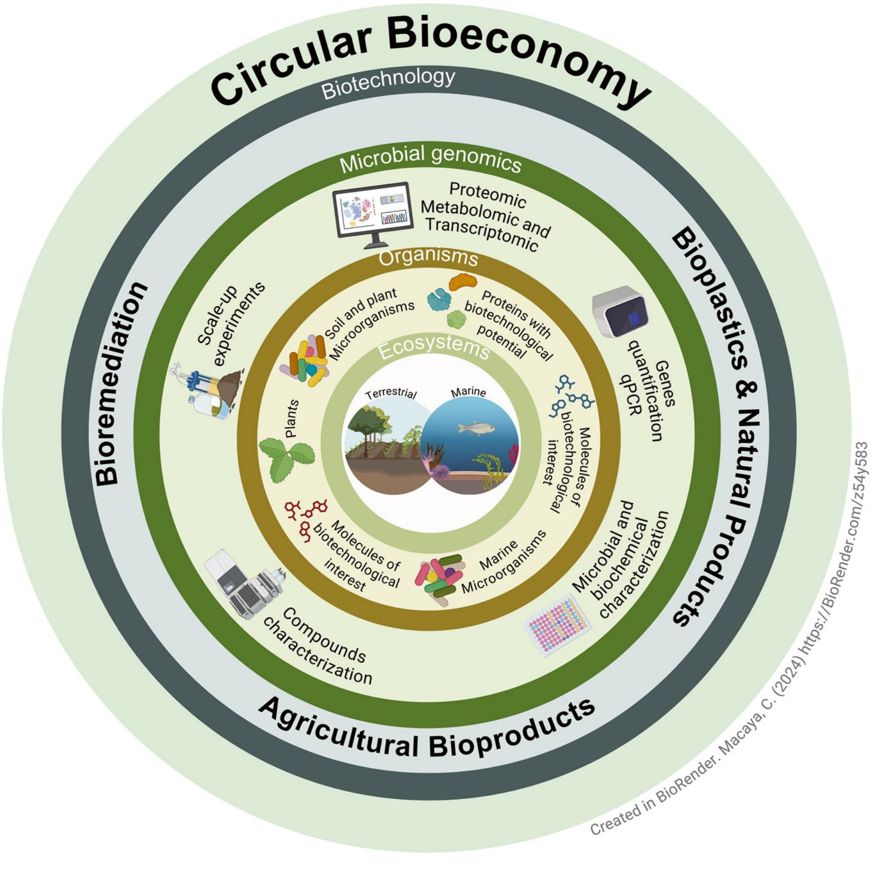

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**Fig. 15.1** The journey from biodiversity resources through their molecular characterization supported by genomics to their biotechnological applications for circular bioeconomy. Graphical representation of the different levels: 1) ecosystems, 2) organisms, 3) techniques (dry lab and wet lab), and cross-cutting disciplines, such as microbial genomics, 4) development of various biotechnological fields, including bioremediation, agricultural bioproducts, bioplastics, and natural bioproducts development, following sustainability principles, and 5) circular bioeconomy, a more efficient and environmentally friendly economic model and consumption, economic growth, trade, services, poverty and inequality reduction, job creation) at a regional or local level (Food and Agriculture Organization of the United Nations (FAO), 2018). Bioeconomic clusters located in several European countries have demonstrated the ability to promote circular schemes, improving the manufacturing of bio-based products (e.g., bioplastics, biofuels) (Stegmann et al., 2020). The bioeconomic sector in Germany has grown 22% from 2002 to 2010, contributing to 6% of the overall economic value in 2010 (FAO, 2018).

## 15.2 Biotechnology

The development of human society has been based on the use of living organisms and biological processes to improve the quality of life. Key steps for the development were the domestication of animals and plants and the use of plant, animal, and microbial natural products for medicine. The history of biotechnology could be classified in different eras (Smith, 2009; Rennenberg et al., 2016). Classical biotechnology includes the fermentation processes for bread and beverage production more than 8000 years ago. In a second era of biotechnology that began at the end of the nineteenth century, diverse biotechnological processes under non-sterile conditions were developed such as urban wastewater treatment, urban composting of solid wastes, and the synthesis of diverse products (e.g., ethanol, acetic acid) by microbial fermentation. Production of antibiotics, enzymes, vaccines, and other biotechnological products under sterile conditions originated in the 1940s in the third phase of biotechnology. The revolution of modern biotechnology started with genetic engineering in California in 1973 by Stanley Cohen, Paul Berg, and Herbert Boyer. Modern biotechnology employs cellular and molecular processes including genetic engineering to develop technologies, products, and services that contribute to the advancement of the society and environmental protection, promoting sustainable development (Smith, 2009; Rennenberg et al., 2016).

The markets of several areas of biotechnology are growing. Environmental bioremediation reached a global market of 186.3 billion in 2023 (Orellana et al., 2022). Sustainable agriculture reached a market of USD13.5 billion in 2023 (The Business Research Company, 2024). Biotechnology associated with human health, which includes the production of antibiotics and biomaterials, had a global market size of USD385 billion in 2023 (Precedence Research, 2024).

Microorganisms (e.g., bacteria, fungi, yeasts, archaea) play a key role in the development of biotechnology and participate in diverse fields such as industry, medicine, agriculture, environmental decontamination, and novel materials. The huge metabolic diversity of microorganisms is crucial for biotechnology (Palmerín-Carreño et al., 2015; Rennenberg et al. 2016; Orellana et al., 2018). Microorganisms contribute significantly to global sustainable development, for example, supporting the search for novel added-value materials and compounds for human health and crop protection, the restoration of contaminated ecosystems and their use in the development of molecular analytical methods (Rennenberg et al., 2016).

Environmental biotechnology is defined as a discipline that applies biological systems and processes to address environmental challenges such as waste management and the clean-up of polluted sites (Smith, 2009; Orellana et al., 2022). Environmental biotechnology involves the development, use, and regulation of biological systems (e.g., microorganisms, plants) and processes (e.g., bioremediation, phytoremediation) for the restoration of contaminated ecosystems (soil, water, and air) and decreasing environmental impacts of industrial processes (Zylstra & Kukor, 2005; Orellana et al., 2022). Environmental biotechnology has revolutionized the agricultural, industrial, and environmental sectors. Next-generation industrial biotechnology has developed tools based on the diversity of microorganisms (e.g., halophile, acidophile biocatalysts) to produce a wide range of bioproducts in processes that minimize costs, water, and energy usage and environmental impacts (Yu et al., 2019). However, scalability and optimization are ongoing challenges that increase the cost of bioproducts (Orellana et al., 2018, 2022; Alvarez-Santullano et al., 2021; Undabarrena et al., 2021). To innovate in the processes and services that environmental biotechnology offers, a responsible use of the resources involved is required to minimize environmental impact throughout the lifecycle of the developed products and processes, directly relating to the principles of the circular bioeconomy (Sarvatli, 2017; Lokko et al., 2018; Schwartz Melgar et al., 2022).

Environmental biotechnology contributes to main dimensions in the development of the circular bioeconomy: 1) Closing material cycles, through the design of processes for the reuse/recycling of materials and waste, 2) Pollution reduction and restoration of contaminated sites, by developing technologies and processes to clean-up soil and water, and 3) Development of sustainable products, manufacturing products with a prolonged useful life and that are recyclable (Aguilar et al., 2019; Orellana et al., 2022).

Policies on the development of knowledge in biological resources and worldwide scientific collaboration were crucial for the circular bioeconomy development of the European Union, the United States of America, and China (Patermann & Aguilar, 2018; Wohlgemuth et al., 2021). Advances in emerging research topics such as the information technologies have allowed the emergence of omics technologies (e.g., genomics, transcriptomics, proteomics, metabolomics) providing a deep understanding of biological systems, which has been pivotal for the development of the worldwide bioeconomy (Patermann & Aguilar, 2018; Wohlgemuth et al., 2021).

## 15.3 Microbial Genomics

The genome of living organisms is composed of its complete genetic material that is generally DNA. In contrast, the genomes of RNA viruses are composed of RNA. The bioinformatic analyses of sequenced genomes of organisms allowed revealing genes involved in metabolism, adaptation, signaling, transport, and diverse molecular and cellular processes. In 1995, the first genome of a microbial cell, the bacterium *Haemophilus influenzae*, was sequenced (Fleischmann et al., 1995). The genome of the model bacterium *Escherichia coli* K-12 was sequenced in 1997 (Blattner et al., 1997). *E. coli* is the main organism used for genetic engineering. Automated DNA sequencing techniques have allowed sequencing of a huge number of microbial genomes. A variety of high-throughput tools have been developed for automated annotation, prediction, and visualization of genomes (Cumsille et al., 2023).

Metabolic reconstruction based on the analysis of the sequenced genomes has been carried out for various bacteria. The high metabolic versatility of specific microorganisms is attractive for biotechnological applications such as bioremediation of contaminated environments, promotion of plant growth, biocontrol of phytopathogens, the synthesis of biopolymers and bioactive compounds. The genome-guided metabolic reconstruction of different bacterial genera such as *Pseudomonas*, *Paraburkholderia, Acinetobacter, Halomonas,* and *Streptomyces* species has been crucial for the selection of bacterial strains with higher metabolic versatility and robust adaptive responses to environmental stresses for diverse biotechnological applications such as bioremediation and biotransformation (Seeger et al., 2003; Chain et al., 2006; Pieper & Seeger, 2008; Saavedra et al., 2010; Ponce et al., 2011; Perez-Pantoja et al., 2012; Durán et al., 2019; Macaya et al., 2019a, 2019b), plant growth promotion and biocontrol of phytopathogens (Canchignia et al., 2017; Vega-Celedón et al., 2021, 2024; Álvarez-Hubert et al., 2024; Larach et al., 2024; Castillo-Novales et al., 2025), synthesis of bioactive compounds (Undabarrena et al., 2016, 2017, 2021; Serna-Cardona et al., 2024), and production of bioplastics (Urtuvia et al., 2014, 2018; Álvarez-Santullano et al., 2021). *Pseudomonas* strains have been widely used for biodegradation of pollutants, plant growth promotion, and biocontrol of phytopathogens (Perez-Pantoja et al., 2012; Canchignia et al., 2017; Vega-Celedón et al., 2021, Larach et al., 2024). *Paraburkholderia* strains are relevant for biodegradation, biotransformation, plant growth promotion, and the synthesis of bioplastics (Seeger et al., 2003; Chain et al., 2006; Pieper & Seeger, 2008; Urtuvia et al., 2014, 2018; Álvarez-Santullano et al., 2021 Vega-Celedón et al 2021; Sepúlveda et al., 2025). *Halomonas* strains have been applied for the synthesis of bioplastics and bioactive compounds and plant growth promotion (Ma et al., 2020; Ye & Chen, 2021; Álvarez-Hubert et al., 2024). *Streptomyces* strains are the most relevant organisms for the synthesis of antibiotics (Undabarrena et al., 2016, 2017; Serna-Cardona et al., 2024). A genome-wide metabolic reconstruction revealed that *Paraburkholderia* species possess higher pathway redundancy of central carbon metabolism than *Burkholderia* species, which may confer robustness for their adaptation to harsh environments during bioremediation or plant growth promotion applications (Álvarez-Santullano et al., 2021). Additionally, genome mining predicts the synthetic capability of each microorganism, which is useful for the design and optimization of biorefinery schemes, reducing experimental time and costs. The simultaneous synthesis of PHB and ectoines by *Halomonas* species that were optimized through metabolic engineering is a remarkable example (Ma et al., 2020; Ye & Chen, 2021). In addition, the combination of genome-based approaches and experimental techniques allows the study of uncultured organisms and microbial communities, providing useful knowledge on microbial ecology for the conservation of ecosystems, management of bioprocesses, and health improvement (Fuentes et al., 2016; Zhou et al., 2022; Pittino et al., 2023; Gandolfi et al., 2024).

The application of genomics contributes to a deep understanding of (1) the variability of genetic components of microorganisms, their classification, and taxonomic identification, (2) predicting potential compounds with antimicrobial activity and novel chemical structures (Foulston, 2019), (3) the metabolism involved in biodegradation, (4) the adaptation of microorganisms to environmental stresses (e.g., salinity, extreme pH, extreme temperature) and contaminants (Plewniak et al., 2018;

Méndez et al., 2025), and (5) the impact of biotechnologies for environmental decontamination and sustainable agriculture on the native microbial community. Circular bioeconomy is based on biological resources derived from the biodiversity. Microbial genomics provides essential knowledge for the conservation of biodiversity and ecosystems through sustainable and efficient bioremediation and agriculture strategies (Buchmann-Duck & Beazley, 2020). Next-generation sequencing is useful for studying the structure, function, and composition of genomes of an entire community of microorganisms from diverse matrices, such as soil, water, sediments. Metagenomic applications in bioremediation include the generation of profiles of antibiotic resistance genes and other mobile genetic elements (Wang et al., 2013, 2014), dynamics of the structure of the microbial community during bioremediation processes of contaminated soils (Morgante et al., 2010; Ping et al., 2015; Fuentes et al., 2016) and the tracking of bacteria during decontamination processes (Morgante et al., 2010; Deng et al., 2016).

## 15.4 Bioremediation

Pollution and anthropogenic activities have adversely impacted >33% of arable soil, limiting agricultural productivity (Abhilash et al., 2016). The clean-up of polluted ecosystems is a major challenge for the 2030 United Nations (UN) Agenda for Sustainable Development, which should be addressed to promote the concept of "One Health" and UN SDGs such as SDG 6 (Clean water and sanitation), SDG 11 (Sustainable cities and communities), SDG 14 (Life below water), and SDG 15 (Life on land). Bioremediation technologies are useful for the clean-up of polluted ecosystems (Fuentes et al., 2014; Orellana et al., 2018, 2022; Macaya et al., 2019b). Main advantages of bioremediation include a natural process, the complete removal of pollutants, potential *in-situ* or *ex-situ* applications, and low carbon footprint (Fuentes et al., 2014; Macaya et al., 2019b; Orellana et al., 2022). The *ex-situ* technologies could be used *on-site* or *off-site* (Orellana et al., 2022). Decontaminated soils and water are crucial for sustainable cities, land and water, and diverse human activities such as urbanization, agriculture, fishery, aquaculture, sports, and tourism (FAO, 2018; Orellana et al., 2018, 2022). Therefore, the valorization of ecosystems after their clean-up via bioremediation and other treatments is also essential for a circular bioeconomy.

### *15.4.1 Environmental Contamination: Persist Pollutants and Their Removal by Microorganisms*

The growth of food, transportation, and industrialization in society raises the use of chemicals and fossil fuels. Despite the growing development of new sustainable energy sources, the consumption of oil and its derivatives has not slowed down.

Their recalcitrance, toxicity, and continuous release into the environment convert these pollutants into a serious threat to human and ecosystem health (Shetty et al., 2023). The understanding of their behavior in the environment enables the development of more effective and sustainable bioremediation technologies (Bala et al., 2022). Major pollutants include petroleum-derived hydrocarbons, pesticides, heavy metals, industrial compounds such as polychlorobiphenyls (PCBs) and perfluoroalkyl and polyfluoroalkyl substances (PFAS), and microplastics, which will be described below.

**Petroleum-derived hydrocarbons (HC)** HC originate from animal and plant biomass that has been subjected to biogeological processes during millions of years (Liu et al., 2022). Petroleum is the main source of energy and materials for various industrial and daily activities, driving the global economy (Varjani & Upasani, 2016; Ahmed et al., 2020). Petroleum derivatives include diesel, gasoline, and jet fuel. Global oil demand in 2023 will be 102.97 million barrels per day, with 45% consumed by OECD countries (US Energy Information Administration, 2024). Petroleum consists mainly of aliphatic hydrocarbons (such as alkanes and alkenes), cycloalkanes (e.g., cyclohexane), monoaromatics (e.g., benzene, toluene, ethylbenzene, *o*-xylene, *m*-xylene and *p*-xylene, BTEX) and polycyclic aromatic hydrocarbons (PAHs) (e.g., anthracene), and trace amounts of heavy metals (Akmaz et al., 2011; Chaudhuri, 2010; Joshi et al., 2019). Due to anthropogenic activities, BTEX and PAHs, which are recalcitrant and carcinogenic, are widely distributed in the environment, representing a significant risk to human health (Fuentes et al., 2014; Sun et al., 2021). Heavy metals such as cadmium, chromium, lead, and mercury are common co-contaminants in hydrocarbon-impacted sites and represent a public health risk (Amezcua-Allieri et al., 2005; Tchounwou et al., 2012; Olaniran et al., 2013; Fuentes et al., 2014).

Pollution events negatively impact the environmental matrix (soil, water, or air), living organisms (plants, animals, microorganisms), and their ecological interactions. The structure, diversity, and abundance of microbial communities (bacteria, fungi, and archaea) are affected by pollution events (Macaya et al., 2019b). Proteobacteria and Bacilli are the main phyla in chronic oil-polluted sites. *Pseudomonas* and *Lactococcus* have been reported in oil wellheads, while *Prauseria* and *Bacillus* have been observed in storage tanks (Liu et al., 2019). *Alcanivorax*, *Marinobacter,* and *Oleispira* genera are strict hydrocarbon-clastic bacteria, which increase significantly in the sea after oil contamination (Yakimov et al., 2007). *Dietzia* sp. strains are capable of degrading short, medium, and long chain alkanes (Wang et al., 2011). Rare taxa, such as *Alkanindiges* that are not abundant in pristine soils, became dominant in the soil after diesel contamination (Fuentes et al., 2016). Hydrocarbon-clastic bacteria play a crucial role in the clean-up of hydrocarbon-impacted environments (Xu et al., 2018).

**Pesticides** The significant increase in the application of pesticides for food production, harvesting, and storage is associated with the food demand growth. The total pesticide use in the agricultural sector during 2022 was 3.7 million tons, representing a 4% increase in consumption compared to the previous year (FAO, 2022a). Pesticides may be pure substances or mixtures, which are used by farmers to control microbes (fungicides), insects (insecticides), and weeds (herbicides). Although these compounds have specific targets, their action and wide use have impacted ecosystems and various forms of life including humans (Lin et al., 2016). Organochlorine insecticides (OC) are used to control pests such as malaria and typhus; however, they are legally banned in several countries. These compounds have been replaced by organophosphates (OP), such as carbamates and pyrethroids (Kumar et al., 2021a, 2021b). Synthetic s-triazine herbicides (atrazine, simazine) are applied to control weeds and grasses in crops. These herbicides alter plant growth and microbial communities, but are also major contaminants of terrestrial and aquatic ecosystems, threatening the sustainability of agricultural soils (Hernández et al., 2011). Diverse bacterial and fungal genera including *Arthrobacter, Aspergillus, Bacillus, Burkholderia, Nocardioides, Pseudomonas, Sphingobacterium, Sphingomonas,* and *Trichoderma* degrade different types of pesticides (Kumar et al., 2021a).

**Polychlorobiphenyls (PCBs)** PCBs are aromatic compounds containing chlorine atoms in different positions on two benzene rings, with more than 200 congeners. Their use became widespread toward the end of the 1920s. Their applications include dielectric materials in transformers and electrical capacitors, and additives in plastics and paints. PCBs are classified as persistent organic pollutants (POPs), which adsorb in soils and sediments, and bioaccumulate in various forms of life of impacted ecosystems (Seeger et al., 1995, 1997; Gomes et al., 2015). Due to their carcinogenic and immunogenic effects, their production was banned in the 1970s. However, PCBs are still in use in electrical equipment manufactured prior to the ban and are widely present in the environment (ATSDR, 2000; Palma et al., 2008; Dias-Ferrerira et al., 2016).

The degradation of PCBs is mediated by bacteria under both aerobic and anaerobic conditions. *Paraburkholderia*, *Pseudomonas*, *Comamonas*, *Cupriavidus*, *Sphingomonas*, *Acidovorax*, *Rhodococcus*, and *Bacillus* strains are capable of degrading PCBs (Pieper & Seeger, 2008). *Desulfitobacterium*, *Desulfomonile*, and *Desulfuromonas* are capable of dehalogenating chlorinated aromatic compounds (de Weerd & Suflita, 1990; Sanford et al., 1996; Krumholz, 1997). *Paraburkholderia xenovorans* LB400 is the model aromatic-degrader that degrades an unusually wide range of aromatic compounds including PCBs and possesses robust adaptation mechanisms to diverse stresses (Seeger et al., 1999; Chain et al., 2006; Rodriguez-Castro et al., 2024; Méndez et al., 2025).

**Heavy metals (HM)** HM can be defined as a group of metals (and metalloids) that may be toxic to various forms of life even at low concentrations. This classification includes cadmium, mercury, copper, arsenic, lead, chromium, nickel, and zinc. Due to the development of intensive agriculture and other industrial activities, HM pollution has emerged as a serious threat to the environment, particularly to soil (Sarwar et al., 2016). This type of contamination is persistent and irreversible, impacting not only terrestrial and aquatic environments but also affecting human health by bioaccumulating in the food chain, causing harmful effects such as skin cancer, brain damage, cardiovascular and respiratory disorders, and infertility (Kankia & Abdulhamid, 2014; Ayangbenro & Babalola, 2017; Alviz-Gazitúa et al., 2019). More than 5 million sites contaminated with heavy metals or metalloids have been reported, affecting over 500 million hectares of soil (Liu et al., 2018). The global economic impact of this contamination is estimated to exceed USD10 billion per year (He et al., 2015). The primary source of HM in soils comes from the Earth's crust, where natural geological processes release elements such as Pb, Cu, Zn, Mn, and Cd into the soil (Muradoglu et al., 2015; Sarwar et al., 2016). Anthropogenic sources include industrial processes and traffic. HM accumulate in roadside soils and even in agricultural soils near roads (Nabuloa et al., 2006). Impacted crops may absorb HM through their roots, which could reach the stems and leaves (Prasad & Freitas, 2000).

Chromium is widely used in various industries; hexavalent chromium Cr(VI) is the most toxic and mutagenic form. Endophytic bacteria such as *Bacillus* sp. L14 remove cadmium from contaminated soils, accumulating this HM in their cytoplasm (Luo et al., 2011). Soluble Cr(VI) reductases have been described in *Pseudomonas putida* (ChrR), transforming Cr(VI) into Cr(IV). The YieF protein reduces Cr(VI) to Cr(III) in *Escherichia coli* (Cheung & Gu, 2007). Soluble Cr(VI) reductases have been described in *Pseudomonas putida* (ChrR), which transforms Cr(VI) to Cr(IV). *Cupriavidus metallidurans* and other species of the genus *Pseudomonas*, such as *Ps. stutzeri,* reduce Hg(II) to Hg(0) (Rojas et al., 2011; Purkan et al., 2016; Bravo et al., 2020).

**Emergent contaminants** Emergent contaminants have been determined in soil, but primarily in aqueous environments such as aquifers, oceans, and water sources (Zahn et al., 2020). The quantification of these pollutants in low levels is an important challenge (Zahn et al., 2020). Main emergent pollutants compounds are perfluoroalkyl and polyfluoroalkyl substances (PFAS) and microplastics (MP). Although PFAS are typically present in low concentrations, higher levels (mg/L) have been observed in water bodies impacted by firefighting activities or near fluorochemical manufacturing industries, negatively affecting the environment and human health (Vedajiri et al., 2018). Microbial bioremediation has not been applied yet, mainly due to their recalcitrance, the toxicity of their intermediates, and the unavailability of degrading microorganisms (LaFond et al., 2023).

MP are defined as plastic particles smaller than 5 mm, which are of increasing environmental concern. The presence of microplastics (MP) has been reported in marine and terrestrial ecosystems. The most common forms of MP include fibers and pellets. Their presence in soils and water represents a significant risk to human health and the environment. The main strategies for managing MP include pyrolysis, chemical degradation, biological degradation, and the development of biodegradable alternatives, such as bioplastics (Chia et al., 2021) (further description in Sect. 15.6). Various strategies have been proposed to clean up MP-containing matrices. MP extraction using filters or pumps, followed by chemical or biological degradation, can be effective. However, scalability is still a limitation (Wong et al., 2020). Due to the occurrence and distribution of MP within matrices it is important to develop remediation strategies (Fu et al., 2020). Analytical tools are crucial to quantify MP release, particularly in areas with unregulated industrial and/or domestic waste management (Bilal & Iqbal, 2020).

These compounds and elements are associated with the expansion of industrialization, urbanization, and socioeconomic growth. Despite this development, the persistent use of these compounds gradually impacts the environment. Urban ecosystems, forests, wetlands, and agricultural soils play a crucial role in urban health by providing multiple benefits to the surrounding biota; contamination directly impacts the microbiota and health of ecosystems, affecting their tangible (e.g.*,* food, water) and intangible (e.g.*,* nutrient cycles, temperature regulation, bioremediation) ecosystem services.

Despite the high toxicity to the microbial communities of pollution events caused by HC, pesticides, HM, and PCBs, specific microorganisms have pollutant-removing capabilities. In pristine ecosystems, hydrocarbonoclastic bacterial genera are present at low levels, representing less than 0.1% of the total community (Fuentes et al., 2016; Rodríguez-Castro et al., 2022). After an oil spill, the abundance of HC-degrading bacteria increases significantly up to 60% of the microbial community (Fuentes et al., 2016). Studies on *s*-triazines bioremediation showed that the application of organic amendments alters the structure of the microbial community, favoring microorganisms capable of degrading *s*-triazines (atrazine, simazine) and using these substrates as nitrogen sources, such as Proteobacteria (e.g., *Pseudomonas*) and Planctomycetes (Martin-Laurent et al., 2004; Rhine et al., 2003; Hernández et al., 2008; Morgante et al., 2010). Supplementation with PHA in marine sediments contaminated with PCBs increases degrading microorganisms, but reduces the microbial community diversity (Botti et al., 2023). Agricultural soils chronically exposed to heavy metals such as copper contain adapted bacterial communities including copper-resistant strains from *Sphingomonas*, *Stenotrophomonas,* and *Arthrobacter* genera with genetic determinants that confer resistance to copper and other heavy metals (Altimira et al., 2012).

### *15.4.2 Bioremediation: Strategies and Innovation*

Microorganisms with enhanced pollutant-removing capabilities and high resistance to environmental stresses (e.g., salinity, pH changes) are selected in polluted sites. The metabolic capabilities of the microbiota of the impacted ecosystems are crucial for bioremediation. Bioremediation is an increasingly applied technology, due to its low cost, biological basis, and environmentally friendly nature (Navia & Seeger, 2006; Fuentes et al., 2014; Macaya et al., 2019b). A high number of contaminated sites require technologies for their decontamination. To date, China has more than 2 million polluted sites, the USA has >500,000 impacted sites, Europe >340,000 sites, and Chile >10,000 contaminated ecosystems including 600 urban sites (State Council of China, 2013; Zvomuya & Murata, 2013; Van Liederkeke et al., 2014). The industry associated with bioremediation processes represents a global market of USD186.3 billion in 2023, with a projected Compound Annual Growth Rate (CAGR) of 9.9% by 2030 (BCCResearch, 2024; Orellana et al., 2022).

Currently, there are various strategies for decontaminating impacted ecosystems. Physical remediation (PR) involves actions to extract the contaminated matrix (e.g., soil, water) through excavation, pumping, or air injection (Fuentes et al., 2014). Chemical remediation (CR) uses chemical agents to transform contaminants into less toxic compounds (Koul et al., 2018). Natural attenuation (NA) is a spontaneous natural process (biological, chemical, and physical) under monitoring to decontaminate the matrix (Pradhan et al., 2021). Bioremediation (or biological remediation) employs the metabolic capabilities of microorganisms (native or exogenous) to degrade contaminants. Compared to PR and CR, bioremediation produces less toxic intermediates. Compared to NA that occurs exclusively under natural conditions, bioremediation accelerates decontamination (Pradhan et al., 2021).

Different bioremediation strategies are used for the clean-up of polluted ecosystems. Biostimulation is a technology wherein nutrients (e.g., nitrogen, phosphorus) or biologically derived surfactants are added to promote the degradation by the indigenous microbiota of the contaminated environment. In bioaugmentation, indigenous or non-indigenous pollutant-degrading microorganisms are introduced to increase the degradation rate of contaminants (Ron, 2000; Navia & Seeger, 2006; Morgante et al., 2010; Fuentes et al., 2014). In bioventing, the contaminated environment is aerated to provide electron acceptor oxygen to stimulate microbial metabolism (Fuentes et al., 2014). The selection of an appropriate bioremediation strategy should be based on the physicochemical properties of the impacted matrix and the pollutants (Fig. 15.2). The bioremediation process may operate *in situ* or *ex situ*. Particularly, for *ex-situ* processes, two variants are: 1) *off-site*, where the contaminated matrix is transported to an external facility, outside the site, and 2) *on-site*, where the contaminated material is removed but treated at the original location (Hernández et al., 2008; Macaya et al., 2019b; Bravo et al., 2020).

Associated with major sustainable development challenges, such as the sustainable management of natural resources and the balance of social evolution, current biotechnologies should be innovative, enabling the production of biomasses (e.g., degrading microbial consortia, production of biostimulants, antioxidants) for sustainable environmental decontamination services (Fuentes et al., 2014). The bioeconomy offers interesting guidelines by promoting improvements in sustainable industrial production, reducing environmental impact, and fostering the safe preservation of the environment (Fig. 15.3) (The European Plant Science Organisation, 2011; Fuentes et al., 2014; Labuto & Carrilho, 2016).

Depending on the type of contamination and the physicochemical characteristics of the impacted matrix, one or more complementary bioremediation strategies

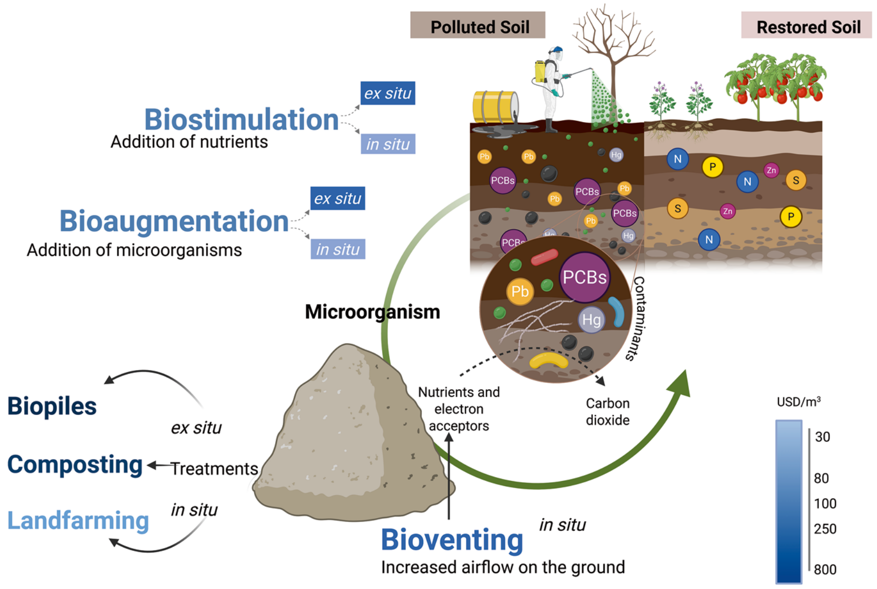

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**Fig. 15.2** Biological decontamination technologies. Graphical representation of the bioremediation strategies: biostimulation, bioaugmentation, bioventing (in which the contaminated environment is aerated to supply oxygen for microbial activity), biopiles, composting, and landfarming. The blue scale range represents the economic cost (in US\$/m$^2$) of each technology, with the lowest cost described in light blue, and the most expensive in dark blue. Adapted from Ester G. Rivera, 2023. Master thesis in Environmental Biochemistry. University of Chile

can be applied. For decontamination, a critical factor is the bioavailability of contaminants, especially in aquatic environments. Microbial biosurfactants enhance the mobility of hydrophobic pollutants, increasing their bioavailability (Singh et al., 2007; Ke et al., 2018; Astuti et al., 2019). Biostimulation with biosurfactants (e.g., saponins) has been successfully used in the decontamination of HC and HM (Kaczorek et al., 2008; Lord, 2010; Kiliç et al., 2011). In accordance with the principles of the circular bioeconomy, the use of local agricultural waste/by-product to alleviate the metabolic stress of pollutant-degrading bacteria contributes to closing the cycle of each by-product. Berry extract has been used as a source of antioxidants in the decontamination of coastal soils contaminated with HC (Ponce et al., 2011).

Biostimulation with the addition of nutrients has been widely used (Macaya et al., 2019b). Feathers are one of the main wastes of the poultry industry, with an estimated global production of 8.5 billion tons (Holkar et al., 2018). *Streptomyces* sp. G11C synthesizes keratinases that degrade feathers, generating a medium rich in proteins, nitrogen, and essential amino acids, which can be used to stimulate native microbiota activity for soil restoration (Habbeche et al., 2014; Holkar et al., 2018; González et al., 2020; Jagadeesan et al., 2023).

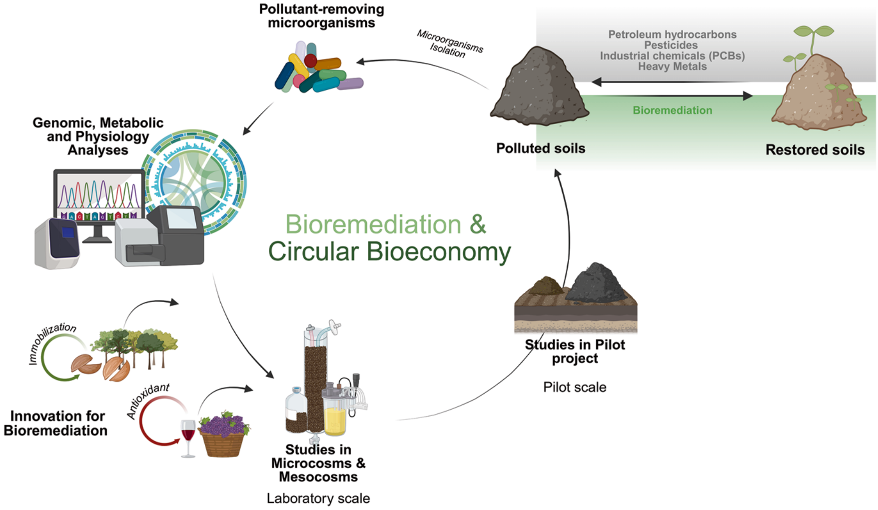

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**Fig. 15.3** Bioremediation processes and circular bioeconomy. Graphical representation of the processes of isolation of soil microorganisms with metabolic capabilities for the removal of pollutants (petroleum hydrocarbons, pesticides, industrial chemicals such as PCBs, and heavy metals), their genomic and functional characterization, innovation processes in bioremediation strategies related to the valorization of agricultural wastes, decontamination studies at laboratory and pilot scales, and the clean-up of impacted soils toward soil restoration

Several factors influence the successful application of a bioaugmentation strategy, including fluctuations in environmental parameters (temperature, salinity, and pH), moisture retention, and contaminant concentration. Regarding implementation costs, these are not significant if existing infrastructure is already in place for maintaining moisture and injecting reducing agents, as these same systems can be used for strain inoculation. While the use of such facilities facilitates the distribution of the inoculum within the matrix, applying it in an aqueous solution poses the risk of washing out and predation of the inoculated microbes (Boon & Verstraete, 2010). Immobilization is useful to improve the survival and stability of pollutant-degrading bacteria, extending the lifespan of bioremediation agents by facilitating cell reuse, reducing costs of re-inoculation, and promoting cell recycling processes. In line with the concept of waste valorization, matrices derived from agro-industrial residues have gained considerable interest in bioremediation processes (Bayat et al., 2015). Studies on contaminated soils and aquifers demonstrate that bioaugmentation is an eco-friendly, effective, and affordable clean-up treatment. Bioaugmentation with *Pseudomonas* sp. strains ADP1 and MHP41 in s-triazine-contaminated soils achieved >80% contaminant removal (Lima et al., 2009; Hernández et al., 2008; Morgante et al., 2010). Bioaugmentation with nitrogen removal bacteria in wastewater enhances aerobic nutrient removal (Chen et al., 2015). In these studies, bioaugmentation significantly changes the microbial community structure.

## 15.5 Agricultural Bioproducts

Climate change has a significant negative impact on agriculture, ecosystems, and health. Agriculture is affected by climate change, which causes drought, flooding, and the increase of extreme temperatures in diverse regions (Raza et al., 2019). Therefore, climate change increases plant abiotic and biotic stress, and favors emerging phytopathogens (Valenzuela et al., 2018; Besoain et al., 2019; Alfaro et al., 2023; Larach et al., 2024). Microorganisms and plant natural products are useful to promote plant growth and to protect plants from biotic and abiotic stresses (Olivera et al., 2021; Vega-Celedón et al., 2021, 2024; Álvarez-Hubert et al., 2024; Montenegro et al., 2024).

Agriculture faces increasingly complex challenges due to population growth and the depletion of natural resources. The world population is projected to increase to over 10 billion people in the next 30 years. Therefore, the food supply must increase by 60% to cope with the projected demand in 2050 (United Nations, 2015). In view of this, the global demand for the use of pesticides and fertilizers has increased (FAO, 2022a). The misuse of pesticides and fertilizers contributed to the desertification of agricultural lands, the loss of biodiversity in ecosystems, especially in microhabitats (Sporen et al., 2024) and the decrease in crop productivity and increase in physiological disorders in humans (Bedair et al., 2022). International regulations such as EU 2015/408 establish the replacement of traditional chemical agents used in agriculture with sustainable alternative methods with similar effectiveness in the control of agricultural diseases (Delgado et al., 2021). The European Union aims to reduce pesticide use by 50% by 2030 (Salerno et al., 2024). This context has driven the search for more sustainable alternatives, such as bioproducts, that are central to transforming agriculture toward more sustainable practices (FAO, 2022a). Bioproducts not only reduce dependence on chemical inputs but also promote the efficient use of natural resources such as soil and water, which contributes to the resilience of agricultural systems against the effects of climate change.

Globally, the increasing demand for organic food and the interest in more human and environmentally responsible agriculture drive significant growth in the bio-based products market. The global agricultural bio-based products market size was estimated at US$9.9 billion in 2023 and is expected to grow at a CAGR of 7.2% from 2024 to 2030. Rising demand for organically cultivated food products is projected to be a key driving factor for the market (Agricultural biologicals market size, share and growth 2030). Organic farming focuses on minimizing or eliminating the use of synthetic mineral fertilizers, chemical protection agents, plant growth regulators, and genetically modified organisms. This issue reflects a trend toward agricultural practices that prioritize sustainability to meet the growing food demands and ensure that this food is produced ethically, safely, and with minimal environmental impact (FAO, 2022b).

Organic agriculture management aims to maximize the use of bioproducts in agricultural production (Aipova et al., 2019). This shift toward sustainable agriculture aims not only to increase productivity and improve the health of ecosystems but also to ensure that future food is safe, nutritious, and produced responsibly.

International policies, such as the UN 2030 Agenda for Sustainable Development, reinforce these commitments to sustainable agriculture, driving the transition toward an economic model that reconciles growth with care for the environment (Matera et al., 2024).

### 15.5.1 Definition and Classification of Agricultural Bioproducts

Agricultural bioproducts are materials from living organisms or their components that are used to improve agricultural productivity, soil health, and crop protection from pests and diseases. Figure 15.4 shows the classification of different

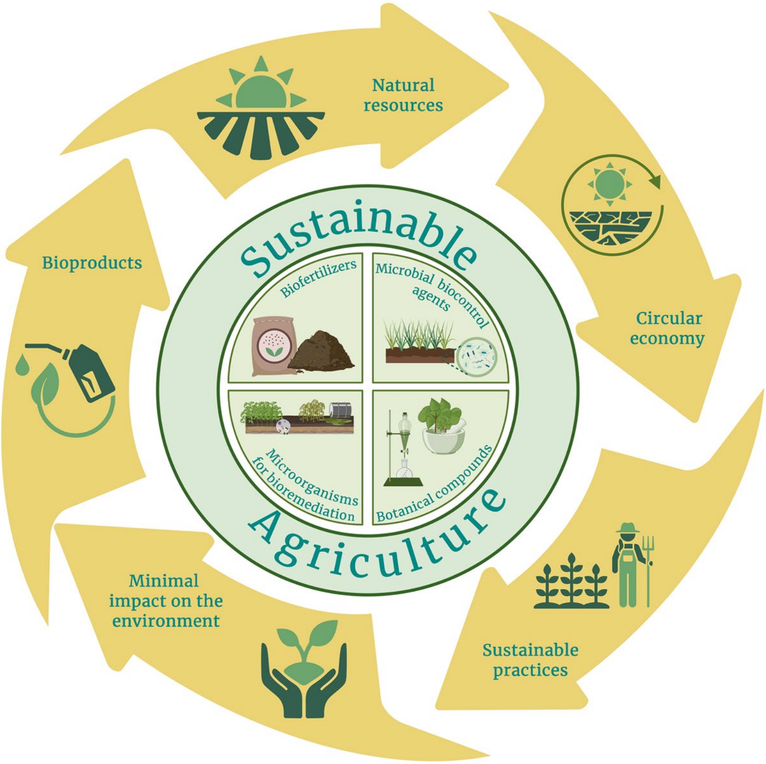

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**Fig. 15.4** Classification of bioproducts for agriculture in the context of circular bioeconomy. Graphical representation highlights the role of bioproducts—biofertilizers, microbial biocontrol agents, microorganisms for bioremediation, and botanical compounds—in sustainable agriculture. Their connection to natural resources, sustainable practices, minimal environmental impact, and the circular economy are indicated bioproducts described: (1) biofertilizers, (2) microbial biocontrol agents, (3) botanical compounds, and (4) microorganisms for the bioremediation of polluted agricultural soils (described in the Sect. 15.4–Bioremediation).

**Biofertilizers** Biofertilizers contain living microorganisms, and their application to the seed, plant surface, or rhizosphere increases the supply of mineral element concentrations to crops, thus promoting growth (Demir et al., 2023). Biofertilizers are alternative fertilizers that increase plant growth and yield and play a multifunctional role in soil and plants. Plant growth-promoting microorganisms (PGPMs) have emerged as a sustainable alternative to conventional chemical fertilizers, a potentially advantageous technique for improving crop productivity, quality, and food security (Lopes et al., 2021; Kumar et al., 2021a). PGPMs act as biofertilizers (Lopes et al., 2021) and include plant growth-promoting bacteria (PGPB) and arbuscular mycorrhizal fungi (AMF) that increase biomass production in plants by synthesizing phytohormones, fixing nitrogen, solubilizing phosphate and potassium, and increasing plant resistance to pathogens and environmental stresses (Ma, 2019; Aloo et al., 2022; Bhardwaj et al., 2014; Velásquez et al., 2020a, 2020b; Kumar et al., 2021a; Vega-Celedón et al., 2021). PGPB and AMF can improve root health in plants by increasing stress tolerance and growth, optimizing nutrient uptake and nutrition through the production of secondary metabolites and increasing disease resistance (Velázquez et al., 2020b; Rillig & Mummey, 2006; Adesemoye & Kloepper, 2009; Vejan et al., 2016; de Andrade et al., 2023). PGPMs promote healthy plant growth and are crucial in reducing greenhouse gas emissions and water pollution, supporting global sustainability goals (Costa et al., 2019).

Abiotic stresses, including cold, heat, drought, and salinity, significantly impact crop production and quality; more than >50% of global yield losses are attributed to abiotic stresses (Wang et al., 2016). Climate change further exacerbates these challenges, with higher exposure of plants to extreme temperature events such as frost. Psychrotolerant PGPB may protect and promote plant growth under low-temperature conditions (Vega-Celedón et al., 2021).

PGPB and AMF form beneficial associations with plants, promoting growth, nutrient availability, and protection against pathogens. PGPB and AMF solubilize nutrients, such as phosphate and potassium, increasing their availability to plants. *Pseudomonas fluorescens* is known for its phosphate-solubilizing capabilities, while *Azospirillum brasilense* enhances nitrogen fixation, crucial for crop productivity (Lugtenberg & Kamilova, 2009; Hashem et al., 2019). Diverse bacteria also produce phytohormones such as auxins, gibberellins, and cytokinins, which directly promote plant growth and improve root architecture, facilitating access to soil nutrients (Gamez et al., 2019; Molloy et al., 2013; Vega-Celedón et al., 2021, 2024). AMF, such as *Funneliformis mosseae*, establish mutualistic relationships with plant roots by forming specialized structures like arbuscules within the root cortex. These fungi improve water and nutrient uptake, particularly phosphorus, and offer plants enhanced resistance to abiotic stresses such as drought and salinity (Argaw & Akuma, 2015; Velásquez et al., 2020a). Additionally, AMF may induce systemic

resistance in plants, stimulating the plant's immune system and conferring more resistance to pathogens (Velásquez et al., 2020b).
Both PGPB and AMF contribute to pathogen suppression through direct and indirect mechanisms. Direct methods include the production of antimicrobial compounds (e.g., lipopeptides by *Bacillus subtilis*) and enzymes (e.g., lipases and proteases by *Pseudomonas veronii*), which inhibit plant pathogens (Ongena & Jacques, 2008; Canchignia et al., 2017). Indirectly, these microorganisms may outcompete pathogens for resources and niches within the rhizosphere, decreasing pathogen proliferation (Solis-Ramos et al., 2023).

**Microbial biocontrol agents** The use of microbial biocontrol agents in agricultural diseases and insect pests is of increasing importance due to their effectiveness in the control of pathogens and in extending the shelf-life of post-harvest products (Carmona-Hernández et al., 2019). Despite challenges such as production costs and regulation, the demand for biopesticides is expected to increase significantly in the coming years, driven by policies that favor more sustainable agricultural practices. This approach reinforces the interrelationship between agricultural productivity and environmental conservation, positioning biopesticides as a key component in the development of sustainable agricultural bioproducts (Šunjka & Mechora, 2022).

Generally, bacteria, fungi, and yeasts are used as microbial biocontrol agents of plant pathogens (Delgado et al., 2021; Olivera et al., 2021; Salerno et al., 2024), reducing the environmental impact and risks to human health (Santos et al., 2020). Biocontrol agents (BCAs) provide an effective and less harmful alternative to conventional chemical pesticides. Their mode of action includes competition for nutrients and space, production of antimicrobial compounds, induction of host defense responses, and parasitism (Romero et al., 2022; Olivera et al., 2021; Santos et al., 2020). A key advantage of BCAs is their specificity toward target pests, which minimizes damage to non-target organisms and contributes to biodiversity in agricultural ecosystems. Furthermore, their application promotes regenerative agriculture practices, which support soil health and crop resilience to climate change (Szewczuk-Karpisz et al., 2022). Climate change also alters disease pressure caused by known and emerging pathogens (Singh et al., 2023a). Because of the latter it is interesting to note the impact of temperatures on the development of microorganisms, and to evaluate their biocontrol efficacy at different temperatures (Larach et al., 2023; Castillo-Novales et al., 2025). Several bacteria used as BCAs in plant diseases are *Gluconobacter cerinus*, *Bacillus subtilis*, *B. amyloliquefaciens*, *B. licheniformis*, and *Paenibacillus pasadenensis* (Olivera et al., 2021; Romero et al., 2022; Matera et al., 2024). *Trichoderma* spp. and *Bacillus* spp. have been widely used for the biological control of plant diseases caused by soil phytopathogens, mainly against *Phytophthora*, *Rhizoctonia*, *Sclerotium*, *Pythium*, and *Fusarium* (Chet & Inbar, 1994; Ahmed et al., 2000, 2003; Ezziyyani et al., 2004). Yeasts reported as BCAs include *Candida oleophila, Metschnikowia fructicola*, *M. pulcherrima, Cryptococcus albidus*, *Hanseniaspora uvarum*, *H. osmophila,* and *Lachancea thermotolerans* (Olivera et al., 2021; Romero et al., 2022; Salerno et al., 2024). Microbial consortia may increase the BCA's efficiency due to the exploitation of their complementary and synergistic characteristics (Vega-Celedón et al., 2021). An example is a bioproduct composed of a bacterium and a yeast (*Gluconobacter cerinus* and *Hanseniaspora osmophila*) that has been reported and patented (WO2017088081A1), and is used to control gray rot and summer bunch rot in post-harvest table grapes with synergic effects (Delgado et al., 2021; Olivera et al., 2021).

In the case of insect-caused pests, BCAs act as bioinsecticides. *Bacillus thuringiensis* (Bt) is a bacterium that produces toxic proteins for various insect pests and is widely used in agriculture to control these insects without harming natural predators (Lacey & Shapiro-Ilan, 2008; Santos et al., 2020). *Beauveria bassiana* is an entomopathogenic fungus that infects and kills insect pests, and is effective in the control of a wide range of insects (Zimmermann, 2007; Cappa et al., 2024).

**Botanical compounds** These compounds have long been recognized for their potential as eco-friendly alternatives to synthetic pesticides in agricultural pest management, offering a sustainable approach to addressing these challenges (Zhang et al., 2024; Gupta et al., 2024). Diverse compounds may have effects on multiple pests caused by fungi, bacteria, and insects (Montenegro et al., 2013, 2018a, 2018b). For example, essential oils from plants such as *Cupressus sempervirens* and *Litsea cubeba* have significant insecticidal properties against pests such as *Sitophilus oryzae* and *Drosophila suzukii* (Gao et al., 2024). The essential oil extracted from *Poiretia latifolia* flowers exhibits strong antifungal activity against pathogens such as *Monilinia fructicola* and *Monilinia laxa*, which are known to cause severe damage to fruit crops (Madrid et al., 2024). These examples underscore the potential of botanical compounds to target a wide range of pests while minimizing the ecological footprint of agricultural practices.

A polygodial terpene-type drimanic compound from *Drimys winteri* shows antifungal activities against the phytopathogens *Aspergillus flavus* and *Fusarium oxysporum* (Montenegro et al., 2024). In addition, this compound blocks the chemosensory receptors in insects, showing a potential application for insect pest control (Zapata & Smagghe, 2010; Prota et al., 2014; Inocente et al., 2019; Anese et al., 2018; Paz et al., 2018; Montenegro et al., 2013; Opiyo, 2021).

Due to their low aqueous solubility and stability, diverse natural compounds have limited use in delivery systems. Nanotechnological methods may be useful to overcome these limitations for agrochemicals (Aravena et al., 2021; Manjesh et al., 2022). Plant extracts of *Psoralea* used in nanoemulsions reduce the viability of the fungus *Fusarium oxysporum* and control fusariosis in tomatoes (Aravena et al., 2021). Plant extracts of *Manilkara subsericea*, *Acorus calamus*, *Allium sativum*, *Copaifera duckei*, *Ricinus communis*, and *Nicotiana tabacum* have been used in nanoemulsions against the insects *Dysdercus peruvianus*, *Sitophilus oryzae*, *Spodoptera littoralis*, *Aedes aegypti*, and *Anopheles culicifacies* (Sharma et al., 2020; Giuliano et al., 2024). Nanoparticles based on crustacean chitin exoskeleton (chitosan) have also been used for Gram-positive and Gram-negative bacterial control (Kumar et al., 2020). Recently, active coatings based on oxidized chitin nanocrystals combined with silk fibroins have been applied for the control of *Colletotrichum gloeosporioides* in avocado (Ferreira et al., 2023).

### 15.5.2 Future Projections

Biofertilizers, BCAs, and botanical compounds are sustainable alternatives to chemical fertilizers and pesticides. These products help to reduce soil and water pollution. The growing demand for these bioproducts reflects increased concern for the environment and higher regulations on the use of synthetic chemicals. By improving soil health, promoting microbial biodiversity, and improving nutrient cycles, these bioproducts favor a more resilient agriculture. These bioproducts will be key to fulfilling the challenges of climate change and the pressure on the natural resources. This will improve global food safety, but also lead to an adaptation of regulations and public policies to ensure their safety and efficacy.

Nanotechnology in agriculture is an emerging field with the potential to revolutionize crop production through improved disease resistance, nutrient use, and crop yield and to contribute to the development of less toxic biopesticides with increased stability and enhanced activity on target pests (Bharani et al., 2014; Wang et al., 2016). The integration of Artificial Intelligence (AI) offers promising opportunities to optimize the application of these bioproducts. By analyzing variables such as temperatures, pH, and electrical conductivity, AI can enable precise and timely utilization, maximizing the effectiveness of bioproducts and paving the way for smarter, more sustainable agricultural practices. AI has been already applied to detect plant illness caused by specific pathogens in tomato plants (Vasconez et al., 2024).

The future of agriculture is intrinsically linked to the adoption of bio-based products, requiring a multi-faceted approach. Government support in the form of financial incentives, subsidies, and research funding is essential to promote the development, testing, and adoption of these products, alongside policies that encourage their use in agricultural practices. Collaboration among researchers, farmers, and industry stakeholders is crucial to incorporate bio-based products into the market, develop effective application methods, and ensure their successful integration into agricultural systems. Consumer awareness also plays a pivotal role; educating consumers about the benefits and importance of organic products is critical to driving demand and supporting the transition to a sustainable food system. This organic revolution is not merely a trend but a necessary step toward establishing a healthier, more resilient, and sustainable food system that benefits both people and the planet.

## 15.6 Bioplastics and Natural Bioproducts

Novel biomaterials and antibiotics are demanded by medicine for the treatment of diverse diseases and for tissue engineering (Undabarrena et al., 2017; Vilchez et al., 2021). Bio-based, biodegradable bioplastics may replace fossil-based plastics, wherein polyhydroxyalkanoate (PHA) is an attractive alternative for biorefining from bacterial biomass (Urtuvia et al., 2014; Álvarez-Santullano et al., 2021; Rosenboom et al., 2022). These biodegradable and biocompatible polyesters have been applied as added-value biomaterials for tissue (skin) engineering and drug delivery (Sanhueza et al., 2020; Vilchez et al., 2021; Sepúlveda et al., 2025). The increasing antimicrobial resistance (AMR) of human pathogens, coupled with emerging human and animal pathogens, which are favored by climate change and rising temperature, requires novel antibiotics (Undabarrena et al., 2016, 2017, 2021). Microorganisms and plants are key players in antibiotic synthesis and discovery.

The production and use of plastics in modern life have become essential for our daily activities. Fossil-based plastics impact the environment through gaseous contaminants, including $CO_2$, nitrogen oxides, and dioxins (Walker & Rothman, 2020). The distribution of macroplastics, microplastics and nanoplastics in natural environments may affect human health, biodiversity, ecological systems and landscapes (Ali et al., 2023; Bai et al., 2021; Kumar et al., 2023; Zhao et al., 2024).

Each year, around 415 million tons of fossil-based plastics are produced. Nearly 65% of the plastics is eventually disposed of in landfills or subjected to incineration, which represents around 86% of total plastic waste (5400 million tons), while the other 14% is recycled (Ali et al., 2023). Bio-based plastics are produced from biomass such as sugars, lignin, and vegetable oils, and other renewable raw materials. Like fossil-based plastics, they can be classified as biodegradable or non-biodegradable (Fig. 15.5) according to their capability to be biologically decomposed in the environment by microorganisms, into water, $CO_2$, $CH_4$, and biomass. The International Standardization Organization established bioplastic biodegradability with 90% of mass converted into $CO_2$ or $CH_4$ in a time span of 60–180 days in different environments and treatment systems according to ISO 14855, ISO 20200, ISO 16929, ISO 17556, ISO 16221, ISO 15985, ISO 11734, ISO 14853 (Folino et al., 2023).

### *15.6.1 Classification and Properties of Bioplastics*

Bioplastics include: 1) bio-based non-biodegradable; 2) bio-based biodegradable; 3) petrochemical-based biodegradable. They are considered particularly well-suited as part of a circular bioeconomy due to various aspects depending on their origin and biodegradability:

1. *Bio-based non-biodegradable.* These types of plastic are synthesized from renewable biological mass, reducing the use of non-renewable petrochemical resources contributing to the decarbonization of the economy. Using waste biomass as raw material reduces the environmental impact associated with landfill disposal or agricultural incineration, promoting circular schemes. Nevertheless, at the end of their lifecycle they are introduced into the right cycle (Fig. 15.5) to end up in mechanical recycling or landfill.
2. *Bio-based biodegradable.* The capability to be biodegraded reduces waste generation at the end of their lifecycle. Biodegradation allows organic recycling of carbon mass to produce raw material of photosynthetic origin or energy, to be integrated in the polymer manufacture line or associated industries (Rosenboom et al., 2022). A comprehensive waste management infrastructure that efficiently collects and processes bioplastics is essential to ensure an effective integration into a circular bioeconomic system (Khodaei et al., 2021; Kuenneth et al., 2022; Mukherjee & Koller, 2023).
3. *Petrochemical-based biodegradable.* Despite their origin, they are considered bioplastics due to their capacity to be decomposed by living organisms. Therefore, at the end of their lifecycle, the main and basic chemical compounds are restored to the environment and used as raw material in the living cycle (Fig. 15.5). Otherwise, specific petrochemical-based biodegradable plastics can be chemically recycled at the building block level through depolymerization techniques such as pyrolysis or solvolysis (Fredi & Dorigato, 2021).

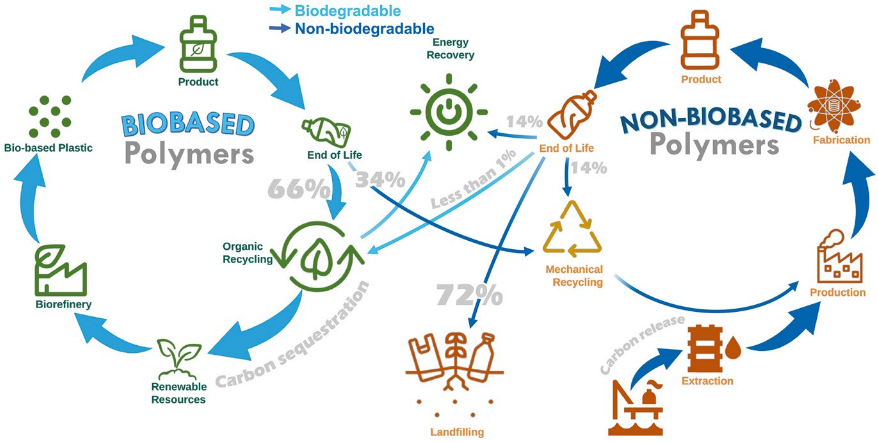

**Fig. 15.5** Bio-based and non-biobased polymers cycles and their disposal at the end of their life-cycle. The life cycle of bio-based and non-biobased polymers shows that up to 66% of bio-based polymers are recycled, whereas 72% of non-biobased polymers are disposed in landfills. Thirty four percent of bio-based polymers are channeled into non-biobased polymers, highlighting future challenges in plastic life-cycle. Arrows indicate the flow and percentage of each process. Light and dark blue arrows indicate biodegradable and non-biodegradable paths, respectively. Percentages are reported by Ali et al. (2023).

**Polymers extracted from biomass** This group includes polysaccharides and proteins; macromolecules synthesized in/by living organisms with specific energetic or structural functions. The most useful polymers used in bioplastics production and research are starch, chitosan, gelatin cellulose, lignin, and zein. Starch is a polysaccharide that is recovered from agricultural waste such as banana and potato peel (Kiran et al., 2022; Imoisili & Jen, 2023), woody sources such as oil palm trunk (Hernando et al., 2024), edible resources such as corn (Rajesh et al., 2024) or cassava (Yang et al., 2023); and microalgae (Six et al., 2024). Chitin, which is mainly produced from the exoskeletons of crustaceans such as shrimp or crab, fungi, or insects, has been used for chitosan bioplastic production that is useful for food preservation (Kiran et al., 2022; Zhao et al., 2023), and for biomedical and pharmaceutical applications (Hisham et al., 2024; Kedir et al., 2022). Gelatin is mainly obtained from collagen from connective tissue, skin, and animal bones. This biopolymer has been widely used in the production of gels, microparticles, and films for pharmaceutical and biomedical applications (Amelia et al., 2024; Hui-Zhong et al., 2023), while novel functional bioplastic applications such as edible film packaging (Ratna et al., 2023). Lignocellulose is comprised of cellulose and lignin, which may be extracted alone or in combination to obtain bioplastics for food packaging and single-use bioplastic applications (Rosenboom et al., 2022). Zein is a particular protein that represents nearly 50% of the total protein in corn and can be obtained from corn dry-milling or wet-milling, which may be used in drug delivery, food packaging, or tissue engineering (Jaski et al., 2022; Yuan et al., 2022; Lan et al., 2023).

**Polymers produced by microorganisms** Diverse microorganisms produce biopolymers as carbon and energy storage. Polyhydroxyalkanoates (PHAs) are a group of linear aliphatic polyesters with different monomeric compositions that influence the physical properties of the final bioplastic. More than 150 types of hydroxyalkanoate monomers have been described, depicting the versatility of these polymers for a wide range of applications (Rehm, 2003). Polyhydroxybutyrate (PHB) is the most abundant PHA produced by different bacteria including *Pseudomonas*, *Bacillus*, *Cupriavidus*, *Paraburkholderia,* and *Burkholderia (Sepúlveda et al., 2025)*. PHAs have been studied for their promising properties (e.g., biocompatibility, biodegradability) and have been proposed for different medical applications such as scaffold design (Sanhueza et al., 2019), wound dressing (Erci & Sariipek, 2023; Volova et al., 2019), tissue engineering (Mohammadalipour et al., 2023), and drug encapsulation (Vilchez et al., 2021). Saccharides such as levan, pullulan, and fructooligosaccharides produced by *Zymomonas, Gluconobacter,* and *Aureobasidium* species have been studied due to their biocompatibility, biodegradability, antioxidant and antimicrobial properties, which are useful for applications in the pharmaceutical, cosmetical, and food industries (Mulla et al., 2023; Singh et al., 2023b; Teixeira et al., 2023).

However, their production volume and mechanical properties are still not comparable either to conventional polymers or to polymers extracted from biomass, and therefore, they are commonly studied when blended with starch, PLA, PVA, or

PCL, which may enhance their availability, mechanical and physicochemical properties, and biodegradability (Fernandes et al., 2024).

**Non-biobased polymers** Biodegradable non-biobased polymers can mobilize carbon released to the surface as fossil-based polymers into the carbon cycle through mineralization, contributing to the left cycle (Fig. 15.4). Polyvinyl alcohol (PVA) is a synthetic and water-soluble polymer, whose industrial uses include textile, paper, adhesive, 3D printers, and biomedical applications and can be degraded by some mixed cultures of *Pseudomonas*, *Alcaligenes,* and *Sphingomonas* (Chiellini et al., 2003; Kawai & Hu, 2009). In addition, PVA is commonly blended with starch, polyvinylpyrrolidone (PVP), pectin, alginate, and dextran, to enhance the mechanical properties of films, nanofibers, gels, and other biodegradable materials (Cano et al., 2016; Huang et al., 2019; Suhasini et al., 2023; Phulmogare et al., 2024; Sam et al., 2021). Additionally, polycaprolactone (PCL) is a hydrophobic, blend-compatible, and biocompatible polyester obtained from caprolactone polymerization with potential use in biomedicine and packaging materials. Nanofiber mats can be prepared using PHB/PCL for loading biocompounds and may be used as wound dressing (Erci & Sariipek, 2023). Moreover, PCL has been used to develop microneedles for drug release (Oliveira Filho et al., 2024) and has been tested as a smart packaging material in the form of nanofibers for monitoring the deterioration of food (Oliveira Filho et al., 2024). Finally, poly(butylene adipate-co-terephthalate) (PBAT) is a thermoplastic polyester, whose mechanical properties are comparable to low-density polyethylene. Some applications in biomedical, food, and agricultural fields have been reported. PBAT films are flexible and useful as pouches, mulch films, or garbage bags (Roy et al., 2024). As packaging material, PBAT can be loaded with essential oils for the preservation of foods (Pattaraudomchok et al., 2024) and shows a faster degradation rate when it is blended with another biodegradable polymer such as polyglycolic acid (Fu et al., 2024).

### *15.6.2 Economic Challenges and Opportunities*

The cost of producing bioplastics increases from 4 to 15 times the cost of producing conventional plastics, which is one of the major reasons why these biopolymers are not competitive with petrochemical plastics (Kosseva & Rusbandi, 2018). This economic difference is mainly due to fermentation, extraction, and purification that are less cost-effective. Nevertheless, this reality may change due to advances in research and technology, along with the instability of petroleum prices. Besides, the use of agro-industrial wastes as raw material for bioplastics production has been studied for both, to diminish the costs of bio-based polymers production (Talan et al., 2020) and to diminish the cultivation land needed to produce the raw materials. Different economic/social effects have been studied in the projected future where bioplastics may substitute current conventional plastics to different extents (Jin et al., 2023). Bioplastic production decreases greenhouse gas (GHG) emissions and the depletion of natural resources if renewable raw materials, adequate labeling, disposal, and closed degradation systems are employed (Walker & Rothman, 2020; Ali et al., 2023). Also, the bioplastic industry may increase land use and job gains, depending on the local and regional economy and its capability to establish a bioplastic industry. However, the implementation of a bioplastic industry depends on the capability to develop infrastructure for establishing a local bioplastic production. The bioplastics industry may contribute to job creation by generating employment opportunities in sectors such as biotechnology, recycling, biorefinery, and agriculture. However, vulnerable stakeholders require recognition and protection to promote a sustainable circular bioeconomy (Blum et al., 2020). For example, financial, technical, and scientific support can be extended through public policy to stakeholders with strategic activities for regional or local economy (e.g., feedstock producers) that can contribute to the bioplastic circular bioeconomy. A systemic approach that addresses technical, economic, environmental, and social sectors through key drivers is essential to develop a framework that enhances bioplastic circular bioeconomy development and sustainability (Parveen et al., 2024).

Furthermore, the energy needed to produce bioplastics is lower than that of petrochemical-based polymers. For example, the total life cycle of low-density polyethylene (LDPE) requires 81.8 MJ $kg^{-1}$, polypropylene needs nearly 86 MJ $kg^{-1}$, while PLA or PHB requires 54.1 and 44.7 MJ $kg^{-1}$, respectively (Costa et al., 2023). This significant difference also has a positive financial and environmental impact.

### *15.6.3 Industrial Biotechnology of Bioplastics and Added-Value Compounds*

Next-generation industrial biotechnology to produce bioplastics and other added-value compounds encourages the usage of biological polymerization, low-cost feedstocks, low freshwater consumption, and contamination-resistant processes to reduce economic and energetic costs (Fig. 15.5) (Rosenboom et al., 2022). This challenge has been addressed with microorganisms resistant to high salinity or capable of metabolizing diverse substrates including non-conventional low-cost substrates (Yu et al., 2019). Halophilic bacteria of the genus *Halomonas* have been used to produce PHA in unsterile seawater-based systems (Tan et al., 2011; Ling et al., 2019). Production of PHAs, ectoine, levan, or pyruvate by *Halomonas* under a salinity of 10–13.7% w $v^{-1}$ of NaCl has been reported; these conditions are useful to prevent contamination (Erkorkmaz et al., 2018; Ma et al., 2020; Ye & Chen, 2021; Dubey & Mishra, 2022). The acidophile *Acidiphilum cryptum* was grown at pH 3.0 to produce PHB and exopolysaccharides from glycerol (González et al., 2023). Xenobiotic-degrading bacteria have been applied to produce PHA homo- and co-polymers from C8–C12 alkanes, benzene, toluene, and phenylacetic acid (Crisafi et al., 2022).

**Low-cost substrates** Microbes catabolize a wide range of substrates to synthetise a variety of polymers and added-value compounds. The use of strategic low-cost substrates obtained from local industry minimizes economic and environmental impacts associated with raw material transport and processing (Fig. 15.5) (Rosenboom et al., 2022). Grape pomace is a waste/by-product stream from the winery industry, accounting for 20–30% of grape mass, whose high content of sugars impacts ecosystems if not adequately treated (International Organization of Vine and Wine (OIV), 2019). PHB and cellulose have been produced from grape pomace as a substrate by *Bacillus subtilis*, *Cupriavidus necator,* and *Halomonas*, respectively, generating co-products such as oils and polyphenols useful for medical and pharmaceutical applications (Kovalcik et al., 2020; Kurt & Cekmecelioglu, 2023). Lignocellulosic biomass is obtained as surplus streams of different industries and is constituted by cellulose, hemicellulose, and up to 35% of lignin, which is highly recalcitrant (Govil et al., 2020). Lignocellulosic biomass has been used to produce poly(butylene adipate-*co*-terephthalate) and poly(butylene succinate) building blocks (Sohn et al., 2022). On the other hand, *Paraburkholderia or Pseudomonas* strains produce PHAs from sugars and aromatic compounds derived from lignocellulosic hydrolysates (Al-Battashi et al., 2022; Salvachúa et al., 2020). Lignocellulosic biomass from agro-industrial hydrolysate wastes/by-products as paddy straw, wheat straw, corn cob, and wood represents high potential to produce bioplastics (Naitam et al., 2022). The usage of raw materials of photosynthetic origin allows bioplastic production in a closed carbon cycle (Mukherjee & Koller, 2023). Countries with agricultural or forestry activity are suitable to establish this scheme, with bioplastic applications in crop fields and production lines, reducing economic and environmental impact in feedstock and transport (Rosenboom et al., 2022). Similarly, synthesis of starch, PHAs, and added-value compounds by microalgae with wastewater as low-cost substrate decreases GHG emissions up to 50% compared to the fossil counterpart (Kuppan et al., 2023).

Glycerol is obtained from the waste/by-products stream of biodiesel production and is a carbon and energy source to produce PHAs or a plasticizer for cellulose and starch (Zhu et al., 2013). Fish-canning wastewater with high salinity has been used to produce PHAs in non-sterile systems, reducing approximately 25% of environmental impact related to the treatment of this stream (Roibás-Rozas et al., 2020; Palmeiro-Sánchez et al., 2021). The synthesis of PHAs from diverse low-cost substrates as waste frying oil, sugarcane molasses, cheese whey, and coffee waste has been reported (Marciniak & Mozejko-Ciesielska, 2021). Bacterial diversity is a useful source of catalysts to address challenges of raw materials to establish an industrial biotechnology tuned with local and regional circular bioeconomy (Możejko-Ciesielska et al., 2023).

Microorganisms possess the anabolic potential to synthesize added-value compounds as antioxidants, antimicrobials, or antitumoral drugs. The recovery of these compounds from waste streams or microbial biomass with a biorefinery approach adds value to the down-stream processes, promoting circular bioeconomy schemes (Fig. 15.6) (Kumar & Verma, 2021). The establishment of biorefineries can increase

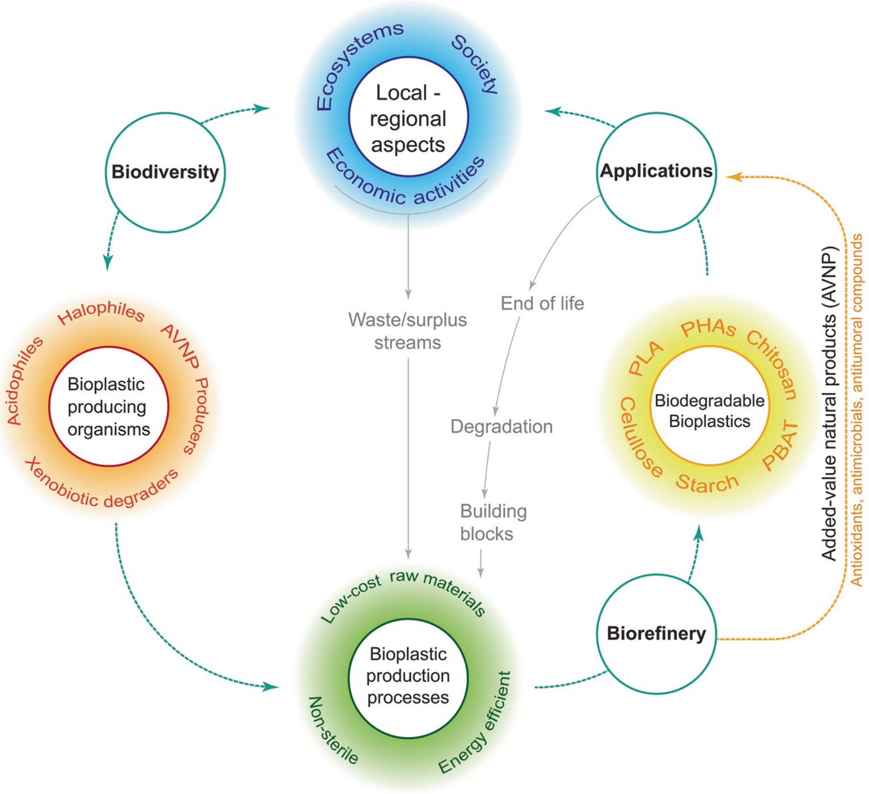

**Fig. 15.6** Bioplastic production in a circular bioeconomy scenario. Local-regional aspects: society develops in a local-regional economy placed in ecosystems that harbor specific biodiversity. Polymer producing organisms: specific biodiversity harbors organisms of biotechnological interest with useful features for sustainable bioplastic production. Bioplastic production processes: organisms of biotechnological interest possess metabolic and physiological capability for establishing low-cost bioplastic production by using non-sterile systems or waste/surplus streams from local-regional economy as feedstocks to produce bioplastics and added-value natural products (AVNP). Biodegradable bioplastics: biological biodiversity offers a wide range of bioplastic, while AVNP may be obtained in a biorefinery scheme, increasing value-chain of bioplastic production. Biorefinery of bioplastics and AVNP represent a synergy that may be enhanced by combining bioplastic with AVNP that possess antioxidant or antimicrobial activities, broadening bioplastic applications according to local-regional requirements.

up to 2% of employment; however, countries with GDP per capita below €27,231 are less benefited due to the lack of infrastructure (Zhu et al., 2024). Antimicrobial and antioxidant compounds as curcumin, caffeic acid and pigments have been used in combination with different bioplastics for applications in tissue engineering as wound dressing, bone implants, or in personal protection elements (Ignatova et al., 2018; Vilchez et al., 2021; Lee et al., 2022). Microorganisms from different ecosystems (e.g., marine water and sediments, marine organisms) are a promising source of novel added-value products such as antibiotics or enzymes (González et al., 2020; Cumsille et al., 2023).

## 15.7 Concluding Remarks

Biotechnology meets the challenges of circular bioeconomy development by transforming waste into valuable resources through sustainable processes, reducing environmental impact, and promoting more efficient uses of natural resources.

Innovating in the improvement of bioremediation strategies through the valorization of local waste provides significant advantages, both for the bioremediation processes, by promoting the survival of microorganisms with metabolic capabilities for contaminant removal, and for the circular bioeconomy, contributing to the closure of the life cycle of products of commercial interest. Due to the growing number of contaminated sites worldwide, as well as the physicochemical nature of each polluted site, bioremediation faces the constant challenge of designing site-specific strategies that adapt to specific contaminants and environmental conditions. Otherwise, agriculture faces complex and multi-dimensional challenges that have been addressed through the development of bioproducts that gather the features to improve the sustainability of food safety. The bioproducts, biofertilizers, microbial biocontrol agents, and botanical compounds are essential to achieve a sustainable and resilient agriculture. Bio-based biodegradable bioplastics are suitable for the design of sustainable products whose lifecycle can be integrated into socioecological systems, although their mechanical or physical properties and production costs are still not comparable to the fossil-based counterpart. Microbial diversity provides alternatives for the biorefinery of bioplastics and natural bioproducts from biomass and wastes/by-products, which may be integrated into a local and regional circular bioeconomy, contributing to additional jobs and the sustainability of ecosystems.

Government support and collaborative research by investigators, farmers, and industrial stakeholders are critical to the effective development and application of bioproducts. Emerging research topics, responsible science-based approaches, collaborative efforts, investment in technologies, and balanced regulation in green policies will be crucial for the development of biotechnology that promotes a circular bioeconomy.

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