

Article

# Microbes in Sustainable Development: Impact on Human Health and Disease Management

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**Abstract:** Microorganisms, often invisible to the naked eye, play a pivotal role in the ecosystems and processes that sustain life on Earth. They are essential not only for the functioning of natural environments but also for advancements in sustainable development, particularly in the domains of human health and disease management. The dynamic interaction between microbes and humans can significantly influence health outcomes, agricultural productivity, environmental sustainability, and the management of diseases. In the context of sustainable development, the role of microbes extends far beyond traditional views that focus on their pathogenic potential. Beneficial microbes, including bacteria, fungi, and viruses, contribute to the development of green technologies, such as bioremediation, waste recycling, and the production of sustainable energy. Additionally, the human microbiome the diverse community of microbes residing in and on the human body affects various aspects of health, from immunity to digestion, and its balance is crucial for preventing a wide range of diseases. The global challenge of managing infectious diseases, particularly in light of emerging pathogens and antimicrobial resistance, requires innovative strategies integrating microbiology with public health policy. Advances in microbiome research and the growing understanding of microbial resilience offer new opportunities for precision medicine, novel vaccines, and alternative therapies, all of which are essential for managing diseases sustainably and equitably.

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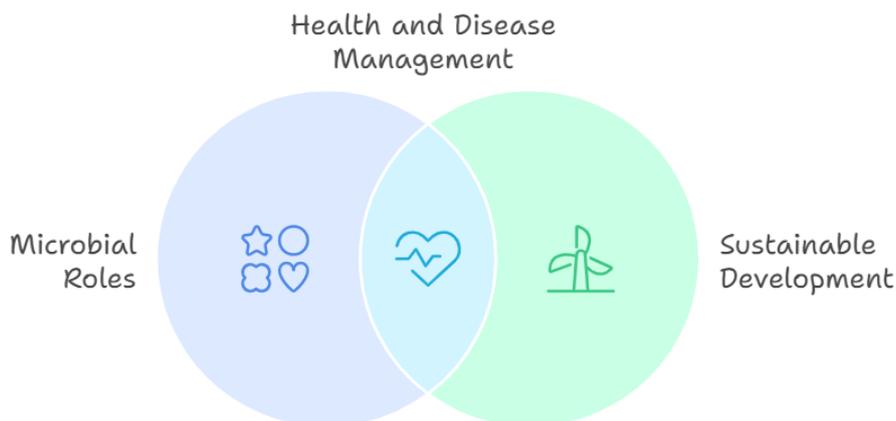
**Keywords:** Sustainable Development, Microbial Bioeconomy Environmental Remediation, Probiotics

## 1. Introduction

The intersection between microbiology and sustainable development is becoming increasingly important as the world faces mounting challenges related to climate change, food security, and health disparities. Exploring the complex relationship between microbes, human health, and disease management is central to fostering a healthier, more resilient future and promoting the responsible use of microbial resources to maintain ecology [4].

The microbial bioeconomy utilizes genetically modified microorganisms as biocatalytic platforms for bioproduction processes [5]. Harnessing the power of tiny life, this method sculpts a future where sustainable, biodegradable products displace finite resources, curbing the tide of environmental pollution a vision perfectly echoing the circular bioeconomy's dance with resource efficiency and the choreography of waste avoidance [6]. New and improved microorganisms and production process optimization have been the main focus of recent advancements in the microbial bioeconomy [7]. Figure (1)

## Microbes in Sustainable Development



**Figure 1.** Sustainable development in microbes

The microbial bioeconomy provides a feasible substitute for conventional production techniques, founded on the global economy's ideas, by employing microorganisms to create sustainable and biodegradable goods. The microbial bioeconomy is expected to grow in importance as a component of the world economy with further advancements and inventions [8]. Genetically modified organisms are essential for a sustainable bioeconomy, enabling the production of a wide range of products including food and feed additives, pharmaceuticals, biomedicine, bioenergy, biofuels, bioplastics, and other recyclable bio-based materials. Furthermore, GMOs play crucial roles in waste management, environmental remediation, building and transportation systems, forestry, and agriculture [9], [10].

### 2. Materials and Methods

The study was conducted to investigate the role of microorganisms in sustainable development, particularly their impact on human health, disease management, and ecological balance. The research incorporated a variety of microbial species, including bacteria, fungi, and viruses, sourced from diverse environmental habitats. The microorganisms were isolated and identified using standard microbiological techniques, including culturing on selective media and genetic sequencing for precise identification.

For assessing the biocontrol potential of microorganisms, various isolates of *Pseudomonas sp.*, *Bacillus sp.*, and *Pseudomonas protegens* were tested for their antimicrobial activity against common plant pathogens. The microorganisms were cultured in liquid and solid media, and their ability to inhibit fungal growth was measured through the well diffusion method. The effectiveness of each strain was evaluated based on the zone of inhibition produced on agar plates inoculated with target pathogens.

To explore the interaction of microbes with plant growth, experiments were conducted using soil samples from agricultural fields. The microbes were introduced into the soil, and their effects on plant growth were monitored through changes in root and shoot length, biomass accumulation, and nutrient uptake. Soil health was assessed by measuring microbial diversity using DNA extraction and subsequent sequencing techniques, allowing for the profiling of microbial communities present before and after inoculation.

The study also involved examining the role of lactic acid bacteria (LAB) in plant growth stimulation and disease suppression. LAB strains were cultured in broth and their production of bioactive compounds, such as organic acids and bacteriocins, was quantified using high-performance liquid chromatography (HPLC). The biocontrol efficacy of LAB was tested in controlled greenhouse conditions, where plant pathogens were introduced, and the plants were treated with LAB cultures.

To evaluate the microbial bioeconomy potential, genetically modified organisms (GMOs) were engineered to enhance the production of biofuels and biodegradable

plastics. These GMOs were cultured in bioreactors, and the production efficiency was measured by tracking the yield of bio-based products through gas chromatography and mass spectrometry.

All experimental data were analyzed statistically using SPSS software, with a significance level set at  $p < 0.05$  for all tests. The results were compared using one-way analysis of variance (ANOVA), followed by Tukey's post-hoc test for multiple comparisons.

### 3. Results and Discussion

By 2050, there will likely be 9.7 billion people on the planet, increasing the demand for food and water. According to this forecast, by 2050, food output must rise by 70% [11], the relentless pursuit of feeding a hungry planet, fuelled by intensive farming's heavy hand with water, agrochemicals, and mineral fertilizers, has tragically led to landscapes scarred by degradation, ecosystems tainted by contamination, and a dwindling inheritance of natural resources. Therefore, sustainable agriculture necessitates food production methods that minimize negative environmental and food chain impacts while reducing pesticide use.

**Table 1.** lists microorganisms and sustainable and biodegradable goods [12].

Microorganism Type	Microorganism	Biodegradable and Sustainable Products	Industry/Application	Role in Achieving Sustainability
Bacteria	<i>Escherichia coli</i>	Bioplastics	Packaging	Reduces reliance on fossil-fuel-based plastics, reduces waste
	<i>Bacillus subtilis</i>	Enzymes	Cleaning and detergent	Reduces environmental impact of cleaning products, promotes sustainable practices
	<i>Saccharomyces cerevisiae</i>	Bioethanol	Fuel	Provides sustainable alternative to fossil fuels
	<i>Pseudomonas putida</i>	Biodegradable polymers	Biodegradable materials	Reduces reliance on non-biodegradable materials, reduces waste
	<i>Lactobacillus acidophilus</i>	Probiotics	Food and beverage	Promotes sustainable agriculture practices, reduces food waste
Fungi	<i>Trichoderma reesei</i>	Cellulases	Paper and pulp	Promotes sustainable forestry practices, reduces waste
	<i>Aspergillus niger</i>	Organic acids	Food and beverage	Provides sustainable alternative to conventional food additives
	<i>Rhizopus oryzae</i>	Biodegradable plastics	Packaging	Reduces reliance on non-biodegradable materials, reduces waste
	<i>Candida albicans</i>	Biosurfactants	Cosmetics and personal care	Provides sustainable alternative to conventional surfactants

### Biological Control Agent and Suppressors of Diseases or Pathogens

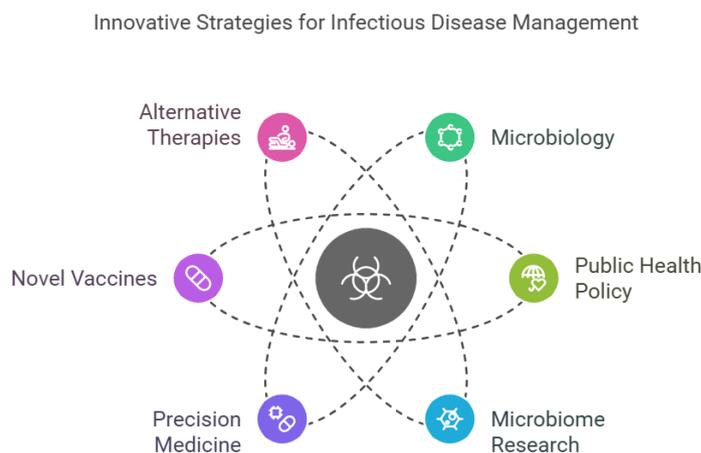
In the grand drama of life, pathogenic microorganisms often play the role of antagonists, negatively impacting the health of most plants and animals, thereby threatening the delicate balance of ecosystems and jeopardizing food production [13], [14]. However, nature offers a counter-narrative, where microbes, sourced from diverse habitats, are being cast as biocontrol agents, their potential unlocked through the identification of their potent bioactive compounds [15], [16], [17]. Research spotlights the capabilities of microbes like *Pseudomonas sp.*, *Cellulosimicrobium sp.*, and *Bacillus sp.* in combatting phytopathogenic fungi and insects [18], [19]. Indeed, a treasure trove of compounds from diverse microorganisms has proven effective against many phytopathogenic fungi [20], [21]. For instance, *Pseudomonas protegens* is a masterful producer of an antifungal agent that successfully targets *Alternaria sp.*, lessening fungal

infections on tomato fruits [21], [22]. Likewise, *Bacillus velezensis* and *Bacillus subtilis* subsp. *spizizenii* have stepped up as biological saviors, defending tomato fruits against fungal invaders [22], [23].

Endophytic bacteria like *Bacillus*, *Curtobacterium*, *Pantoea*, and *Pseudomonas* species are also recognized as biocontrol agents for plant diseases, while some rhizobacteria isolates from *Bacillus*, *Pseudomonas*, and *Arthrobacter* genera suppressed *Phytophthora cinnamomi* growth through volatile emissions [24]. Some of these bacteria are commercially available for disease suppression due to their ability to inhibit pathogenic microorganisms. For example, *Paenibacillus* isolates exhibit bioactivity against various plant pathogens and *Paenibacillus polymyxa* induces systemic resistance in plants like tomatoes [25]. Additionally, liquid cultures of *B. subtilis*, *P. fluorescens*, and *Azotobacter chroococcum* induced systemic resistance in cucumber against Cucumber mosaic cucumovirus [26].

Additionally, certain microorganisms, including bacteriophages, are crucial for enhancing human health. They have been researched for medications or vaccinations to aid in the prevention and treatment of diseases (such as cancer and chronic neurodegenerative diseases). Within minutes of infection, the bacteriophages can identify and destroy a specific bacterium [27].

There are about 1015 bacteriophages in the human stomach [28]. Beyond the realm of human health, where they are being utilized to combat bacterial infections, bacteriophages have been recently approved for a new role: safeguarding the food chain by mitigating infections [29]. Furthermore, the power of microbes is being harnessed to tackle the spread of invasive species, especially plants.



**Figure 2.** Strategies for infectious disease

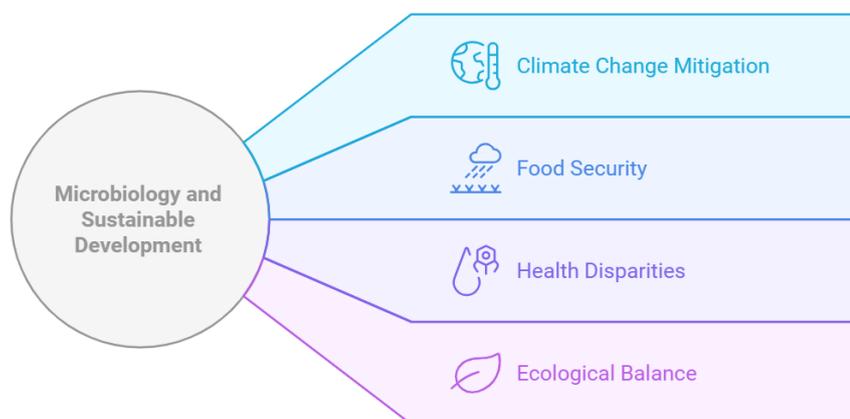
### Microbiota for human health

Soil is a vital resource for agriculture, human health, and the environment, serving as a major source of food, fiber, and biodiversity. Healthy soils provide essential nutrients and clean water for plant growth, which are critical for producing wholesome food. While there is growing awareness of the impact of diet on human health, the importance of soil health, which supports 95% of our food, is often overlooked [30]. A healthy society relies on healthy soil. Soil microorganisms play a crucial role in determining the nutritional value of our food by mineralizing organic matter into plant-accessible inorganic forms. The vibrant and diverse microbiome residing in soil is a key conductor in its complex ecology, driving primary productivity and orchestrating the vital ballet of nutrient cycling. The foundations of sustainable and productive agroecosystems are built upon healthy soils, which can be nourished through practices that respect its integrity: minimizing disturbance, protecting its surface with cover crops, championing crop diversity through rotations, and enriching its microbiome with organic matter [31].

The heavy-handed reliance on synthetic fertilizers and pesticides has severed the natural connections within agroecosystems, detaching them from the intrinsic cycling of vital plant nutrients like nitrogen and phosphorus. Biofortification, a sustainable approach to increasing the nutritional content of crops, is gaining attention, focusing on

enhancing micronutrients like iron and zinc in staple crops through agronomic methods, plant breeding, or transgenic approaches [32]. The availability of soil nutrients is a major determinant of the success of biofortified staple crops, impacting human nutrition and health. The biofortification of various minerals and vitamins has shown encouraging results across numerous crops and climates. Studies by Van Der Heijden et al. demonstrated that the combined application of arbuscular mycorrhizal fungi (AM) and native plant growth-promoting rhizobacteria (PGPR) had the greatest impact on yield and micronutrient biofortification in wheat grain.

Probiotics, those tiny titans of the microbial world, are defined as "live microbial feed supplements which beneficially affects the host by improving its microbial balance," and are commonly thought of as specially formulated food supplements designed to boost well-being. While the precise mechanisms behind their beneficial effects remain a puzzle, a chorus of studies suggests that probiotics have the power to alter pH levels and neutralize pathogens, all through the masterful production of antimicrobial compounds, such as organic acids, diacetyl, acetoin, hydrogen peroxide, and bacteriocins. By inhibiting dangerous bacteria, limiting the growth of other microbes, and maybe occupying the pathogens' receptor sites and pursuing them for an available nutrient, these activities help to maintain microbiological safety [33], [34].



**Figure 3.** Microbiology's role in sustainable development

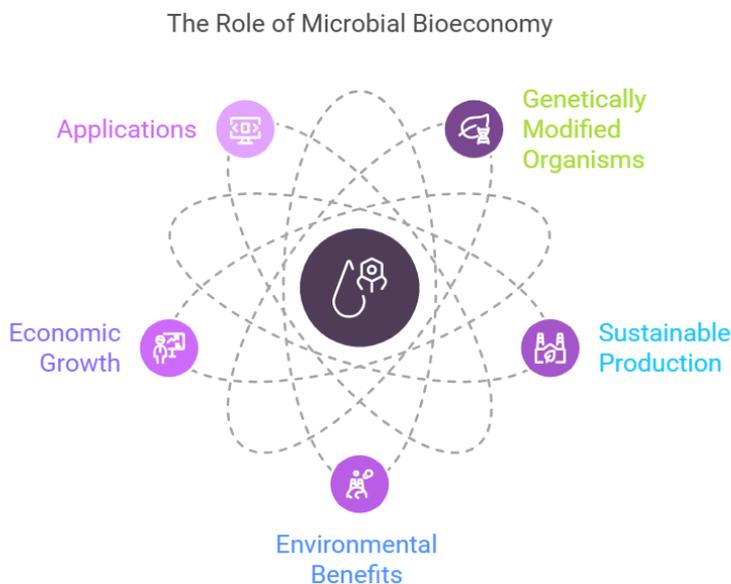
### Useful microbes

The planet is habitable because of the microbes that are found everywhere. A significant portion of the planet's microbial mass is most likely carried by the oceans. In fact, between 50 and 90 percent of the ocean's biomass is made up of bacteria. It has been estimated that there are roughly 1030 million microbial cells in the world's waterways, with a mass equivalent to 240 billion African elephants [35]. Venturing into the vast expanse of the Sargasso Sea, Craig Venter and his team, by filtering and sequencing 200 liters of its waters, unveiled a hidden world of microbial diversity, revealing 1800 genomic species and 148 bacterial phylotypes previously unknown to science.

Moreover, a mere gram of surface soil, seemingly ordinary dry land, can teem with an astounding array of life, harbouring tens of thousands of protists, 200 meters of interwoven fungal hyphae, trillions of viruses, and over a billion bacterial and archaeal cells [36]. Microorganisms colonize all living things, and as was previously noted, each human's stomach contains over 40 trillion germs [37]. Our bodies are thought to include about 30 trillion human cells, which implies Beyond providing vitamins, microbes aid in digestion by breaking down starches and fibers, support endocrine metabolism, and are critical for the development and maintenance of our immune systems. Germ-free mice exhibit significant abnormalities in the development of gut-associated lymphoid tissues and antibody production, including fewer and smaller Peyer's patches and mesenteric lymph nodes [38].

Early antibiotic treatment of mice also results in immunological dysfunctions, highlighting the critical role that microbial colonization plays in immune maturation [39]. According to recent research, a healthy microbiome is essential for our immune system's

capacity to combat infections, tumors, and chronic inflammation [40]. Microbes, those miniature workhorses of nature, are the unsung heroes driving countless industrial processes, from the creation of essential chemicals, novel energy sources, powerful enzymes, and life-saving pharmaceuticals, to the management of waste, the control of pollution, and the ancient art of fermenting staple foods such as bread, cheese, beer, and wine [41], [42]. Additionally, they possess the ability to degrade a wide array of substances, including plastics and fossil fuels. Lastly, we must remember that microbes play a crucial role in sustaining agriculture.



**Figure 4.** Role of microbial bioeconomy

#### **Mechanism of action of LAB in controlling disease and stimulating plant growth**

Certain LAB species, possessing a unique arsenal of abilities, have emerged as promising candidates in biological control agents (BCAs) [43], [44]. While they may not yet hold the same legendary status as other BCA groups like *Pseudomonas*, *Burkholderia*, *Streptomyces*, *Bacillus*, and *Trichoderma*, several LAB species have been shown to possess the power to suppress the actions of phytopathogens while also stimulating the very plants they are meant to protect [45], [46]. As masterful multi-taskers, LAB directly assist in plant disease control and growth by orchestrating the uptake of crucial nutrients like phosphorus and potassium, fixing atmospheric nitrogen, and secreting plant hormones and siderophores. Indirectly, they serve as formidable biocontrol allies, unleashing a barrage of antimicrobial compounds, including the mysterious diketopiperazines, the potent hydroxy derivatives of fatty acids, the intriguing 3-phenyllactate, the targeted antibacterial bacteriocins and bacteriocin-like inhibitory substances (BLIS), the pH-shifting organic acids, the reactive hydrogen peroxide, the intriguing pyrrolidone-5-carboxylic acid, the flavorful diacetyl, and the broad-spectrum reuterin [46]. They also bolster plant defenses by inducing systemic resistance and depriving pathogens of vital iron resources. It's been suggested that LAB might even employ multiple mechanisms of attack against phytopathogens, an intricate symphony of biological warfare [47].

#### **Direct mechanisms**

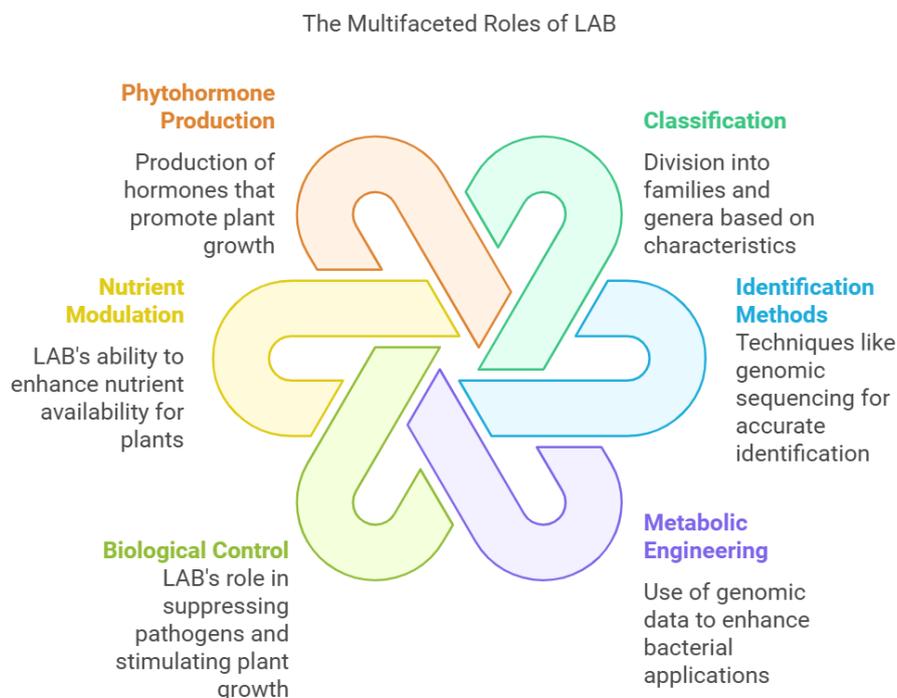
##### **Modulating the intake of nutrients and the fixation of nitrogen**

Certain strains of lactic acid bacteria (LAB), like tiny alchemists, hold the power to unlock hidden nutrients, enhancing the availability of vital elements from compost and other organic or inorganic leftovers, making them accessible to plants [48]. Phosphorus (P), a crucial macronutrient for plant life, often lies dormant in the soil, bound as an inorganic precipitate or trapped within organic molecules. Meanwhile, potassium (K), a key player in plant development and yield, is often found in a fixed, less accessible form. Yet, *Lactococcus lactis*, wielding a genetic toolbox, possesses the secret to freeing phosphorus, boasting gene sequences that code for two distinct forms of alkaline

phosphatase, the enzymes that actively catalyze the mineralization of phosphate, liberating it from its confines [49]. The acidity produced by LAB from organic acid production also contributes to the solubilization of P and K, making them accessible for plant uptake. Besides solubilizing phosphate, certain LAB strains can fix atmospheric nitrogen [50], [51]. The magical transformation of atmospheric nitrogen (N<sub>2</sub>) into plant-usable ammonia and nitrate, known as biological nitrogen fixation (BNF), is orchestrated by the nitrogenase enzyme complex. Recently, a remarkable discovery unveiled the diazotrophic prowess of *L. lactis*, isolated from the mucilage-rich microbiota of Sierra Mixe maize, proving it is capable of performing BNF [49], [50], [51]. Delving into the genetic mysteries of *L. lactis*, protein domain analysis of previously unknown genes has illuminated their key roles. These genes are involved in a range of activities, from the strategic deployment of iron and siderophores, the breaking down of polysaccharides, the precise navigation of glycan-mediated host adhesion, the essential synthesis of the FeMo cofactor (NifB), and a novel array of oxidoreductase functions, all collectively underscoring their vital contribution to the BNF trait.

### Phytohormones production

In the intricate world of plant growth, both plants and bacteria act as tiny hormone factories, producing potent phytohormones in minute quantities that exert significant influence. According to Kumar et al, these phytohormonal messengers are key players in shaping the plant's root system, extending root hair length and surface area, thereby facilitating more efficient nutrient and water uptake. The symphony of phytohormone synthesis also boosts metabolic activity, bolstering the plant's resilience against abiotic stresses, fortifying its defenses, and ensuring proper cellular functioning (Khan et al., 2020). Furthermore, a diverse array of LAB species are capable of secreting auxins, like the well-known indole-3-acetic acid (IAA), and phytohormones, like gibberellin (GA), each holding distinct roles in promoting plant growth [52], [53]. For instance, the culture fluid of *L. plantarum*, when analyzed using HPLC-MS, revealed the presence of GA4 and GA7, growth promoters that enhance the development of wheat coleoptiles, though the exact mechanisms of action for these phytohormonal players remain a mystery yet to be fully solved [54], [55].



**Figure 5.** The multifaceted roles of LAB

## **Indirect mechanisms**

### **Organic acids**

Studies paint a vivid picture of organic acid production as a cornerstone of the lactic acid bacteria (LAB) arsenal, enabling them to unleash their antimicrobial prowess against a vast spectrum of target bacteria [56], [57]. While lactic acid reigns as the most common metabolite produced by LAB, a variety of other acids, including acetic, propionic, formic, benzoic, and PLA acids, also contribute to their potent action. Lactic acid, through a multi-pronged attack, exerts its antibacterial effects, disrupting the delicate membrane functions of pathogens, inhibiting their active transport systems, lowering their intracellular pH, and hindering various metabolic processes, leading ultimately to the demise of the target microorganism [1], [58], [59]. However, this potency is not absolute; the production of lactic acid and its ability to lower pH vary based on the LAB species or strain, the concoction of the culture mix, and the environmental conditions in which they thrive [2]. The presence of lactic acid in its undissociated form at low pH acts as a microbial executioner, eliminating a wide range of bacteria, fungi, and yeasts. Thus, lactic acid wields a diverse palette of actions against various microorganisms.

### **Hydrogen peroxide**

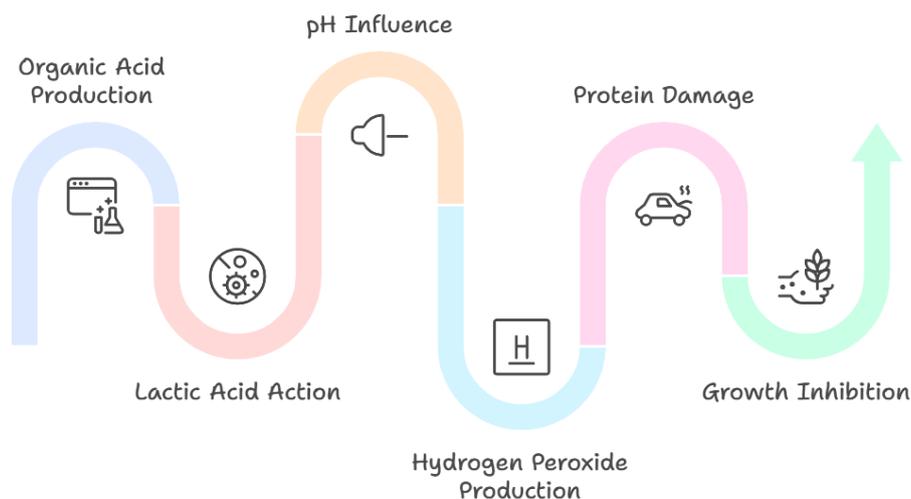
In the presence of oxygen, LAB also produces the reactive oxygen species hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). The basic molecular structures of proteins essential in cellular metabolism are irreversibly damaged by hydrogen peroxide's potent oxidising effect on microbial cells [36]. Once produced, H<sub>2</sub>O<sub>2</sub> has the ability to prevent the growth of pathogenic and psychoactive microbes. However, recent research suggests that the antimicrobial activity of H<sub>2</sub>O<sub>2</sub> is likely limited due to the small amounts produced by bacteria, and its effects are primarily associated with other antifungal compounds [39].

### **Bacteriocin**

Bacteriocins, those meticulously crafted microbial weapons, are ribosomally synthesized antimicrobial peptides produced by bacteria, capable of selectively targeting and dismantling both related and unrelated bacterial strains, all without causing harm to their own producers [41]. Their modes of action are diverse and devastating, interfering with the very construction of cell walls, ripping apart cytoplasmic membranes, curtailing the critical process of protein synthesis, disrupting DNA replication and transcription, and even sabotaging the formation of septa [42], [43]. Within the LAB world, specific members possess the talent for producing bacteriocins and bacteriocin-like inhibitory substances (BLIS). While the LAB cells themselves are immune to their own bacteriocins, these compounds—mostly small, heat-stable, or large, heat-sensitive proteins, or protein complexes—exhibit powerful antibacterial prowess against a wide array of other microorganisms [46].

Bacteriocin production is significantly influenced by pH, nutrient sources, and incubation temperature. Based on biochemical and genetic characterization, LAB bacteriocins are categorized into four classes: class 1 lantibiotics, class 2 small heat-stable nonlanthionine peptides, class 3 large heat-labile proteins, and class 4 complex bacteriocins containing chemical moieties like lipids and carbohydrates (Hernández et al., 2005). Intriguingly, the power of bacteriocins extends beyond direct microbial warfare, with the potential to induce a plant's own resistance, contributing to the control of bacterial infections in commercially vital crops [50].

## Antimicrobial Mechanisms of LAB



**Figure 6.** Antimicrobial mechanisms of LAB

### Reuterin

Under anaerobic conditions, the presence of glycerol can directly or indirectly induce the production of reuterin, an antibacterial molecule derived from glycerol, by certain *Lactobacilli*. Lactic acid bacteria (LAB), lacking the machinery for oxidative metabolism, cannot directly consume glycerol as their main source of fuel. Instead, they orchestrate a clever workaround, breaking down glycerol using another carbon source as a springboard [52]. This metabolic maneuver leads to the production of reuterin, a potent, pH-independent inhibitory substance with broad-spectrum action, known to disrupt DNA replication while resisting degradation by lipolytic and proteolytic enzymes (Singh, 2018). Reuterin showcases a formidable reach, demonstrating effectiveness against a variety of fungi including *Fusarium*, *Penicillium*, and *Aspergillus* (Vimont et al., 2018), and is linked to the prevention of mycotoxin development in fermented foods. Moreover, reuterin proves itself a versatile antimicrobial agent, capable of halting the growth of viruses, yeasts, fungi, protozoa, enteropathogens, and both gram-positive and gram-negative bacteria [54].

### Cyclic dipeptides

Cyclic dipeptides (CDPs), those miniature molecular rings also known as 2,5-diketopiperazines, stand as the smallest examples of cyclic peptides. In the grand scheme of microbial biosynthesis, bacteria emerge as the principal producers, responsible for crafting over 90% of all known CDPs (Mishra et al., 2017). These intriguing compounds, such as cyclo(Gly-Leu), cyclo(Phe-Pro), cyclo(Phe-OH-Pro), and cyclo(Phe-OH-Pro)(Leu-Leu), isolated from the LAB realm, have been revealed to possess antibacterial capabilities [56]. Cyclic peptides have garnered significant attention due to their stability under various conditions, including heat, pH, and enzymes. For instance, the antifungal compound cyclo(Gly-Leu) from *Lb. plantarum* VTT E-78076 demonstrated antifungal activity against *Fusarium avenaceum*, a plant fungal pathogen [57]. While showing potential as an antibacterial, further research is needed to fully understand their mode of action and range of applications.

## Antimicrobial Agents from Lactic Acid Bacteria



**Figure 6.** Antimicrobial agent from LAB

**Table 2.** Selected lactic acid bacteria with biological control and bio-stimulant properties (Jaffar et al., 2023)

Strain	Source	Pathogen/Crop	Mechanism/Effect
<b>(i) Biocontrol</b>			
Lactobacillus sp	Tomato rhizosphere	Ralstonia solanacearum, Xanthomonas axonopodis pv. citri, X. campestris pv. vesicatoria, Erwinia pyrifoliae, Pectobacterium carotovorum	None
Lactobacillus Plantarum	Cucumber pickle	Pseudomonas campestris, Ralstonia solanacearum, Xanthomonas campestris pv. vesicatoria, Pectobacterium carotovorum	Organic acids
Lactobacillus plantarum	Kimchi	Aspergillus flavus	3,6-bis(2-methylpropyl)-2,5-piperazinedion
Lactobacillus sp	Dairy products	Fusarium oxysporum	. SAR, antifungal metabolites
Lactobacillus plantarum	Fermented mare milk	Botrytis cinerea, Alternaria solani, Phytophthora drechsleri, Fusarium oxysporum and Glomerella cingulate	Proteinaceous and no proteinaceous antifungal compounds
L. fermentum	Fermented food, dairy products	A. niger, Fusarium graminearum, A. oryzae	Proteinaceous, PLA
Lactobacillus plantarum	Durian fruit	Colletotrichum capsici, broad spectrum	Unknown
Lactobacillus plantarum	Ginger root	Colletotrichum capsici, broad spectrum	Unknown
Lactobacillus paracasei	Tomato, soil	Ralstonia solanacearum	Unknown
W. paramesenteroides	Fermented wax gourd	Rhizopus stolonifera, Sclerotium oryzae, Rhizoctonia solani, Botrytis cinerea, Sclerotinia minor, Rhodotorula sp.	Organic acids
Lactobacillus acidophilus	Chicken intestine	Fusarium sp., Alternaria alternata, P. paneum, Cladosporium sp., Rhizopus oryzae	Organic acids
Lactobacillus	Tomato, soil	Paracasei Ralstonia solanacearum	SAR
Weisella cibaria, Lactococcus lactis subsp. lactis	Papaya seed	Erwinia mallotivora	Organic acids, hydrogen peroxide

L. pentosus	Fruit, fermented food	A. oryzae, A. niger, Fusarium sp.	PLA
Lactobacillus pentosus, Leuconostoc fallax	Fermented vegetables	Alternaria brassicicola, Xanthomonas campestris pv. campestris, Pectobacterium carotovorum	Unknown
Lactobacillus plantarum	Yellow pithaya	Fusarium fujikuroi	Unknown
Lactobacillus acidophilus	Mango	C. gloeosporioides	Antifungal compound, lytic enzyme
Lactiplantibacillus plantarum	Collection of Pure Cultures of Industrial Microorganisms LOCK at the Lodz University of Technology, pickled vegetables, milk	Pectobacterium carotovorum, Streptomyces scabiei, Alternaria solani, Alternaria tenuissima, Alternaria alternata, Phoma exigua, Rhizoctonia solani, Colletotrichum coccodes	Organic acids
<b>(ii) Bio stimulant</b>			
Lactobacillus sp.	Rhizosphere soil of tomato	Pepper	IAA, phosphate solubilization, and biocontrol property Increased root and shoot length, root fresh weight and chlorophyll content
Enterococcus faecium	Rhizosphere soil of oriental melon (Cucumis melo L.)	Rice	Phytohormones (GA, IAA), mineral solubilization, and biocontrol property -Increased shoot and root length, plant fresh weight, chlorophyll content, nutrient uptake
L. plantarum	PGPR Corp. (Korea)	Cucumber	Succinic acid, lactic acid increased growth, nutrient availability and amino acid content
Lactobacillus sp.	Sugarcane fermentation	Citrus seedling	Nitrogen fixation, phosphate solubilization increased height, stem diameter, root and shoot weigh
Enterococcus sp.	Rhizosphere soil of grass pea	Fusarium oxysporum f. sp. lentis	IAA, phosphate solubilization, stress response and biocontrol property
E. faecium LB5, L. lactis LB6, LB7, and LB9	Rhizosphere soil of wheat	Fusarium graminearum	Phosphate solubilization and biocontrol property
Lactobacillus sp.	Vietnamese traditional Nem chua	Peanut seed	IAA, phosphate solubilization, and biofilm formation -Increased seed germination, vigor index, plant length, and total fresh weight
Lactobacillus sp.	Silage and rhizosphere soil	Adzuki bean (Vigna angularis), Arabidopsis	3-phenyllactic acid (PLA) -Root promoting activity in Adzuki bean, promote auxin signaling pathway – increased lateral root density in Arabidopsis
Weissella cibaria, Lactococcus lactis	subsp. Lactis Papaya seed	Papaya	Synthesis of ammonia, siderophores, and phosphate solubilization - increased the dry weight of the shoot and root of papaya plants
Lactobacillus sp.	The aerial part of pomegranate plants	Fusarium sp.	Phytohormones (GA, IAA) and biocontrol property

#### 4. Conclusion

In conclusion, microbiology plays a crucial role in sustainable development, offering solutions to global challenges like climate change, food security, and health. The microbial bioeconomy, leveraging genetically modified microorganisms, provides sustainable alternatives to traditional production methods, reducing environmental impact and enhancing resource efficiency. Microbes are also essential in agriculture for disease control, promoting plant growth, and improving soil health, all while minimizing environmental harm. As research advances, the potential of microorganisms to address health, food, and environmental issues will continue to grow, supporting a more sustainable and resilient future.

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