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Review

Toward a Resilient Future: The Promise of Microbial Bioeconomy

Adenike Akinsemolu [1], Helen Onyeaka [2,*], Omololu Fagunwa [3] and Adewale Henry Adenuga [4]

1 Institute of Advanced Studies, University of Birmingham, Birmingham B15 2TT, UK
2 School of Chemical Engineering, University of Birmingham, Birmingham B15 2TT, UK
3 School of Pharmacy, Queen's University Belfast, 97 Lisburn Road, Belfast BT9 7BL, UK
4 Economics Research Branch, Agri-Food and Biosciences Institute AFBI Headquarters, 18a Newforge Lane, Belfast BT9 5PX, UK
* Correspondence: h.onyeaka@bham.ac.uk

Abstract: Naturally occurring resources, such as water, energy, minerals, and rare earth elements, are limited in availability, yet they are essential components for the survival and development of all life. The pressure on these finite resources is anthropogenic, arising from misuse, overuse, and overdependence, which causes a loss of biodiversity and climate change and poses great challenges to sustainable development. The focal points and principles of the bioeconomy border around ensuring the constant availability of these natural resources for both present and future generations. The rapid growth of the microbial bioeconomy is promising for the purpose of fostering a resilient and sustainable future. This highlights the economic opportunity of using microbial-based resources to substitute fossil fuels in novel products, processes, and services. The subsequent discussion delves into the essential principles required for implementing the microbial bioeconomy. There is a further exploration into the latest developments and innovations in this sub-field. The multi-sectoral applications include use in bio-based food and feed products, energy recovery, waste management, recycling, and cascading. In multi-output production chains, enhanced microbes can simultaneously produce multiple valuable and sustainable products. The review also examines the barriers and facilitators of bio-based approaches for a sustainable economy. Despite limited resources, microbial-based strategies demonstrate human ingenuity for sustaining the planet and economy. This review highlights the existing research and knowledge and paves the way for a further exploration of advancements in microbial knowledge and its potential applications in manufacturing, energy production, reduction in waste, hastened degradation of waste, and environmental conservation.

Keywords: sustainability; microorganisms; energy; biotechnology; biocatalysis; biotransformation; industrial applications; circular bioeconomy

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1. Introduction

Human survival and development depend on natural resources, such as water, energy, and raw materials, which are unsteadily available. As human development increases and the global population rises, based on predictions, from 7.6 to 9.7 billion by 2050 and further to 11.2 billion by 2100 [1] the demand for available resources is increasing, making sustainability one of the major challenges with which the world's population is contending [2] The need for optimal utilisation of available scarce resources in a sustainable manner that guarantees their use for future generations can, therefore, not be overemphasised [3]. The sustainable use of available resources secures a continuous food supply, renewable energy, and a continuous raw materials supply, achieving zero hunger and other sustainable development goals [4,5] Guaranteeing the continuous availability of these resources for present and future needs is the core principle of bioeconomy [6].

The term "bioeconomy" was first coined by Zeman in the 1960s and is derived from the Greek words "bios", "oikos", and "nomos", which mean life, house, and law, respectively. The German Federal Government Bioeconomy Council also defines bioeconomy as the utilisation and production of biological resources (with knowledge inclusive) to provide services, processes, and products across all industry sectors and trade in a sustainable economy [7].

In the bioeconomy, resources are either sourced through nature or recycled after human usage. Besides land, water, air, biomass, technologies, and knowledge, microorganisms are also a crucial resource in the bioeconomy. Microorganisms are genetically altered to render them suitable for bioproduction processes [8] and serve as biocatalytic platforms for the microbial bioeconomy. The microbial bioeconomy involves utilising microorganisms to create sustainable and biodegradable products, replace non-renewable resources, and reduce environmental pollution. This concept aligns with the circular bioeconomy, which prioritises minimising waste and maximising resource efficiency [9].

The utilisation of microorganisms in the production of goods and services dates back to ancient civilisations with examples such as the Egyptians using yeast to bake leavened bread [10]. Recent developments in the microbial bioeconomy have focused on developing new and enhanced microorganisms as well as optimising production processes [11] For example, metabolic engineering and synthetic biology have allowed for the development of microorganisms with enhanced capabilities, such as the ability to produce biofuels from non-edible feedstock [12]. Additionally, advanced fermentation technologies have enabled the creation of high-value products, such as biodegradable plastics and specialty chemicals [13]. The microbial bioeconomy can promote economic sustainability and reduce the environmental impact of production processes [14]. By replacing non-renewable resources with renewable alternatives and using waste streams as feedstocks, the microbial bioeconomy can help reduce greenhouse gas emissions and other forms of pollution. For instance, using rice hull ash instead of cement in making concrete mix reduces carbon emissions [15]. Similarly, leveraging microorganisms can improve production process efficiency, save costs, and increase competitiveness [7].

By using microorganisms to produce biodegradable and sustainable products, the microbial bioeconomy offers a viable alternative to traditional production methods, which are based on the global economy principles. With continued advances and innovations, the microbial bioeconomy will likely become an increasingly important part of the global economy [7]. Genetically modified organisms (GMOs) are vital for a sustainable bioeconomy; they are employed in the creation of food and feed additives, pharmaceuticals, biomedicine, bioenergy, biofuels, bioplastics, environmental remediation and waste management, building and transportation system, forestry and agriculture, and other recyclable bio-based materials and products [7,16–21]. Wesseler et al. 2022. Some of these microorganisms and the products formed are shown in Table 1.

Table 1. Examples of microorganisms and the biodegradable and sustainable products they can produce.

Microorganism Type	Microorganism	Biodegradable and Sustainable Products	Industry/ Application	Role in Achieving Sustainability	References
Bacteria	*Escherichia coli*	Bioplastics	Packaging	Reduces reliance on fossil-fuel-based plastics, reduces waste	[22]
	Bacillus subtilis	Enzymes	Cleaning and detergent	Reduces environmental impact of cleaning products, promotes sustainable practices	[23]
	Saccharomyces cerevisiae	Bioethanol	Fuel	Provides sustainable alternative to fossil fuels	[24]
	Pseudomonas putida	Biodegradable polymers	Biodegradable materials	Reduces reliance on non-biodegradable materials, reduces waste	[25]

Table 1. *Cont.*

Microorganism Type	Microorganism	Biodegradable and Sustainable Products	Industry/ Application	Role in Achieving Sustainability	References
Fungi	*Candida albicans*	Biosurfactants	Cosmetics and personal care	Provides sustainable alternative to conventional surfactants	[26]
	Lactobacillus acidophilus	Probiotics	Food and beverage	Promotes sustainable agriculture practices, reduces food waste	[27]
	Trichoderma reesei	Cellulases	Paper and pulp	Promotes sustainable forestry practices, reduces waste	[28,29]
	Aspergillus niger	Organic acids	Food and beverage	Provides sustainable alternative to conventional food additives	[30]
	Rhizopus oryzae	Biodegradable plastics	Packaging	Reduces reliance on non-biodegradable materials, reduces waste	[31]

2. Methodology

This review discusses the microbial bioeconomy principles, current state, and recent advances and innovations. A systematic review was conducted to examine the applications of the microbial bioeconomy in various sectors, including food and beverage production, biotechnology, and environmental remediation. The review explores how microorganisms can help achieve economic sustainability and discusses some of the future trends in this field.

A keyword search of existing research, knowledge, and reports was performed using the keywords "microbial bioeconomy," "sustainability", "microorganisms", and "principles". The results were filtered for relevance, the author's authority, and timeliness and synthesised.

3. Applications of the Microbial Bioeconomy for Economic, Environmental, and Social Sustainability

3.1. Principles of the Microbial Bioeconomy

To achieve a sustainable and efficient microbial bioeconomy, adherence to certain guiding principles is crucial. Adhering to these principles can help create an environmentally friendly, economically sustainable, and socially responsible microbial economy.

Seven (7) Key Principles Central to the Microbial Bioeconomy

1. Use of renewable resources: The microbial bioeconomy relies on renewable resource utilisation, such as plant biomass, organic materials, and agricultural waste, as feedstocks for the production of products of high value. This approach helps to not only reduce reliance on non-renewable resources, such as fossil fuels, but also create a more sustainable and efficient economy [32]
2. Sustainable production: The microbial bioeconomy produces products and services that are environmentally friendly and sustainable. This involves using renewable resources, converting waste materials into valuable products, and optimising production processes to minimise waste and reduce greenhouse gas emissions [33].
3. Efficient utilisation of resources: The microbial bioeconomy seeks to use resources efficiently to minimise waste and reduce the environmental impact of production. This involves closed-loop systems where waste from one process is used as a resource [5].
4. Adaptability: The microbial bioeconomy technologies should be adaptable to different environments and conditions and should be able to be easily modified or scaled up as needed [34].
5. Innovation: The microbial bioeconomy should be driven by the development of new technologies and approaches along with a focus on innovation [35].

6. Collaboration: The development and implementation of the microbial bioeconomy technologies often require collaboration between researchers, industry, and government [36].
7. Transparency: The microbial bioeconomy should be transparent and open with information about processes and products and make this information readily available to stakeholders [33].

The seven principles are shown graphically in Figure 1.

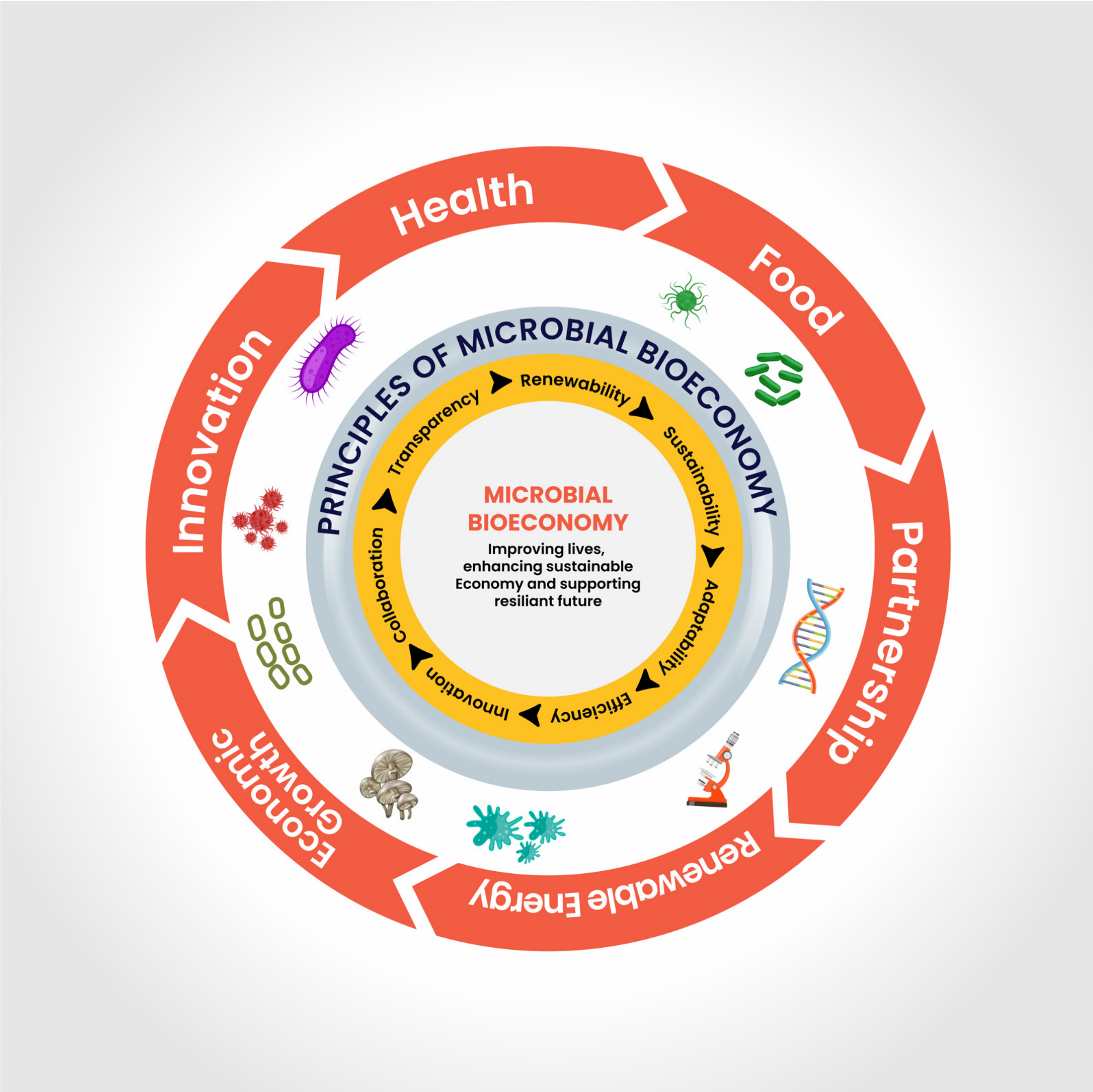

Figure 1. Principles of the Microbial Bioeconomy.

3.2. The Microbial Bioeconomy Current State

Based on a report by the [37] the global microbial market is worth €250 billion, with an annual growth of 5.6%. By 2030, it is predicted to reach €700 billion due to the rising demand for sustainable products, biotechnology advancements, and supportive policies. The European Union (EU) bioeconomy generated €2.29 trillion turnover in 2015 [38] However, the COVID-19 pandemic caused a 2% decrease in 2019 and a 0.4% decrease in 2020 in employment and gross value addition [38].

One of the key trends in the microbial bioeconomy is the growing demand for renewable and sustainable products and services driven by a growing awareness of the social and environmental impacts of non-renewable resources such as fossil fuels. Additionally, an improved public understanding of climate change and the devastations caused by non-renewable products have changed consumer preferences and resulted in more robust regulatory policies [37]. This trend creates new products and processes that rely on microorganisms, such as biofuels, biomaterials, and bioplastics [7].

Another significant trend is the increasing focus on waste management and resource recovery. Microorganisms are expected to play a critical role in this area by using anaerobic digestion and other processes to convert waste into valuable products, such as biogas, fertilisers, and biochemicals [39].

The microbial bioeconomy contributes to economic sustainability through biocatalysis, biotransformations, anaerobic digestion, and bioremediation processes. Biocatalysis has advantages over traditional chemical processes due to its improved selectivity and specificity [40,41]. Similarly, biotransformation is used in industries, such as fine chemicals, pharmaceuticals, food, and animal feed, to produce vitamins, flavour compounds, biofuels, and other biomaterials [40,42]. Utilisation of these bio-based processes can offer several advantages over traditional chemical processes, such as improved sustainability and lower production costs. For example, this biologically dependent process can use renewable resources, such as waste materials and biomass, as substrates either by decreasing or eliminating the use of chemicals and their environmental impacts. This can also lead to economic benefits, such as reducing raw material costs and developing new markets and products [43]. Anaerobic digestion and bioremediation processes can convert waste materials and pollutants into valuable products, such as biogas, fertilisers, and biochemicals, which can be used to produce other goods and services [44].

3.3. Recent Advances and Innovations in the Microbial Bioeconomy

Recent advances in biotechnology have led to significant progress, particularly in the development and application of microorganisms for producing goods and services. Advances in metabolic engineering and synthetic biology have made significant progress in creating new microbial strains with improved productivity and efficiency. The *Penicillium chrysogenum* X-1612 strain was genetically modified using X-ray mutagenesis for enhanced genetic expression [45] (These advances have also paved the way for developing sustainable products and processes, including the production of biofuels from waste materials and using microorganisms to remove pollutants from water and air [46,47].

In addition to technical advances, there have also been significant innovations in commercialising microbial products and services. For example, the rise of biotechnology start-ups and the increasing availability of venture capital have facilitated the development and growth of the microbial bioeconomy with greater availability in some countries than others. The most common way through which start-ups are commercialising microbial products and services is the repurposing of biomass from agricultural products, consultancy, and training [48].

3.4. Applications of the Microbial Bioeconomy in Various Sectors

The microbial bioeconomy is a fast-growing field with various commercial and industrial applications, bio-based product production, food and feed, energy recovery and composting, waste management, recycling, and cascading, as well as multi-output production chains [48].

3.4.1. Bio-Based Products, Food, and Feed

The use of microorganisms in producing bio-based products, including food and animal feed, has been widely acknowledged for a long time. One key advantage of using microorganisms to produce bio-based products is their capacity to utilise a variety of feedstocks. For instance, microorganisms, such as yeast and bacteria, can convert plant-based feedstocks, such as corn and wheat, into valuable products, such as lactic acid and ethanol [49] This renders the use of microorganisms a more cost-effective and efficient option to produce biofuels [50] Additionally, they can produce a variety of food products, such as fermented foods including yogurt, which is made using *Lactobacillus delbrueckii subsp. Bulgaricus* and *Streptococcus thermophilus* [51].

Similarly, *Salmonella typhimurium*, and *Bacillus subtilis* and *Escherichia coli* are well-studied to produce vitamins [52]. Microorganisms can be used for the production of high-quality proteins as animal feed, such as single-cell proteins (SCP) that include *Rhodopseudomonas faecalis* PA2 [53]. This can help reduce the reliance on limited and potentially environmentally damaging protein sources, such as fishmeal and soymeal, yielding better protein sources while promoting sustainability and environmental conservation.

3.4.2. Energy Recovery

Microorganisms are also used for energy recovery and composting by converting organic waste into a valuable soil amendment that improves its physical properties, such as drainage, water retention, structure, permeability, aeration, and water infiltration. There has been a growing interest recently in composting to recover energy from organic waste while promoting economic sustainability [54]. One of the main benefits of composting is that it decreases the quantity of waste sent to landfills, where organic waste decomposes anaerobically and produces methane, a potent greenhouse gas. In contrast, when organic waste is composted, it decomposes in the presence of oxygen and produces carbon dioxide, a less harmful greenhouse gas. By promoting anaerobic decomposition, certain microorganisms can convert food waste into biogas, providing a renewable energy source while promoting the sustainability of waste disposal processes by reducing the production of methane [55].

3.4.3. Waste Management, Recycling, and Cascading

Human activities have led to the proliferation of landfills and incineration facilities, which can be environmentally damaging and costly to maintain. Microorganisms can convert organic waste, such as food and agricultural wastes, into biofuels and biochemicals [46]. This reduces the amount of refuse that is sent to landfills and generates revenue from selling these products.

Another important component of the microbial bioeconomy in relation to waste management is composting; it involves the breakdown of organic matter in waste, converting them to compost. A diverse community of microorganisms, including bacteria, fungi, and protozoa, conducts the composting [11,56].

Composting provides economic benefits by reducing the cost of waste disposal and providing an alternative to landfill disposal [56]. It can also generate revenue through selling high-demand compost among farmers and gardeners, supporting local agriculture and food production for economic sustainability [57].

Several vital microorganisms play essential roles in composting; they include bacteria in the genera *Clostridium*, *Bacillus*, and *Pseudomonas*, and fungi from *the Aspergillus*, *Penicillium*, and *Trichoderma* genera [52].

Additionally, the microbial bioeconomy can be utilised in a cascading approach, where waste from one process is used as feedstock for another, allowing resources to be used efficiently and multiple valuable products to be produced from a single waste stream, which is a central principle of the circular economy approach [58]. For instance, *Saccharomyces cerevisiae* can convert waste wood into bioethanol [47] which can then be used as a feedstock for bioplastic production [59].

3.4.4. Integrated and Multi-Output Production Chains

The microbial bioeconomy can also support integrated and multi-output production chains, leading to cost-effective and efficient production. This method utilises microorganisms to simultaneously produce multiple products from a single feedstock. Studies have shown how effective this method is in producing biofuels and chemicals from a single microbial strain [60–63] and in producing biofuels, animal feed, and bioplastics using microalgae [64,65]. Such integrated production can increase the industrial process efficiency and sustainability. The discovery of CRISPR/Cas9 and other genetic engineering techniques has enabled the precise modification of various strains to produce targeted products. This flexibility has facilitated rapid and efficient responses to changes in market demand [66].

3.5. Role of the Microbial Bioeconomy in Achieving Sustainability in the Economy and Environment

The microbial bioeconomy plays a significant role in achieving both economic and environmental sustainability by using renewable resources and reducing waste and pollution. By using biomass and biological knowledge to provide food, feed, industrial products, bioenergy, and ecological services, the microbial bioeconomy aligns with several sustainable development goals, such as affordable and clean energy (Goal 7), sustainable cities and communities (Goal 11), and responsible consumption and production (Goal 12) [18,67,68]. By creating a balance between sustainability and economic aspirations, the microbial bioeconomy can help address global challenges, such as climate change mitigation, global food security, and sustainable resource management, leading to a more resilient and sustainable economy that benefits both people and the planet [69,70]. It creates a more resilient and sustainable economy that benefits both people and the planet by utilising the unique capabilities of microorganisms [18]. The contribution of the microbial bioeconomy to sustainable economic development may vary depending on the resources available in different regions and countries. However, the following sections outline potential ways that the microbial bioeconomy can support the achievement of the Sustainable Development Goals (SDGs).

3.5.1. Job Creation and Rural Development

The microbial-based bioeconomy can create jobs, drive economic growth, and contribute to achieving the Sustainable Development Goals of the United Nations, particularly No Poverty (SDG 1), Zero hunger (SDG 2), and Decent Work and Economic Growth (SDG 8) [71,72]. As biomass is widely available, the microbial bioeconomy can create modern jobs (biotechnologists and bioeconomists) in rural areas and promote social inclusion [69,73,74], For instance, in 2019, approximately 17.4 million people in the EU were working in the bioeconomy sectors, which was 8.3% of its total labour force. Bio-based employment can be generated from advances in the microbial bioeconomy as described in the following practical examples. *Spirulina,* a kind of blue-green algae, is an excellent source of protein and other nutrients, making it a potentially sustainable and nutritious food source. *Spirulina* cultivation can create jobs in the aquaculture and agriculture industries, as well as in the processing and packaging of spirulina-based products [72]. *Spirulina platensis* is also being explored for its potential use in animal feed production. Because of its high protein content, *spirulina* is used in animal feed, which can create jobs in the animal husbandry and feed manufacturing industries. Using microorganisms in waste treatment, biopesticide production, and bioremediation products can create jobs in the environmental industry and in research and development, engineering, and operations. Additionally, biopesticides made from microorganisms can help control agricultural pests and reduce the reliance on chemical pesticides, which have adverse effects on human health and the environment [75,76]. This can create jobs in the agricultural and biotechnology industries.

3.5.2. Climate Change Mitigation and Neutrality

Microorganisms play a vital role in mitigating and achieving climate neutrality, as they are used in various industrial processes that can help reduce greenhouse gas emissions and promote environmental sustainability. Using biological resources for food, feed, bio-based products, and bioenergy can align with the United Nations' Sustainable Development Goals (SDGs), such as Affordable and Clean Energy (SDG 7); Industry, Innovation, and Infrastructure (SDG 9); and Responsible Consumption and Production (SDG 12) [7]. Microorganisms, such as yeast and algae, can produce biofuels, such as ethanol and biodiesel, as alternatives for fossil fuels. The production of biofuels using microorganisms can reduce lifecycle greenhouse gas emissions, as biofuels have a lower net GHG emission compared to fossil fuels [77]. Additionally, microorganisms produce bioplastics from renewable materials, such as corn starch or sugarcane. Bioplastics reduce our dependence on fossil-based plastics, which emit greenhouse gases. They can be biodegraded by microorganisms, reducing plastic waste in the environment. The microbial bioeconomy can help create greener cities that operate on closed material and energy cycles, thereby, reducing emissions, waste, and losses [69]. For instance, in Hamburg, Germany, the world's first building with an algae façade made of glass bioreactors produces heat and biomass, and binds CO_2 through the green algae's photosynthesis. Model calculations suggest that the façade can convert approximately 48% of the incoming sunlight into usable bioenergy [69].

3.5.3. Ecosystem and Biodiversity Restoration

Microbes play a crucial role in ecosystem and biodiversity restoration in several ways. For example, certain bacteria can break down pollutants and waste products, making them less harmful to the environment [78]. This process, known as bioremediation, can help clean up contaminated soil and water, making it safer for plants, animals, and humans. One example of a bacterium that can be used in bioremediation is *Pseudomonas cepacia*. This bacterium secretes a bio-surfactant that cleans up hydrocarbon contamination [79]. Microorganisms, such as bacteria and fungi, can degrade organic waste and pollutants, aiding in wastewater treatment and soil remediation. Specific examples of microorganisms that are used in the bioremediation of crude oil include *Pseudomonas cepacian* [79,80]. *Bacillus cereus* [81], *Aspergillus oryzae* [82], *Bacillus coagulans* [80], *Citrobacter koseri* [80] *and Serratia ficariam* [83]. These microorganisms can degrade pollutant hydrocarbons, heavy metals, and pesticides and are also used in the bioremediation of dyes in textile industry wastewater. Specific examples of microorganisms effective in dye bioremediation include *Exiguobacterium indicum* [84] (*Exiguobacterium aurantiacums* [85] *Bacillus cereus* [86] *and Acinetobacter baumanii* [87].

Penicillium, which is known for breaking down cellulose, a major component of plant cell walls [88] can help release nutrients into the soil, making them more available to plants. Additionally, *Penicillium* can produce antibiotics that can kill or inhibit the growth of other microbes, which can help control soil-borne diseases. Other fungi involved in this process include *Trichoderma*, *Rhizopus*, and *Fusarium*.

Trichoderma is a diverse genus of fungi. Some can break down varieties of organic compounds, including lignin, cellulose, and hemicellulose [89]. This renders it an effective tool for improving soil health and supporting the growth of plants. *Rhizopus* is another fungus in which most group members can help decompose organic matter and release nutrients into the soil, and it is known for its ability to break down starch and other complex sugars. One of the most well-known is *Rhizopus stolonifer* (the common bread mould), making it an essential contributor to the soil nutrient cycle [90].

Furthermore, bacteria, such as *Microcystis aeruginosa*, for example, are responsible for converting carbon dioxide into organic compounds, which can be used as a source of energy by other organisms [91]. By participating in this process, microbes help maintain the balance of carbon in the atmosphere, which is essential for the planet's health. By cleaning up pollutants and improving soil health, microbes can help support crops and other vegetation growth, providing food and other resources.

3.6. Barriers to the Development of the Microbial Bioeconomy

Several limitations must be considered when using microorganisms in the bioeconomy [92]. One of the main limitations is the complexity of the microorganisms themselves. The genetic makeup of microorganisms can vary significantly, even within the same species, making it challenging to standardise the production process. Major advances are required, including genome sequencing and the creation of systems that can facilitate multitrophic and multi-layered production of microorganisms [93]. In addition, the process of genetically modifying microorganisms, an important component of the microbial bioeconomy, is complex and expensive, making it difficult to scale up production for commercial viability [93]. The use of these organisms raises ethical and safety concerns as they could escape into the environment and potentially cause harm to other organisms and could also spread to wild populations. Addressing these limitations is important for the successful implementation of the microbial bioeconomy.

To ensure sustainable production and prevent environmental harm, the microbial bioeconomy must consider resource availability and feedstocks. It involves developing microbial-based products and services while addressing bottlenecks through scientific policy and economic approaches. Policy recommendations include increasing research investments, incentivising microbial-based products, and facilitating public–private partnerships. Multi-disciplinary research from microbiologists, chemists, economists, and farmers is necessary, as in the case of biogas production, to evaluate the innovations' scientific and societal impacts. Clear communication and close engagement with society are also crucial [94].

Another barrier lies in combining biodiversity with synthetic biotechnology for industrial-scale CO_2 capture. The CO_2 emission from fossil fuels and increased global warming are major challenges that will have significant and lasting implications for future generations. The first indicators of artificial climate change are the rising frequency of droughts, wildfires, heat waves in southern nations, excessive rainfall, and flooding [95,96].

Microbial genomes hold valuable instructions for developing long-term CO_2 collection methods. There are seven distinct pathways involved in CO_2 fixation with the pathway used by cyanobacteria, green plants, algae, and related microbes being the most familiar. Additionally, the Wood–Ljungdahl pathway, an ancient evolutionary route, is well-preserved in acetogenic bacteria and methanogenic archaea that are commonly found in harsh environments [97,98].

The reverse tricarbonyl acid cycle, the 3-hydroxypropionate bicycle, the 3-hydroxypropionate/4-hydroxybutyrate cycle, the dicarboxylate/4-hydroxybutyrate cycle (DC/HB cycle), and a few more highly effective methods to fix CO_2 from the environment have also been developed by nature [99]. Thus, there can be an improvement in the methods for designing the artificial creatures and procedures required for industrial CO_2 capture by better understanding the molecular and structural principles [97].

4. Conclusions

The rapid growth of the microbial economy promises to advance sustainability through its positive implications on environmental conservation; reduced wastage, particularly in the food and agriculture industries; the repurposing of waste; and the development of new products using alternative cheaper and environmentally friendly raw materials. In the past decades, significant advancements in research and knowledge in the microbial economy have driven the increased application of the concept in the energy sector through the production of biofuels; the increased application of the concept in the manufacturing and processing sectors through the use of microorganisms to enhance, improve, and transform some processes; and entrepreneurship through the rising number of start-ups whose products and services capitalise on biological knowledge. The observed proliferation of the adoption of the microbial economy across several sectors of the economy has shown all indications of continuing in the foreseeable future. Future studies should explore the above-identified barriers to the mass adoption and application of the microbial economy in different industries, processes, and activities to drive better waste utilisation, new product and process innovation, environmental conservation, energy reclamation, soil and environmental conservation, and sustainability.

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References

1. United Nations. *The World Population Prospects 2022: Summary of Results*; UN Department of Economic and Social Affairs, Population Division: New York, NY, USA, 2022. Available online: https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2022_wpp_key-messages.pdf (accessed on 8 December 2022).
2. D'Adamo, I.; Gastaldi, M.; Morone, P.; Rosa, P.; Sassanelli, C.; Settembre-Blundo, D.; Shen, Y. Bioeconomy of sustainability: Drivers, opportunities and policy implications. *Sustainability* **2021**, *14*, 200. [CrossRef]
3. Tien, N. Natural Resources Limitation and the Impact on Sustainable Development of Enterprises. *Int. J. Res. Financ. Manag.* **2020**, *3*, 80–84.
4. Karp, A.; Beale, M.H.; Beaudoin, F.; Eastmond, P.J.; Neal, A.L.; Shield, I.F.; Townsend, B.J.; Dobermann, A. Growing Innovations for the Bioeconomy. *Nat. Plants* **2015**, *1*, 15193. [CrossRef] [PubMed]
5. Antar, M.; Lyu, D.; Nazari, M.; Shah, A.; Zhou, X.; Smith, D.L. Biomass for a Sustainable Bioeconomy: An Overview of World Biomass Production and Utilization. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110691. [CrossRef]
6. Albrecht, K.; Ettling, S. Bioeconomy Strategies across the Globe. *Int. J. Rural. Dev.* **2014**, *3*, 10–13.
7. Thrän, D. Introduction to the Bioeconomy System. In *The Bioeconomy System*; Thrän, D., Moesenfechtel, U., Eds.; Springer: Berlin/Heidelberg, Germany, 2022; pp. 1–19, ISBN 978-3-662-64414-0.
8. Onyeaka, H.; Ekwebelem, O.C. A Review of Recent Advances in Engineering Bacteria for Enhanced CO2 Capture and Utilization. *Int. J. Environ. Sci. Technol.* **2022**, *20*, 4635–4648. [CrossRef]
9. United States Environmental Protection Agency. What Is a Circular Economy? In *US EPA Publications and Reports*; United States Environmental Protection Agency: Washington, DC, USA, 2022.
10. Lonestar College. History of Biotechnology. 2022. Available online: https://www.lonestar.edu/history-of-biotechnology.htm (accessed on 8 December 2022).
11. Liu, T.; Klammsteiner, T.; Dregulo, A.M.; Kumar, V.; Zhou, Y.; Zhang, Z.; Awasthi, M.K. Black soldier fly larvae for organic manure recycling and its potential for a circular bioeconomy: A review. *Sci. Total Environ.* **2022**, *833*, 155122. [CrossRef]
12. Hanif, M.; Bhatti, I.A.; Zahid, M.; Shahid, M. Production of Biodiesel from Non-Edible Feedstocks Using Environment Friendly Nano-Magnetic Fe/SnO Catalyst. *Sci. Rep.* **2022**, *12*, 16705. [CrossRef]
13. Nduko, J.M.; Taguchi, S. Microbial Production of Biodegradable Lactate-Based Polymers and Oligomeric Building Blocks From Renewable and Waste Resources. *Front. Bioeng. Biotechnol.* **2021**, *8*, 618077. [CrossRef] [PubMed]
14. Bian, B.; Bajracharya, S.; Xu, J.; Pant, D.; Saikaly, P.E. Microbial Electrosynthesis from CO_2: Challenges, Opportunities and Perspectives in the Context of Circular Bioeconomy. *Bioresour. Technol.* **2020**, *302*, 122863. [CrossRef]
15. Romero-Perdomo, F.; González-Curbelo, M.Á. Integrating Multi-Criteria Techniques in Life-Cycle Tools for the Circular Bioeconomy Transition of Agri-Food Waste Biomass: A Systematic Review. *Sustainability* **2023**, *15*, 5026. [CrossRef]
16. Kircher, M. Economic trends in the transition into a circular bioeconomy. *J. Risk Financ. Manag.* **2022**, *15*, 44. [CrossRef]
17. Wesseler, J.; Kleter, G.; Meulenbroek, M.; Purnhagen, K.P. EU Regulation of Genetically Modified Microorganisms in Light of New Policy Developments: Possible Implications for EU Bioeconomy Investments. *Appl. Econ. Perspect. Policy* **2022**, 1–21. [CrossRef]
18. Bose, D.; Dey, A.; Banerjee, T. Aspects of Bioeconomy and Microbial Fuel Cell Technologies for Sustainable Development. *Sustainability* **2020**, *13*, 107–118. [CrossRef]
19. Gilbert, J.A.; Stephens, B. Microbiology of the built environment. *Nat. Rev. Microbiol.* **2018**, *16*, 661–670. [CrossRef]
20. Shi, T.-Q.; Peng, H.; Zeng, S.-Y.; Ji, R.-Y.; Shi, K.; Huang, H.; Ji, X.-J. Microbial Production of Plant Hormones: Opportunities and Challenges. *Bioengineered* **2017**, *8*, 124–128. [CrossRef]
21. Voidarou, C.; Antoniadou, M.; Rozos, G.; Tzora, A.; Skoufos, I.; Varzakas, T.; Lagiou, A.; Bezirtzoglou, E. Fermentative Foods: Microbiology, Biochemistry, Potential Human Health Benefits and Public Health Issues. *Foods* **2020**, *10*, 69. [CrossRef]
22. Atiwesh, G.; Mikhael, A.; Parrish, C.C.; Banoub, J.; Le, T.A.T. Environmental impact of bioplastic use: A review. *Heliyon* **2021**, *7*, e07918. [CrossRef]

23. Bhange, K.; Chaturvedi, V.; Bhatt, R. Simultaneous production of detergent stable keratinolytic protease, amylase and biosurfactant by Bacillus subtilis PF1 using agro industrial waste. *Biotechnol. Rep.* **2016**, *10*, 94–104. [CrossRef]
24. Azhar, S.H.M.; Abdulla, R.; Jambo, S.A.; Marbawi, H.; Gansau, J.A.; Faik, A.A.M.; Rodrigues, K.F. Yeasts in sustainable bioethanol production: A review. *Biochem. Biophys. Rep.* **2017**, *10*, 52–61. [CrossRef]
25. Ene, N.; Soare Vladu, M.G.; Lupescu, I.; Ionescu, A.D.; Vamanu, E. The Production of Biodegradable Polymers-medium-chain-length Polyhydroxyalkanoates (mcl-PHA) in *Pseudomonas putida* for Biomedical Engineering Applications. *Curr. Pharm. Biotechnol.* **2022**, *23*, 1109–1117. [CrossRef]
26. Gupta, P.L.; Rajput, M.; Oza, T.; Trivedi, U.; Sanghvi, G. Eminence of microbial products in cosmetic industry. *Nat. Prod. Bioprospecting* **2019**, *9*, 267–278. [CrossRef] [PubMed]
27. Iseppi, R.; Zurlini, C.; Cigognini, I.M.; Cannavacciuolo, M.; Sabia, C.; Messi, P. Eco-friendly edible packaging systems based on live-*Lactobacillus kefiri* MM5 for the control of Listeria monocytogenes in fresh vegetables. *Foods* **2022**, *11*, 2632. [CrossRef] [PubMed]
28. Peciulyte, A.; Anasontzis, G.E.; Karlström, K.; Larsson, P.T.; Olsson, L. Morphology and enzyme production of *Trichoderma reesei* Rut C-30 are affected by the physical and structural characteristics of cellulosic substrates. *Fungal Genet. Biol.* **2014**, *72*, 64–72. [CrossRef] [PubMed]
29. Harman, G.E.; Kubicek, C.P. *Trichoderma and Gliocladium. Volume 1: Basic Biology, Taxonomy and Genetics*, 1st ed.; CRC Press: London, UK, 1998; ISBN 978-0-429-07893-4.
30. Rasoulnia, P.; Mousavi, S.M. Maximization of organic acids production by *Aspergillus niger* in a bubble column bioreactor for V and Ni recovery enhancement from power plant residual ash in spent-medium bioleaching experiments. *Bioresour. Technol.* **2016**, *216*, 729–736. [CrossRef] [PubMed]
31. Birania, S.; Kumar, S.; Kumar, N.; Attkan, A.K.; Panghal, A.; Rohilla, P.; Kumar, R. Advances in development of biodegradable food packaging material from agricultural and agro-industry waste. *J. Food Process Eng.* **2021**, *45*, e13930. [CrossRef]
32. Chandel, A.K.; Garlapati, V.K.; Kumar, S.P.J.; Hans, M.; Singh, A.K.; Kumar, S. The Role of Renewable Chemicals and Biofuels in Building a Bioeconomy. *Biofuels Bioprod. Biorefining* **2020**, *14*, 830–844. [CrossRef]
33. Issa, I.; Delbrück, S.; Hamm, U. Bioeconomy from Experts' Perspectives—Results of a Global Expert Survey. *PLoS ONE* **2019**, *14*, e0215917. [CrossRef]
34. Jadhav, D.A.; Mungray, A.K.; Arkatkar, A.; Kumar, S.S. Recent Advancement in Scaling-up Applications of Microbial Fuel Cells: From Reality to Practicability. *Sustain. Energy Technol. Assess.* **2021**, *45*, 101226. [CrossRef]
35. Schütte, G. What Kind of Innovation Policy Does the Bioeconomy Need? *New Biotechnol.* **2018**, *40*, 82–86. [CrossRef] [PubMed]
36. Lokko, Y.; Heijde, M.; Schebesta, K.; Scholtès, P.; Van Montagu, M.; Giacca, M. Biotechnology and the Bioeconomy—Towards Inclusive and Sustainable Industrial Development. *New Biotechnol.* **2018**, *40*, 5–10. [CrossRef] [PubMed]
37. European Commission, Directorate-General for Research and Innovation. A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment: Updated Bioeconomy Strategy, Publications Office. 2018. Available online: https://data.europa.eu/doi/10.2777/792130 (accessed on 8 December 2022).
38. Piotrowski, S.; Carus, M.; und Carrez, D. European Bioeconomy in Figures. 2016. Available online: https://biconsortium.eu/sites/biconsortium.eu/files/documents/European%20Bioeconomy%20in%20Figures%202008%20-%202016_0.pdf (accessed on 8 December 2022).
39. Joshi, S.; Robles, A.; Aguiar, S.; Delgado, A.G. The Occurrence and Ecology of Microbial Chain Elongation of Carboxylates in Soils. *ISME J.* **2021**, *15*, 1907–1918. [CrossRef]
40. Singh, R. Microbial Biotransformation: A Process for Chemical Alterations. *J. Bacteriol. Mycol. Open Access* **2017**, *4*, 47–51. [CrossRef]
41. Marulanda, V.A.; Gutierrez, C.D.B.; Alzate, C.A.C. Thermochemical, Biological, Biochemical, and Hybrid Conversion Methods of Bio-Derived Molecules into Renewable Fuels. In *Advanced Bioprocessing for Alternative Fuels, Biobased Chemicals, and Bioproducts*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 59–81. ISBN 978-0-12-817941-3.
42. Bell, E.L.; Finnigan, W.; France, S.P.; Green, A.P.; Hayes, M.A.; Hepworth, L.J.; Lovelock, S.L.; Niikura, H.; Osuna, S.; Romero, E.; et al. Biocatalysis. *Nat. Rev. Methods Primers* **2021**, *1*, 46. [CrossRef]
43. Ahmed, I.; Zia, M.A.; Afzal, H.; Ahmed, S.; Ahmad, M.; Akram, Z.; Sher, F.; Iqbal, H.M.N. Socio-Economic and Environmental Impacts of Biomass Valorisation: A Strategic Drive for Sustainable Bioeconomy. *Sustainability* **2021**, *13*, 4200. [CrossRef]
44. Nattassha, R.; Handayati, Y.; Simatupang, T.M.; Siallagan, M. Understanding Circular Economy Implementation in the Agri-Food Supply Chain: The Case of an Indonesian Organic Fertiliser Producer. *Agric. Food Secur.* **2020**, *9*, 10. [CrossRef]
45. Adrio, J.L.; Demain, A.L. Genetic Improvement of Processes Yielding Microbial Products. *FEMS Microbiol. Rev.* **2006**, *30*, 187–214. [CrossRef]
46. Karmee, S.K. Liquid Biofuels from Food Waste: Current Trends, Prospect and Limitation. *Renew. Sustain. Energy Rev.* **2016**, *53*, 945–953. [CrossRef]
47. Cunha, M.; Romaní, A.; Carvalho, M.; Domingues, L. Boosting Bioethanol Production from Eucalyptus Wood by Whey Incorporation. *Bioresour. Technol.* **2018**, *250*, 256–264. [CrossRef]
48. Donner, M.; de Vries, H. Innovative Business Models for a Sustainable Circular Bioeconomy in the French Agrifood Domain. *Sustainability* **2023**, *15*, 5499. [CrossRef]

49. Lin, Y.; Tanaka, S. Ethanol Fermentation from Biomass Resources: Current State and Prospects. *Appl. Microbiol. Biotechnol.* **2006**, *69*, 627–642. [CrossRef] [PubMed]
50. Singh, R.; Langyan, S.; Rohtagi, B.; Darjee, S.; Khandelwal, A.; Shrivastava, M.; Singh, A. Production of biofuels options by contribution of effective and suitable enzymes: Technological developments and challenges. *Mater. Sci. Energy Technol.* **2022**, *5*, 294–310. [CrossRef]
51. Nagaoka, S. Yogurt Production. In *Lactic Acid Bacteria*; Kanauchi, M., Ed.; Methods in Molecular Biology; Springer: New York, NY, USA, 2019; Volume 1887, pp. 45–54. ISBN 978-1-4939-8906-5.
52. Wang, Y.; Liu, L.; Jin, Z.; Zhang, D. Microbial Cell Factories for Green Production of Vitamins. *Front. Bioeng. Biotechnol.* **2021**, *9*, 661562. [CrossRef]
53. Patthawaro, S.; Saejung, C. Production of Single Cell Protein from Manure as Animal Feed by Using Photosynthetic Bacteria. *Microbiol. Open* **2019**, *8*, e913. [CrossRef]
54. Saradha Devi, G.; Vaishnavi, S.; Srinath, S.; Dutt, B.; Rajmohan, K.S. Chapter 19—Energy Recovery from Biomass Using Gasification. In *Current Developments in Biotechnology and Bioengineering*; Varjani, S., Pandey, A., Gnansounou, E., Khanal, S.K., Raveendran, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 363–382. [CrossRef]
55. National Space Agency. Electrified Bacteria Clean Wastewater, Generate Power. NASA Spin-off 2019. Available online: https://spinoff.nasa.gov/Spinoff2019/ee_1.html (accessed on 8 December 2022).
56. Bernal, M.P.; Sommer, S.G.; Chadwick, D.; Qing, C.; Guoxue, L.; Michel, F.C., Jr. Current Approaches and Future trends in Compost Quality Criteria for Agronomic, Environmental, and Human Health Benefits. *Adv. Agron.* **2017**, *144*, 143–233.
57. Panoutsou, C.; Alexopoulou, E. Costs and Profitability of Crops for Bioeconomy in the EU. *Energies* **2020**, *13*, 1222. [CrossRef]
58. Capozzi, V.; Fragasso, M.; Bimbo, F. Microbial Resources, Fermentation and Reduction of Negative Externalities in Food Systems: Patterns toward Sustainability and Resilience. *Fermentation* **2021**, *7*, 54. [CrossRef]
59. Knowledge of Wharton Staff. The Brazilian Bioplastics Revolution. 2009. Available online: https://knowledge.wharton.upenn.edu/article/the-brazilian-bioplastics-revolution (accessed on 8 December 2022).
60. Jang, Y.S.; Lee, J.Y.; Lee, J.; Park, J.H.; Im, J.A.; Eom, M.H.; Lee, J.; Lee, S.H.; Song, H.; Cho, J.H.; et al. Enhanced butanol production obtained by reinforcing the direct butanol-forming route in Clostridium acetobutylicum. *mBio* **2012**, *3*, e00314-12. [CrossRef]
61. Aindrila, M. Tolerance engineering in bacteria for the production of advanced biofuels and chemicals. *Trends Microbiol.* **2015**, *23*, 498–508. [CrossRef]
62. Adegboye, M.F.; Ojuederie, O.B.; Talia, P.M.; Babalola, O.O. Bioprospecting of microbial strains for biofuel production: Metabolic engineering, applications, and challenges. *Biotechnol. Biofuels* **2021**, *14*, 5. [CrossRef] [PubMed]
63. Nyyssölä, A.; Ojala, L.S.; Wuokko, M.; Peddinti, G.; Tamminen, A.; Tsitko, I.; Nordlund, E.; Lienemann, M. Production of Endotoxin-Free Microbial Biomass for Food Applications by Gas Fermentation of Gram-Positive H2-Oxidizing Bacteria. *ACS Food Sci. Technol.* **2021**, *1*, 470–479. [CrossRef]
64. Benemann, J. Microalgae for Biofuels and Animal Feeds. *Energies* **2013**, *6*, 5869–5886. [CrossRef]
65. Onen Cinar, S.; Chong, Z.K.; Kucuker, M.A.; Wieczorek, N.; Cengiz, U.; Kuchta, K. Bioplastic Production from Microalgae: A Review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 3842. [CrossRef] [PubMed]
66. Guo, N.; Liu, J.-B.; Li, W.; Ma, Y.-S.; Fu, D. The Power and the Promise of CRISPR/Cas9 Genome Editing for Clinical Application with Gene Therapy. *J. Adv. Res.* **2022**, *40*, 135–152. [CrossRef] [PubMed]
67. United Nations. *The Sustainable Development Goals Report 2022. United Nations Publications*; United Nations: New York, NY, USA, 2022. Available online: https://unstats.un.org/sdgs/report/2022/ (accessed on 8 December 2022).
68. Tan, E.C.D.; Lamers, P. Circular Bioeconomy Concepts—A Perspective. *Front. Sustain.* **2021**, *2*, 701509. [CrossRef]
69. Wesseler, J.; von Braun, J. Measuring the bioeconomy: Economics and policies. *Annu. Rev. Resour. Econ.* **2017**, *9*, 275–298. [CrossRef]
70. Staffas, L.; Gustavsson, M.; McCormick, K. Strategies and Policies for the Bioeconomy and Bio-Based Economy: An Analysis of Official National Approaches. *Sustainability* **2013**, *5*, 2751–2769. [CrossRef]
71. Gomez, J.A.; Höffner, K.; Barton, P.I. From Sugars to Biodiesel Using Microalgae and Yeast. *Green Chem.* **2016**, *18*, 461–475. [CrossRef]
72. Jung, F.; Krüger-Genge, A.; Waldeck, P.; Küpper, J.-H. Spirulina Platensis, a Super Food? *J. Cell. Biotechnol.* **2019**, *5*, 43–54. [CrossRef]
73. Azevedo, S.G.; Sequeira, T.; Santos, M.; Mendes, L. Biomass-related sustainability: A review of the literature and interpretive structural modeling. *Energy. Elsevier* **2019**, *171*, 1107–1125.
74. Demirbas, A. Political, Economic and Environmental Impacts of Biofuels: A Review. *Appl. Energy* **2009**, *86*, S108–S117. [CrossRef]
75. Behera, L.; Datta, D.; Kumar, S.; Kumar, S.; Sravani, B.; Chandra, R. Role of Microbial Consortia in Remediation of Soil, Water and Environmental Pollution Caused by Indiscriminate Use of Chemicals in Agriculture: Opportunities and Challenges. In *New and Future Developments in Microbial Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 399–418. ISBN 978-0-323-85577-8.
76. Lin, F.; Mao, Y.; Zhao, F.; Idris, A.L.; Liu, Q.; Zou, S.; Guan, X.; Huang, T. Towards Sustainable Green Adjuvants for Microbial Pesticides: Recent Progress, Upcoming Challenges, and Future Perspectives. *Microorganisms* **2023**, *11*, 364. [CrossRef] [PubMed]
77. United States Environmental Protection Agency. Economics of Biofuels. In *US EPA Publications and Reports*; United States Environmental Protection Agency: Washington, DC, USA, 2022.

78. Rabbani, A.; Zainith, S.; Deb, V.K.; Das, P.; Bharti, P.; Rawat, D.S.; Kumar, N.; Saxena, G. Microbial Technologies for Environmental Remediation: Potential Issues, Challenges, and Future Prospects. In *Microbe Mediated Remediation of Environmental Contaminants*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 271–286. ISBN 978-0-12-821199-1.
79. Soares da Silva, R.D.C.F.; Luna, J.M.; Rufino, R.D.; Sarubbo, L.A. Ecotoxicity of the Formulated Biosurfactant from *Pseudomonas cepacia* CCT 6659 and Application in the Bioremediation of Terrestrial and Aquatic Environments Impacted by Oil Spills. *Process Saf. Environ. Prot.* **2021**, *154*, 338–347. [CrossRef]
80. Fagbemi, O.K.; Sanusi, A.I. Chromosomal and Plasmid Mediated Degradation of Crude Oil by *Bacillus coagulans*, *Citrobacter koseri* and *Serratia ficaria* Isolated from the Soil. *Afr. J. Biotechnol.* **2017**, *16*, 1242–1253. [CrossRef]
81. Deng, Z.; Jiang, Y.; Chen, K.; Gao, F.; Liu, X. Petroleum Depletion Property and Microbial Community Shift After Bioremediation Using *Bacillus halotolerans* T-04 and *Bacillus cereus* 1-1. *Front. Microbiol.* **2020**, *11*, 353. [CrossRef]
82. Singh, R.; Kumar, M.; Mittal, A.; Mehta, P.K. Microbial Enzymes: Industrial Progress in 21st Century. *3 Biotech* **2016**, *6*, 174. [CrossRef]
83. Dos Santos, R.A.; Rodríguez, D.M.; da Silva, L.A.R.; de Almeida, S.M.; de Campos-Takaki, G.M.; de Lima, M.A.B. Enhanced production of prodigiosin by Serratia marcescens UCP 1549 using agrosubstrates in solid-state fermentation. *Arch Microbiol.* **2021**, *203*, 4091–4100. [CrossRef]
84. Solís, M.; Solís, A.; Pérez, H.I.; Manjarrez, N.; Flores, M. Microbial Decolouration of Azo Dyes: A Review. *Process Biochem.* **2012**, *47*, 1723–1748. [CrossRef]
85. Palanivelan, R.; Sakthi Thesai, A.; Ramya, S.; Ayyasamy, P.M. Effect of Multiple Factors on Azo Dye Decolorization using a Moderate Halophilic Bacterium *Exiguobacterium aurantiacum* (ESL52). *Glob. Sci.* **2019**, *22*, 206–216.
86. Emadi, Z.; Sadeghi, R.; Forouzandeh, S.; Mohammadi-Moghadam, F.; Sadeghi, R.; Sadeghi, M. Simultaneous Anaerobic Decolorization/Degradation of Reactive Black-5 Azo Dye and Chromium (VI) Removal by *Bacillus cereus* Strain MS038EH Followed by UV-C/H2O2 Post-Treatment for Detoxification of Biotransformed Products. *Arch. Microbiol.* **2021**, *203*, 4993–5009. [CrossRef]
87. Sreedharan, V.; Saha, P.; Rao, K.V.B. Dye Degradation Potential of *Acinetobacter baumannii* Strain VITVB against Commercial Azo Dyes. *Bioremediation J.* **2021**, *25*, 347–368. [CrossRef]
88. Todero Ritter, C.E.; Camassola, M.; Zampieri, D.; Silveira, M.M.; Dillon, A.J.P. Cellulase and Xylanase Production by *Penicillium echinulatum* in Submerged Media Containing Cellulose Amended with Sorbitol. *Enzym. Res.* **2013**, *2013*, 240219. [CrossRef] [PubMed]
89. Do Vale, L.H.F.; Filho, E.X.F.; Miller, R.N.G.; Ricart, C.A.O.; de Sousa, M.V. Cellulase Systems in Trichoderma. In *Biotechnology and Biology of Trichoderma*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 229–244, ISBN 978-0-444-59576-8.
90. Briggs, G.M. *Inanimate Life*; Milne Open Textbooks: Geneseo, NY, USA, 2021; ISBN 978-1-942341-82-6.
91. Straub, C.; Quillardet, P.; Vergalli, J.; de Marsac, N.T.; Humbert, J.-F. A Day in the Life of Microcystis Aeruginosa Strain PCC 7806 as Revealed by a Transcriptomic Analysis. *PLoS ONE* **2011**, *6*, e16208. [CrossRef]
92. Talwar, N.; Holden, N.M. The Limitations of Bioeconomy LCA Studies for Understanding the Transition to Sustainable Bioeconomy. *Int. J. Life Cycle Assess.* **2022**, *27*, 680–703. [CrossRef] [PubMed]
93. Yarnold, J.; Karan, H.; Oey, M.; Hankamer, B. Microalgal Aquafeeds as Part of a Circular Bioeconomy. *Trends Plant Sci.* **2019**, *24*, 959–970. [CrossRef]
94. United Kingdom Department of Business, Energy and Industrial Strategy. *Growing the Economy: A National Strategy to 2030*; United Kingdom Department of Business, Energy and Industrial Strategy: London, UK, 2018. Available online: https://www.gov.uk/government/publications/bioeconomy-strategy-2018-to-2030/uk-bioeconomy-strategy-background-analytical-note (accessed on 8 December 2022).
95. Karl, T.R.; Trenberth, K.E. Modern global climate change. *Science* **2003**, *302*, 1719–1723. [CrossRef] [PubMed]
96. IPCC. Climate Change 2014. Synthesis Report. 2014. Available online: https://www.ipcc.ch/assessment-report/ar5/ (accessed on 8 December 2022).
97. Antranikian, G.; Streit, W.R. Microorganisms Harbor Keys to a Circular Bioeconomy Making Them Useful Tools in Fighting Plastic Pollution and Rising CO_2 Levels. *Extremophiles* **2022**, *26*, 10. [CrossRef]
98. Schuchmann, K.; Müller, V. Autotrophy at the thermodynamic limit of life: A model for energy conservation in acetogenic bacteria. *Nat. Rev. Microbiol.* **2014**, *12*, 809–821. [CrossRef]
99. Steffens, L.; Pettinato, E.; Steiner, T.M.; Mall, A.; König, S.; Eisenreich, W.; Berg, I.A. High CO_2 levels drive the TCA cycle backwards towards autotrophy. *Nature* **2021**, *592*, 784–788. [CrossRef]