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Microbial Bioproducts for a Greener Future: Paving the Way for A Sustainable Bioeconomy

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Abstract

THE current review explores the novel subjects in microbial biotechnology and its fundamental impact on fostering a sustainable bioeconomy, illustrating the unique resilience of microorganisms (MOs) in degrading various pollutants and transforming agricultural waste into valuable products. It highlights how MOs can be harnessed for environmental cleanup, particularly in bioremediation efforts that utilize their natural capabilities to detoxify soil and water contaminated by industrial activities. The article discusses innovative strategies such as microbial valorization of agrowastes, which not only mitigates pollution but also contributes to the circular economy via converting waste into bioproducts like biofuels, enzymes, and fertilizers. Furthermore, it covers advancements in microbial fuel cells (MFCs), which leverage the energy-producing potential of specific bacteria to generate electricity from organic matter. This technology represents a magnificent solution to the global energy crisis while addressing waste management challenges. Additionally, this review underscores the importance of understanding microbial acclimatization processes and custom-engineering microbes to enhance their efficiency in diverse environments. Overall, this work advocates for integrating microbial biotechnology into sustainable practices, aiming for a cleaner environment and a more resilient economy.

Keywords: Bioremediation, Circular bioeconomy, Microbial fuel cells, Waste valorization.

Introduction

Clean-up Capabilities of Microorganisms

Background

Microorganisms (MOs) have the best adaptation capability, able to degrade and accumulate various compounds like hydrocarbons, pharmaceutical substances, radionuclides, and metals. Mos, like bacteria, are crucial in the natural cycle of materials and decomposition of organic waste, making them essential in traditional waste and sewage management due to their stability and less polluting properties [1]. Scientists have discovered bacteria capable of cleaning toxic and radioactive wastes, highlighting their growing role in biotechnology. These microbes can survive in toxic environments and immobilize, degrade, remove, or detoxify environmental contaminants. Many bacterial strains have been employed successfully to regulate toluene, a toxic chemical molecule present in petrol, glue and household solvents [2].

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MOs can be manipulated to improve their clean-up capabilities by using contaminants as food, transforming them into basic elements like carbon dioxide and water through mineralization. Incomplete degradation or a change in chemical structure can also occur, potentially impacting the toxicity and mobility of the original agent. Some bacteria consume certain poisons as part of their normal function [3].

Microbial Valorization of Agrowastes

Agricultural waste is often dumped and burned in open spaces in many developing nations, causing soil contamination, water and air pollution, and contributing significantly to global warming. As a result, a creative way to treating agrowastes is required so that they are not just an environmental nuisance, yet, may also be turned into high-end goods through microbial valorization in the most environmentally benign way [4].

The conversion of agrowaste to bioproducts is at the core of waste-to-wealth conversion, and it benefits the environment while also contributing to the global bio- and circular economy. These massive wastes could be converted into bioproducts, employed in ethanol creation, paper manufacturing, water glass production, biogas and electricity creation, compost and organic fertilizers, heavy metal elimination, or utilized as additives in cement combinations or valorized by MOs to create enzymes and feed additives [5].

Lately, a variety of agricultural wastes were repurposed to make metal nanoparticles using a green chemical strategy or functionalized with nanoparticles for diverse uses. Undoubtedly, reprocessing agricultural waste to make valuable goods is an effective way towards environmental sustainability [6].

Acclimatization of Microbes

MOs proliferate in the presence of pollution, which might include an early gap known as the acclimatization lag. During this time, no significant biological changes in pollution levels occur. This phase might be induced by several issues, especially indigenous microbial populations [7]. The initial biomass could be so low that no meaningful degradation proceeds until a threshold biomass concentration is reached, or the overall microbial population may be abundant, yet expected degrading populations might need enrichment. Assessment of indigenous microbial activity is one way to estimate potential hazardous or inhibiting circumstances at a place. Low bacterial numbers may suggest a toxicity concern or a stressed microbial community [8].

Biodegradation

Biodegradation is the breakdown of organic molecules by MOs, which contributes to the natural carbon cycle. This cascade enables carbon to be recycled and repurposed across the biosphere. MOs in the carbon cycle are used in waste management, which includes composting, landfills, and sewage treatment facilities [9]. This technique simplifies complicated compounds, decreasing waste from garden waste to crude oil while increasing environmental health. Various bacteria, fungi, insects, worms, and other saprophytic creatures perform this breakdown by consuming decaying matter and recycling it into novel forms [10].

Microbial Role in Generation of Bioenergies

The global energy crisis is imminent due to increased energy demand, leading to a shift towards sustainable, renewable energy sources like biotechnology and microbiology, as a viable solution to global warming [11].Therefore, it is very desirable to have new power production based on renewable energy that emits zero net CO_2 emissions, Research on using microbes as fuel cell catalysts began in the 1970s, but recent improvements in microbial fuel cells (MFCs) with higher energy output have occurred [12].

In a MFC, a vast array of MOs could contribute to the generation of power. Using self-sustaining MFCs, scientists have discovered a novel metabolic class of electronic microbes that can convert a wide range of organic chemicals into energy. Complete oxidation of organic molecules is a capability of known organisms related to electricigen. Based on scholars, MFCs were proposed for several reasons [13, 14]. MFCs are environmentally friendly, durable, and energy-efficient devices that utilize MOs to generate electricity from decomposing substrates in sludge, sea sediments, and wastewater [15]. MFCs consist of an anode, cathode, and electrolyte, separated via a membrane. Biofilm or plankton MOs oxidize the anodic chamber, producing protons, metabolites and electrons. Electric current is generated via electrons flowing through the external load, making the process ecologically benign [16]. A dual-chamber MFC, powered by graphene and carbon-based electrodes, efficiently generates energy and distillery effluent, providing a sustainable solution for energy recovery and pollution removal [17].

Landfills

Bioreactor landfills are contemporary technical advancements that outperform standard sanitary landfills and controlled dumping. These landfills employ excellent microbial processes to change and stabilize the easily and moderately decomposing organic waste contents in a short time [18]. Bioreactors are classified into three distinct groups:

aerobic, anaerobic, and hybrid. All three processes rely on the return of collected leachate mixed with water to keep moisture scores in the landfill stable. To reduce hazardous emissions, the MOs responsible for decomposition are encouraged to disintegrate at a faster pace [19].

Vermicomposting

Vermicompost is natural organic manure made from the excreta of earthworms fed on scientifically semi-decomposed organic waste. Worms are employed in this procedure to enrich the compost. These aid in the breakdown of trash, and the addition of worm excreta increases the nutritional content of the compost. In addition to red worms, this involves composting with bacteria, fungi, and insects. This compost needs both oxygen and moisture to stay healthy. Vermi-composting is typically favored over microbial composting in tiny regions because it needs less mechanization and is easier to run. However, it is necessary to ensure that harmful substance are not introduced to the cascade, since this may kill the earthworms [20, 21].

The biodung and vermicomposting technique employed a combination of water hyacinth, grass clippings, and animal dung as organic waste. The outcomes showed that the organic waste was efficiently cured over a 60-day period utilizing vermicomposting and partial biodung composting. This increases the delivery of vital micronutrients and comprises growth-promoting components like as cytokinins and auxins [22].

Microbial interventions against oil spills and radioactivity

A variety of MOs could consume oil as a source of nourishment, and plenty of them create powerful surface-active chemicals that may emulsify oil in water and aid in its elimination. Some bacteria use oil to grow. Most oil spills in the water have been effectively cleaned using MOs employing natural oil-eating MOs. This process can assist in cleaning up not just oil spills as well as chlorinated chemicals and storage tank leaks [23].

Certain bacteria can produce nanowires that can be utilized to immobilize and prevent the spread of hazardous elements such as uranium. Bacteria present naturally in soil electroplate uranium, rendering it insoluble and preventing it from dissolving and contaminating groundwater [24]. These bacteria may be introduced into uranium contamination areas involving nuclear power plants and mines to aid containing the radiation, potentially minimizing the devastating repercussions of such leaks [25].

Microbial Role in Enzyme Production

Enzymes are proteins that catalyze the processes of life. Families and superfamilies are used to classify enzymes that have a common ancestor based on sequence and structural similarities. [26,27]. Enzymes' molecular function is described as its capacity to catalyze biological reactions; it is manually categorized by the Enzyme Commission, and viable ways to statistically compare catalytic reactions are only beginning to surface [27].

Because of their many advantageous qualities, enzymes possess a vital role in industry [28, 29]. Utilizing microbial sources has been crucial to the creation of industrial enzymes. Because they may be economically created using cheap substrate and quick fermentations, microbes are beneficial. Strain enhancement for higher production has proven to be quite successful, and screening is easy. Various animal and plant enzymes were substituted by microbial enzymes in the 1980s and 1990s. Diagnostics, therapy, leather, Food, textiles, detergents, pulp and paper are just a few of the industries that have used them [30, 31].

Enzymes manufactured via MOs like yeast, fungi, and bacteria offer several benefits over enzymes originated from animals or plants [31, 32]. These advantages include ease of cultivation, high growth rates, genetic manipulability, and the capability of enzymes' formation that can act properly under different industrial conditions [32]. MOs produce a wide range of enzymes, comprising xylanases, pectinases, proteases, lipases, cellulases amylases, and more [33].

Lipases are enzymes that catalyze the hydrolysis of oils and fats. They are generated via yeast, fungi, and bacteria. Microbial lipases constitute approximately 90% of the global lipase market [34–36]. Proteases are enzymes that break down proteins into smaller peptides or amino acids. They are employed in industries such as brewing, dairy, baking, food processing, and animal feed [37, 38].

Amylases are enzymes that hydrolyze starch into smaller sugars. They have distinct applications in the food industry, particularly in baking and starch processing [39]. Cellulases are enzymes that break down cellulose, a complex carbohydrate found in plant cell walls. Cellulases have applications in industries such as biofuel production, textile processing, and paper and pulp industry [40, 41].

Microbial enzymes could be genetically engineered to improve their stability and al conditions. performance under specific industri This allows for the production of enzymes that can function optimally at different temperatures, pH levels, and in the presence of inhibitors [42]. The regulation of enzyme formation in microbes is a multifaceted process that involves genetic, biochemical, and environmental factors [43]. Microbial enzymes had a crucial function in various industries because of their efficiency, specificity, and eco-friendly characteristics [44]. Figure 1 illustrates some of the important usages of microbial enzymes across distinct sectors.

Biofertilizers and Biopesticides

Overuse of chemical pesticides has an adverse influence on the agricultural ecosystem, soil fertility, and crop growth [45]. A biofertilizer, a biological element, is utilized to treat this issue in order to get around these limitations. Microbial inoculants are a viable substitute and psychostimulants that can easily overcome the environmental issues resulted from pesticides and chemical fertilizers [46]. Microbial inoculants and biofertilizers hold living MOs that invade the rhizosphere, stimulating plant development through a biological cascade similar to nitrogen fixation and rock phosphate solubilization [47].

Biofertilizers contain beneficial microbial inoculants like rhizobacteria, which promote plant growth and serve as zinc solubilizer, phosphate, sulfur, and nitrogen fixer, acting as biopesticides [48], Biopesticide refers to the utilization of beneficial MOs to control insects, like plants, animals, and certain minerals [49]. The three main forms of biopesticides are microbial, plant, and biochemical pesticides. Ninety percent of all biopesticides are used worldwide. Bacillus thuringiensis (Bt) is the most commercially efficient biopesticide currently available [50].

Biofertilizers

Biofertilizers are eco-friendly, cost-effective, and could be employed on farms, increasing crop yield by 10-40% and retaining fertility for 3-4 years, improving soil texture, pH, and other traits [51]. Beneficial MOs known as biofertilizers improve the biological and chemical characteristics of soil by fixing nitrogen, phosphate, or cellulolytic activity; they also encourage plant growth and elevate soil microflora, which increases soil fertility [52].

Rhizobium and legume roots, such as rhizobacteria, which live in the rhizosphere's soil or on the surface of the root, have symbiotic relationships. Azolla, Rhizobium, and Blue-Green Algae (BGA) are examples of broad-spectrum biofertilizers. Crop-specific bioinoculants include Anabaena, phosphorus-fixing cyanobacteria, Azospirillum, and vesicular-arbuscular mycorrhiza (VAM) [53]. These MOs are referred to as phytofertilizers and rhizobacteria that promote plant growth (PGPR).

Biopesticides

Biopesticides, a novel tool for eliminating or managing pest species like weeds, plant diseases, and insects, are attracting international attention because they are less hazardous to people and the environment than conventional pesticides [54]. Biopesticides, including biochemical pesticides, microbial pesticides, Nanobiopesticides, and plant-controlled pesticides with genetic material, have seen a 10% global increase in usage annually [55, 56].

Microbial Role in Pigment Production

A great source of bioproducts with uses in a variety of industrial sectors is MOs. They can be grown in regulated physical-chemical environments and employ industrial waste as sources of nitrogen and carbon for fermentation, which lowers manufacturing costs. Microbes (prodigines, phycobiliproteins, oxyindoles), plants (photosynthetic and protective pigments), and animals (chromatophores and carotenoids) are among the many creatures from which natural pigments can be extracted. These pigments have a number of economic uses [57].

Microbial pigments are produced by fungi, microalgae, and bacteria (both Archaea and Bacteria domains). They make up a wide range of possible biotechnological uses for coloring in the pharmaceutical, culinary, cosmetic, and textile sectors. Microbial pigments serve a variety of purposes, including environmental adaptation and survival, defense against UV light and ROS, antibacterial and fungicidal properties to maintain the environment's and nutrients' territoriality, and preventing the establishment of other microbial species in their habitat. Additionally, certain pigments can support photosynthetic processes in cells that produce energy [58].

Numerous parameters, including solvent selection, pigment type, microbial cell wall complexity, and the presence of culture media residues, can affect the microbial pigment yield obtained during extraction methods [59]. Distillations, Soxhlet extraction, and water/solvent infusions are examples of conventional methods for extracting various pigment groups [60]. Even though these techniques are still in use today, it is well known that they have drawbacks, including high solvent usage, poor extraction, drawn-out procedures, chemical degradation of pigment structure at high temperatures, and consequent loss of bioactivity [61]. Furthermore, organic solvents like acetone, benzene, petroleum ether, hexane, and methanol are frequently used in these procedures. According to *Sanjeewa et al.*, these solvents are poisonous, extremely flammable, and non-biodegradable [62].

Therefore, pigment extraction without the use of organic solvents other than ethanol or water is undesirable due to sustainability and green technology approaches [63]. As a result, in contrast to traditional approaches, new and sophisticated processes have been created to extract pigments that reduce environmental dangers. Melanin, carotenoids, and chlorophylls can be obtained using more recent and practical extraction procedures, including electric-pulsed, enzymatic, ultrasonic, and microwave-assisted methods [64]. With low to average solvent consumption (water, aqueous, and non-aqueous), these methods are typically less time-consuming, highly effective, and economically feasible for extraction on an industrial scale. On the other hand, they can require high temperatures and pressures throughout the procedure [61].

Microbe-derived pigments have antifungal and antibacterial properties. This characteristic can improve the safety of pharmaceutical and cosmetic formulations, particularly the shelf lives of the most perishable items [65]. The antibacterial action encompasses bacteria (like pyocyanin), fungi (like violacein), and viruses (like prodiginines) [66]. Melanin, prodigiosin, violacein, and other microbial pigments have antioxidant, anti-inflammatory, and anticancer qualities. Well-known for its bioactive qualities, prodigiosin from S. marcescens has been proposed as a potential medication for the treatment of neurological and cancerous conditions [67].

Microalgae and cyanobacteria are examples of natural sources with microbial origins that create high-value pigments like carotenoids, phycocyanins, and chlorophylls that are used to develop product colors with loads of yellow, orange, red, green, and blue [68]. Because of their potential integration into biorefineries and sustainable production in the industry, experts have backed the use of microalgae for the production of pigments and other bioproducts, including vitamins and lipids [69].

Various bacterial and fungal taxa have been identified and investigated for their ability to produce melanin, which is used in the cosmetics industry as an ingredient in cutaneous goods like sunscreen because of its strong UV radiation protective capabilities. When this pigment is isolated and added to a cosmetic formulation with photoprotective aim, it can be used safely for human consumption. This extends the pigment's ability to block UV radiation from generating microbial cells. This application has already been documented in certain scientific publications. Rubropunctamine and monascin, which are both derived from the fungus M. purpureus, were added to sunscreens to increase their photoprotective efficacy by roughly 36.5% and 13%, respectively [70].

Microbial Role in Dye Degradation

The higher need for colors in the food, paper, cosmetic, textile, and leather industries is a result of industrialization. Consequently, the production of effluent from dye industry operations would rise. Pollution has a negative impact on the environment and may cause a direct or indirect risk to the health of all life forms on Earth. Animals, humans, and plants are all harmed by the many dyes and their structural components found in effluent from the dye industry. It is more difficult to decolorize synthetic dyes than natural dyes because they are more resistant to physical and chemical remediation techniques. For speedier dye decomposition, microbial degradation has been extensively studied and evaluated. The use of genetically modified microbes (GEMs) is crucial for attaining total color degradation. [71].

Dye classification is done according to the dye's application and structure. Based on their structures, azo dyes, nitro dyes, phthalein dyes, triphenylmethane dyes, indigoid dyes, and anthraquinone dyes are categorized. On the other, the other, dyes such as acid, basic, vat, ingrain, disperse, moderate, and reactive are categorized according to application [71, 72]. The use of azo dye as a food ingredient is controlled worldwide. The basis for the toxicity of Azo dyes is benzidine and its analogues, such as dimethoxy- and dimethyl-benzidine. It might have mutagenic effects on dogs, rats, humans, and monkeys that result in diseases like cancer. It has been found that a number of dyes negatively impact ecosystems [73, 74].

Each microbe has a unique capacity for detoxification, decolorization, and dye degradation. Most frequently, bacteria are utilized in bioremediation. The field of bioremediation has undergone an important change due to genetic engineering. Under certain environmental conditions, genetically modified organisms can improve dye degradation/decolorization [75].

Gene modification or gene transfer from one species to another can yield genetically modified organisms, or GMOs. Functional genes from a variety of bacterial strains, including *Mycobacterium marinum*, *Pseudomonas putida*, *Bacillus idriensis*, *Ralstonia eutropha*, *Sphingomonas desiccabilis*, and *E. coli*, have been transferred into other species in order to develop genetically modified organisms (GMOs) [76]. *E. coli* SS125 could be produced by adding the azoreductase gene from *Bacillus latrosporus* RRK1 to Escherichia coli DH5a and pAZR-SS125 plasmid. This allowed *E. coli* SS125 to degrade Remazol red dye [77].

Discussion on Current Challenges

Regulatory Hurdles

The regulatory landscape for microbial bioproducts is evolving and, in many ways, still catching up with the science. Rules for products like live biotherapeutics (which include living microbes for use in medicine) are complex, largely because these products are unlike traditional chemicals or pharmaceuticals [78]. One major regulatory challenge is the lack of clear and harmonized guidelines, especially around manufacturing standards and quality control. For example, current regulations can be vague about safety testing and the level of proof needed before a product can reach the market. This ambiguity is especially tough for small companies or academic labs trying to turn discoveries into real-world products, uncertainty can mean lengthy and expensive approval processes [79].

Another sticking point is that microbial bioproducts often fall into two or more regulatory categories (for instance, as both a biological and a drug in the US), making the oversight fragmented and sometimes contradictory [79]. This slows the pace of innovation and discourages newcomers, even as regulatory agencies acknowledge the need for new guidance fit for living, evolving "products." Add to this the difficulties of complying with Good Manufacturing Practice (GMP) guidelines when working with complex, living materials, and the gap between innovation and implementation widens further [80].

Public Perception

On the whole, people seem cautiously optimistic about using microbes for greener technologies, surveys show a majority express positive or at least curious attitudes, especially when benefits like reduced chemical inputs or improved sustainability are clearly communicated. But there's also a strong undercurrent of skepticism, often tied to fears around anything "bioengineered" or misunderstanding the difference between helpful and harmful microbes. The legacy of negative associations (microbes as agents of disease) can't be ignored. When terms like "microbial biotechnology" pop up, some instinctively recall media scares or controversies about GMOs, even when not relevant [81].

Studies of public opinion highlight the importance of concrete, relatable examples and clear language to build trust. For instance, consumers are more open to microbial bioproducts in contexts they already understand, like fermented foods. But when it comes to new applications in agriculture, health, or environmental cleanup, confusion and concern rise, especially if the information is technical, overly promotional, or isn't well connected to perceived benefits [81]. People tend to be more supportive when they see clear links to their own health, environmental wellbeing, or when they're engaged through familiar platforms, like social media. Ultimately, transparency, education, and open dialogue are key to shaping broader acceptance [82].

Field Application Limitations

Even when regulatory and public acceptance boxes are ticked, practical barriers still loom large once microbial bioproducts reach farms, factories, or clinics. A big challenge is replicating the promising results of lab experiments in real, messy environments [83]. Variability in soil, weather, and pre-existing microbial communities can all dramatically change how effective a microbial product will be. This unpredictability is especially acute in agriculture, where products might work well in one location and flop elsewhere due to interactions with local microbes, climate stress, or differences in agricultural practices [84]. Certain advantages and limitations of the microbial applications are demonstrated in Table (1).

Product consistency also remains a headache. Microbial formulations are inherently more variable than chemicals, and keeping the microbes alive, active, and effective through storage and shipping is tricky. Shelf life can be short, and product quality may degrade before it ever gets applied in the field or on crops. Field trials often highlight these weaknesses: sometimes the beneficial microbes just don't survive in their new environments, or they get outcompeted by native species. This drives home the need for better formulations, improved delivery methods, and more robust strain selection processes [85].

Comparison between Current Microbial Bioproduct Technologies with Traditional Approaches

From an environmental standpoint, today's microbial bioproduct platforms offer several clear advantages. Microbial systems can convert low-value feedstocks (such as agricultural residues, wastewater, or even captured CO2) into valuable products, reducing reliance on arable land and competing food crops [86]. The ability of engineered microorganisms to thrive on unconventional substrates cuts the environmental footprint of raw material sourcing. Additionally, innovative approaches like microbial bioremediation use selected strains to break down pollutants directly at contaminated sites, minimizing the need for intensive physical or chemical treatments and helping restore ecosystems without secondary pollution [87]. Modern bioreactors and controlled fermentation systems also allow precise management of conditions, reducing resource waste and maximizing yields without excess emissions or byproducts [88].

Traditional industrial-scale chemical processes, by contrast, are generally more rigid and produce more waste. The need for high-temperature reactions or harsh solvents increases their environmental impact, particularly if fossil-fuel-derived energy is the main source. Although some natural fermentation methods have a relatively modest footprint, their scalability and efficiency are limited compared to what can be achieved through synthetic microbial biology [89].

Moreover, integrated bioprocessing, where multiple valuable products are derived from a single raw material stream, improves profitability and resource efficiency at the same time. For example, the use of byproducts or wastewater in microbial feed can offset disposal costs and create circular economies within industrial settings. By contrast, traditional bioproduct approaches often treat waste as a problem rather than a resource, failing to capitalize on these potential synergies [90].

Nevertheless, some challenges persist for microbial bioproducts. The economic case can falter if production inputs (like nutrients or energy for bioreactors) are costly or if regulatory hurdles slow technology deployment. Furthermore, while microbial systems are inherently adaptable, their long-term stability and performance under real industrial conditions require continuous improvement [86, 91].

Advances in Nanotechnology

Nanotechnology; Fruit and Vegetable Industry

As already described, nanotechnology has made its way far ahead in the food industry. The agricultural, medicinal, and fruit and vegetable industries cannot remain unaffected under this scenario. Scientists are trying to increase the shelf life of fresh organic products to fulfill the nutritional needs of a growing population. From horticulture to food processing, packaging, and pathogenic detection technology, nanotechnology plays a vital role in the safety and production of vegetables and fruits [92].

Nanotechnology, Poultry and Meat Industry

A significant portion of the food business, the poultry sector generates millions of dollars annually for food companies worldwide. Healthy poultry businesses serve as the foundation for a number of commercial food chains that operate all over the world. The food industry is very concerned about the prevalence of common foodborne illnesses that come from farms that raise meat, milk, and poultry. By enabling more poultry consumption while preserving the affordability and safety of produced chicken products, nanobiotechnology is undoubtedly contributing to the fight against food pathogens including those that arise from Salmonella and Campylobacter illnesses [93].

Nano-enabled disinfectants, surface biocides, protective gear, water and air filters, packaging materials, biosensors, and detective tools are just a few examples of nano-based tools and materials that arebeing employed to verify chicken products' traceability and authenticity [94]. Additionally, before the food enters the supply chain, nano-based components are employed to lower foodborne pathogens and spoiling organisms [95].

Nanotechnology and Agri-Industries

The foundation of the economies of many countries worldwide is agriculture. By meeting their dietary needs, it contributes significantly to the global economy overall and is essential to population maintenance. It is acknowledged that agriculture would be significantly impacted by the drastic changes in global weather patterns brought about by global warming [96]. In this situation, taking proactive steps to improve the security and sustainability of agricultural methods is always preferable. Thus, modern technology is being used all over the world. This interaction of sustainable technologies has also seen the successful application of nanotechnology. It is crucial to the manufacturing, processing, packaging, storage, and shipping of industrial agricultural goods [97].

Nanotechnology and Renewable Energy (Solar) Industry

Many of the environmental issues facing the globe today can be resolved by using renewable energy sources. As a result, the renewable energy sector is a significant component of the environmental sector. Therefore, nanotechnology must be taken into account in global energy concerns. The use of nanotechnologies in the production of energy from geothermal, biomass, solar, hydrogen, and tidal waves is growing. However, before maximizing the advantages of combined nanotechnology and renewable energy, scientists are certain that much more needs to be learned [98].

Nanotechnology has found use in the development of renewable energy sources. Particularly, solar collectors have received a lot of attention since their use is promoted globally and because, in the event of extreme solar radiation, the generation and reliance on solar energy will be beneficial for meeting future energy needs. Research data are available regarding the theoretical, numerical, and experimental approaches adopted for upgrading solar collectors with the employment of nanotechnologies [99].

Among these applications are the nanoengineering of flat solar plates, direct absorption plates, parabolic troughs, wavy plates, and heat pipes. The use of nanofluids is becoming common in most of these instruments and solar collection devices and is essential to increasing the working efficiency of these devices. However, there is a gap regarding the use of nanomaterials in the useful manufacturing design of solar panels and their associated potential efficiencies that could be brought to the solar panel industry. Additionally, work needs to be done regarding the cost-effectiveness and efficiency analyses of conventional and nanotechnology-based solar devices in order to adopt suitable measures for the next generation of nanosolar collectors [100].

Conclusion

In conclusion, the integration of microbial biotechnology into sustainable practices presents a transformative opportunity for addressing environmental challenges and promoting a circular economy. By leveraging the natural capabilities of microorganisms, we can not only remediate polluted sites but also convert agricultural waste into valuable resources. The advancements in technologies like microbial fuel cells further illustrate the potential for innovative solutions that align with our energy needs while minimizing ecological footprints. Embracing these biotechnological approaches will be crucial in navigating the complexities of modern sustainability challenges and fostering a bioeconomy that benefits both society and the planet.

Abbreviations

MFCs	Microbial fuel cells
MECs	Electromethanogenesis
BOD	Biochemical oxygen demand
EPA	Environmental Protection Agency
APIs	Active pharmaceutical ingredients.
TCA Cycle	Citric Acid Cycle
PPP	Pentose Phosphate Pathway
PSB	Phosphorus solubilizing bacteria

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Declaration of Conflict of Interest

The authors declare that there is no conflict of interest.

TABLE 1. Advantages and Limitations of Microbial Applications in Various Sectors

	The Industry	Application	Enzyme examples	References
1	**Bioremediation**	Eco-friendly, cost-effective, efficient in detoxifying organic/inorganic pollutants.	Limited by acclimatization lag, slow in high-toxicity sites, requires optimal environmental conditions.	[101]
2	**Nanobiopesticides**	Higher precision and efficacy, less environmental impact, longer persistence.	Regulatory concerns, high development cost, risk of nanoparticle accumulation.	[102]
3	**Vermicomposting**	Produces nutrient-rich compost, improves soil structure, low-tech.	Not suitable for large-scale/mechanized systems, sensitive to toxic inputs.	[102]
4	**Microbial Fuel Cells (MFCs)**	Produces bioelectricity, treats wastewater, renewable and sustainable.	High internal resistance, low scalability, seasonal performance fluctuation.	[103]
5	**Biofuel Production**	Converts waste to ethanol, biodiesel; reduces reliance on fossil fuels.	Substrate-dependent, costly downstream processing.	[5]
6	**Microbial Enzymes in Industry**	Broad industrial applications (food, pharma, textile), biodegradable, specific activity.	Cost of purification, sometimes unstable under extreme pH/temp.	[104]
7	**Biopesticides**	Target-specific, safe for non-target species, eco-friendly.	Slower action than chemicals, limited spectrum, needs precision application.	[105]
8	**Microbial Pigments**	Natural, non-toxic, antioxidant, antimicrobial; used in food, pharma, textiles.	Low yields, complex extraction, limited stability.	[106]
9	**Dye Degradation**	Effective on synthetic dyes, works via enzymatic action, cost-effective.	Efficiency varies with dye type, slower under aerobic conditions	[107]
10	**Oil Spill Bioremediation**	Uses natural oil-degrading microbes, no secondary pollution.	Depends on temperature, nutrient supply, and microbial availability.	[108]
11	**Biofertilizers**	Enhances soil fertility, nitrogen fixation, eco-safe alternative to chemical fertilizers.	Sensitive to environmental conditions, short shelf life, requires proper inoculum formulation.	[109]

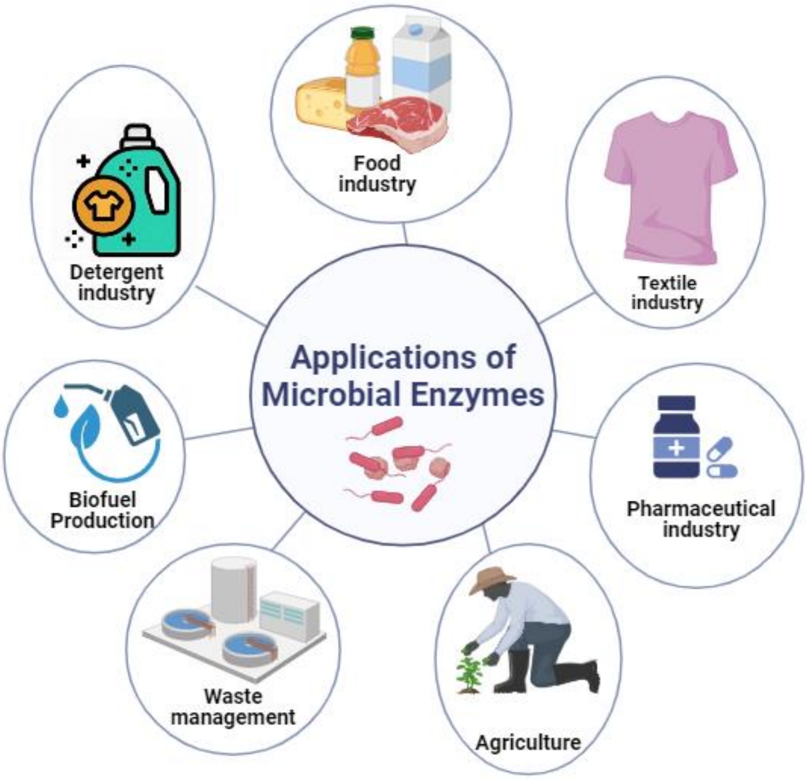

Fig. 1. Application of microbial enzymes.

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المنتجات الحيوية الميكروبية لمستقبل أكثر اخضرارًا: تمهيد الطريق لاقتصاد حيوي مستدام

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الملخص

يقوم هذا المقال بتسليط الضوء على المواضيع الجديدة في مجال التكنولوجيا الحيوية الميكروبية ودورها المحوري في تعزيز اقتصاد حيوي مستدام، موضحًا قدرة الكائنات الدقيقة الملحوظة على التكيف وتحليل العديد من الملوثات فضلاً عن تحويل المُخلفات الزراعية إلى منتجات قيّمة. ويركز البحث على كيفية تسخير هذه الكائنات الدقيقة في تنظيف البيئة، لا سيما في جهود المعالجة الحيوية التي تستخدم قدراتها الطبيعية لإزالة سموم التربة والمياه الملوثة بالأنشطة الصناعية. ويناقش المقال أيضاً استراتيجيات مبتكرة، مثل الاستفادة الميكروبية من النفايات الزراعية، والتي لا تخفف التلوث فحسب، بل تساهم أيضًا في الاقتصاد المستدام من خلال تحويل النفايات إلى منتجات حيوية مثل الوقود الحيوي والإنزيمات والأسمدة. علاوة على ذلك، يتناول البحث التطورات في خلايا الوقود الميكروبية، التي تستفيد من إمكانات إنتاج الطاقة لبكتيريا محددة لتوليد الكهرباء من المواد العضوية. وتمثل هذه التقنية حلاً مبتكراً لأزمة الطاقة العالمية، مع معالجة تحديات إدارة النفايات. بالإضافة إلى ذلك، يؤكد هذا المقال على أهمية فهم عمليات التأقلم الميكروبي وهندسة الميكروبات حسب الطلب لتعزيز كفاءتها في بيئات متنوعة. وبشكل عام، يدعو هذا العمل إلى دمج التكنولوجيا الحيوية الميكروبية في الممارسات المستدامة، بهدف بيئة أنظف واقتصاد أكثر مرونة.

الكلمات الدالة: المنتجات الحيوية، المُخلفات، الاستدامة، التأقلم، التكنولوجيا الحيوية.