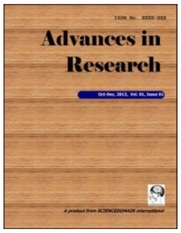

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Saprophytic, Symbiotic and Parasitic Bacteria: Importance to Environment, Biotechnological Applications and Biocontrol

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Authors' contributions

This work was carried out in collaboration between all authors. Authors FSG and EVP managed the literature searches and wrote the first draft of the manuscript. Authors LCBBC and PMGP designed the study and managed the study performed. All authors read and approved the final manuscript.

Review Article

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ABSTRACT

Microbial communities have a vast importance to the ecosystem being of use by humans for health or industrial purposes. Most bacteria can be distinguished into three groups: saprophytic; symbiotic and parasitic. Saprophytic bacteria, which are the major decomposers of organic matter, can be applied in treatment of metalliferous mine, radioactive environmental wastes, biodiesel production, among others. Symbiotic bacteria live in a mutually beneficial association with other organisms providing essential nutrients to their host organisms. However, some bacteria are able to cause diseases (i.e, parasitic bacteria also referred to as pathogens). To control the growth of these parasitic bacteria, antimicrobial peptides and polypeptides such as lectins are promising raw materials for the production of new antibiotics. Lectins are able to interact with carbohydrates in bacterial cell walls and promote antibacterial activity. The aim of this review was to describe the importance of bacteria to environments, their use as biological control agents and the application of lectins to control pathogenic bacteria.

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1. INTRODUCTION

Bacteria are single-celled microorganisms classified as prokaryotes. There are over 3.6 billion years bacteria present on Earth, colonizing almost every possible occurrence of life. This long co-evolution enabled bacteria to develop several beneficial relationships with the environment since they form part of this system. The number of bacterial species that have been described is low (~7,000) in relation to the millions of bacteria that have been predicted to reside on Earth [1].

Microbial communities have vast importance to the ecosystem. They are important components of the forest ecosystem since they facilitate organic matter decomposition and nutrient cycling in the soil [2]. Free-living bacteria are of importance in agriculture as they abound in the rhizosphere (i.e, the region around the root) and have more than one mechanism of accomplishing increased plant growth, such as the production of enzymes, bioactive factors, antibiotics, metabolites as well as growth promoters [3].

Bacteria in terms of their morphology are classified as bacilli (rods), cocci (spherical), spiral and many others (Fig. 1). The bacillus is rod-shaped and found as isolated bacilli, diplobacilli or streptobacilli. A coccus is circular and can be isolated as diplococcus, tetracoccus, sarcina micrococcus, streptococcus or staphylococcus. Other bacterial shapes of low occurrence include spirillum (*Treponema pallidum*), vibrio (*Vibrio cholerae*), transitional forms such as coccobacillus and involution forms, a survival mechanism to adverse environmental conditions such as spores [4].

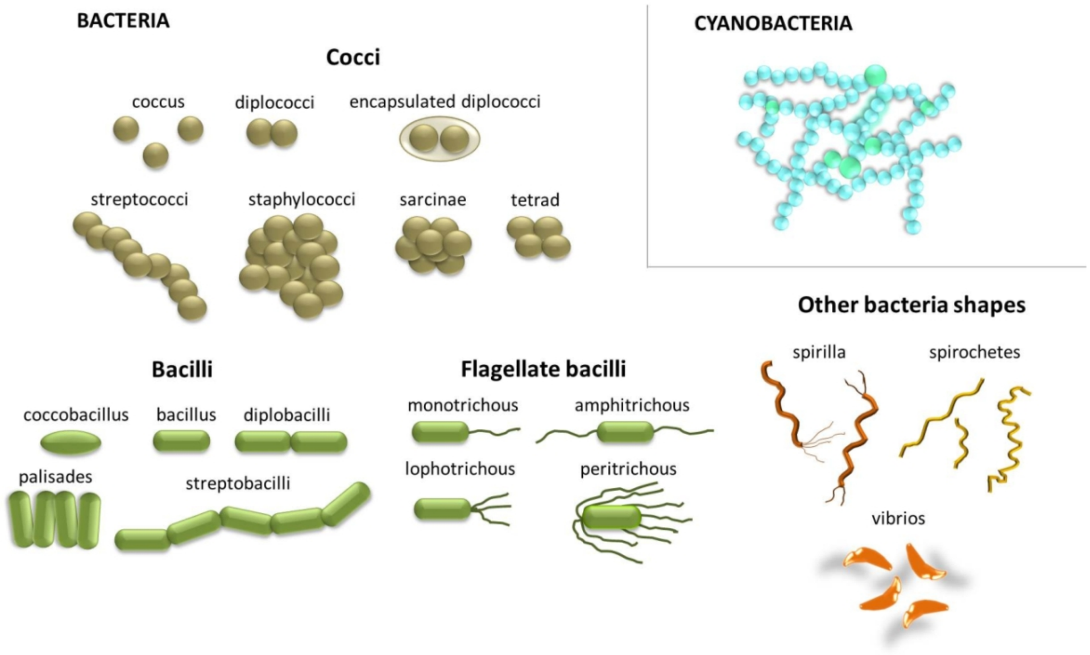

Fig. 1. Types and shapes of bacteria (cyanobacteria, cocci, bacilli, spiral)

Most bacteria are heterotrophic i.e. they are unable to manufacture their own organic food being dependent on external sources. These bacteria can be distinguished into three groups: 1) saprophytic; 2) symbiotic and 3) parasitic. Many bacteria that are associated with plants are actually saprophytic and do not harm the plant itself. However, a small number, around 100 species can cause plant diseases and thereby promoting losses in agriculture [5].

Microorganisms may be beneficial to human microbiota, complex infective bacteria that inhabit sites in and on the human body such as gut, skin, and oral cavity. Special situations as in patients whose normal innate defenses fail to function properly can lead to an imbalance of an individual species that are pathogens in the classical sense such as *Enterobacter sp*., *Escherichia coli* and *Pseudomonas aeruginosa*, among others [6].

The control of bacteria grown is a way to avoid ecosystem imbalance and disease caused by some of these microorganisms. However, massive use of antibiotics for this purpose has led to bacterial resistance, generated by selection processes including increase in the frequency of resistance bacterial genes [7]. As an alternative, antimicrobial polypeptides such as lectins have been isolated and characterized from tissues and organisms from every kingdom and phylum [8]. The complete understanding of mechanisms of action from new alternatives to biological control may provide models and strategies for developing novel antimicrobial agents that may also increase immunity, restore potency or amplify the mechanisms of conventional antibiotics and minimize antimicrobial resistance mechanisms among pathogens.

2. SAPROPHYTIC BACTERIA

The saprophytic bacteria are the major decomposers of organic matter (Fig. 2), breaking down complex mixtures such as cellulose, hemicelluloses, lignin and proteins into simple soluble forms (catabolic reactions) and freeing their atoms to be re-used by other bioprocesses (anabolic reactions) [9]. The biological relevance of saprophytic bacteria to the environment has been used in several biotechnological applications. The ability of some acidophilic bacteria to withstand raised concentrations of certain metals through biological oxi-redution reactions has been applied in a variety of industrial fields such as treatment of metalliferous mine wastes, acid mine waters and sulphurous flue gases [10,11]. The Matsuo Mine in Japan applied this biological treatment system using *Thiobacillus ferrooxidans* to treat $28m^3$/min of mine water at pH 2.5 oxidising more than 95% of soluble ferrous iron [10]. Microbial systems can detoxify the metal ions by either extracellular biomineralization, biosorption, complexation, precipitation or intracellular bioaccumulation. The cell wall reductive enzymes or soluble secreted enzymes can be involved in the reductive process of metal ions by bacteria [11].

Some environmental factors such as availability of iron, sulphide and a micro-aerobic environment are important for proliferation of the magnetotactic bacteria such as *Magnetospirillum magneticum*. Magnetic minerals produced by these bacteria such as greigite and biogenic magnetite form a post-depositional remnant magnetization that is indicative of rapid local environmental change [12]. Archeologists to establish the chronology and environmental history of a place use these biomarkers. Linford et al. [12] discovered bacterial magnetosomes at the village of Yarnton (Oxford, UK) suggesting a transformation of the previously dry river valley to an active flood plain.

Radiation-resistant microorganisms have been used in the treatment of highly radioactive environmental wastes due to their ability to transform, detoxify, or immobilize a variety of metallic and organic pollutants [13,14] and used for decontamination of acid mine drainage waters through anaerobic degradation [15]. The techniques traditionally applied for the treatment of radioactive environmental residuals have been based on chemical methods of neutralization and precipitation [13-15]. These quick and effective techniques have several disadvantages, such as the need for building additional plant treatments, the high cost of the chemical reagents used and the generation of an important volume of sludges that need to be relocated [15].

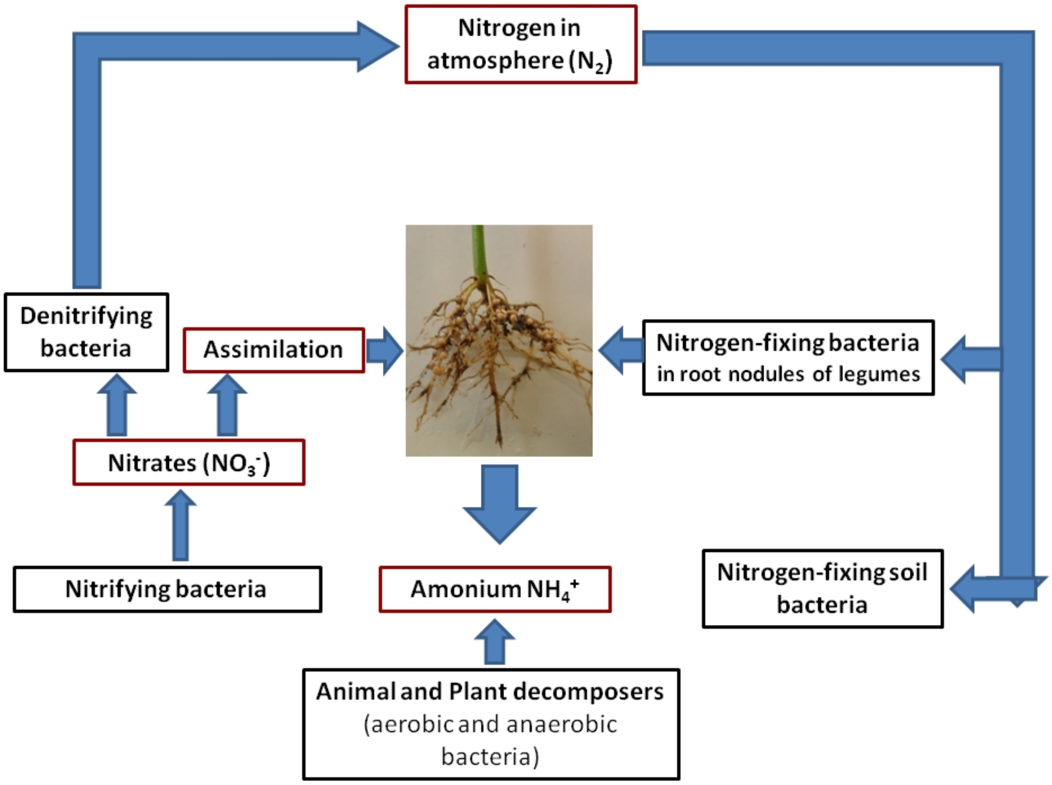

Fig. 2. Importance of saprophytic and symbiotic bacteria to the nitrogen cycle

Some bacteria, when subjected to any form of environmental stress, produce a signal transduction cascade in which certain promoters are induced, leading to expression of proteins that adjust to the ecological impact of altering the environment [16,17]. Bioluminescent bacteria have being used as tools to detect some special compounds that are toxic and/or are of current interests as inorganic and organic pollutants of water, soil and air, as well as to monitor the level of toxicity of the effluents from industries into urban wastewaters, effluents from plant treatments and water [16,17]. Recombinant bioluminescent bacterial strains are increasingly receiving attention as environmental biosensors due to their advantages, such as high sensitivity and selectivity, low costs, ease of use and short measurement times. Exposure of a recombinant *E. coli* strain, containing a fusion of a promoter to the *Vibrio fisheri lux* genes (Ecolum-5), to a toxic or lethal condition (DNA, superoxide or protein/membrane damage) results in a decrease in bioluminescence [16]. The toxicity of benzene in air was determined using the Ecolum-5 [17].

Biodiesel production is been stimulated because of search for renewable fuels. The transesterification of vegetable oils or animal fats, with ethanol or methanol generates glycerol as the main byproduct. With the increasing production of biodiesel, glycerol is becoming of great environmental and economical concern due to its toxicity to aquatic organisms [18]; fermentation processes of this byproduct can result in value-added products, such as 1,3-propanediol (1,3-PD) and ethanol. The 1, 3-PD has many applications in polymers, cosmetics, foods, adhesives, lubricants, laminates, solvents, antifreeze, and in medicine; ethanol could be used in the esterification of biodiesel. Several bacterial strains have been isolated and characterized for their ability to convert this raw glycerol into 1, 3-propanediol (1, 3-PD) and ethanol [19,20]. Rossi et al. [21] showed that a *Klebsiella pneumoniae* strain was able to simultaneously produce up to 9.4 g/L of 1, 3-PD with yields of 0.41 mol product mol^{-1} glycerol and 6.1 g/L of ethanol with yields of 0.14 mol product mol^{-1} glycerol.

3. SYMBIOTIC BACTERIA

Symbiotic bacteria live in a mutually beneficial association with other organisms. Such bacteria derive the essential nutrients (proteins, carbohydrates and lipids) from their host organisms and in return, help the host through some of their biological activities. Plant growth-promoting bacteria can positively provide the plant with compounds which are synthesized by the bacteria or by facilitating the uptake of nutrients from the environment by the plant [22,23]. Nitrogen-fixing bacteria of *Rhizobium* genus can fix atmospheric nitrogen and supply it to plants (Fig. 2). Most of biological nitrogen fixation (80%) is carried out by diazotrophic bacteria, such as the *Rhizobium* genus, in symbiosis with legumes. Moreover, some bacteria which are free-living in soil (e.g., cyanobacteria, *Pseudomonas, Azospirillum*, and *Azotobacter*) may fix significant amounts of nitrogen [22].

Other bacteria can synthesize many compounds with positive effect on plants such as siderophores, chelating agents which has more affinity to metals than plant siderophores and can solubilize and sequester iron from the soil providing it to plant cells; antibiotics, which antagonize phytopathogenic fungi and pathogenic bacteria; phytohormones, including auxins and cytokinins, enhancing various stages of plant growth; and enzymes that can modulate plant growth and development [23,24,25].

Bacteria may be beneficial when they go into association with other organisms (plants and animals) in the removal of contaminants from the environment, a process called bioremediation [26]. Glick [23] reported that the symbiotic association of the bacterium *Enterobacter cloacae* in the roots of the plant *Brassica campestris* led to an increase in the number of seeds that germinated and the amount of biomass that the plant was able to attain due to reduction in the level of ethylene, an inhibitor of root elongation. Furthermore, the bacterium synthesized antibiotics which inhibited the proliferation and invasion of phytopathogens.

Additionally, bacteria can remove from the environment many potentially toxic compounds like metals, organic compounds (such as petroleum hydrocarbons and pesticides), inorganic compounds (such as compounds of arsenate, sodium, nitrate, ammonia or phosphate) as well as radioactive compounds of uranium, cesium or strontium [23]. The bacterium *Kluyvera* *ascorbata* protects *B. campestris* against high levels of nickel in the soil, which produce siderophores [27].

A group of bacteria called microbial flora (Fig. 3) are able to affect beneficially the host animal with contributions to nutrition, health and development. Microbial flora can secret vitamins; participate in the synthesis of proteins and nucleic acids; and act in the digestion of carbohydrates. The genera present in the intestinal tract (probiotic bacteria) generally seem to be those from the environment or the diet. Furthermore, microbial flora prevents colonization by pathogens by competing for attachment sites or for essential nutrients in the oral cavity, intestine, skin, and vaginal epithelium. Probiotics in aquaculture of genus *Lactobacillus* can prevent pathogens proliferating in the intestinal tract, on the superficial structures, or in the water [28].

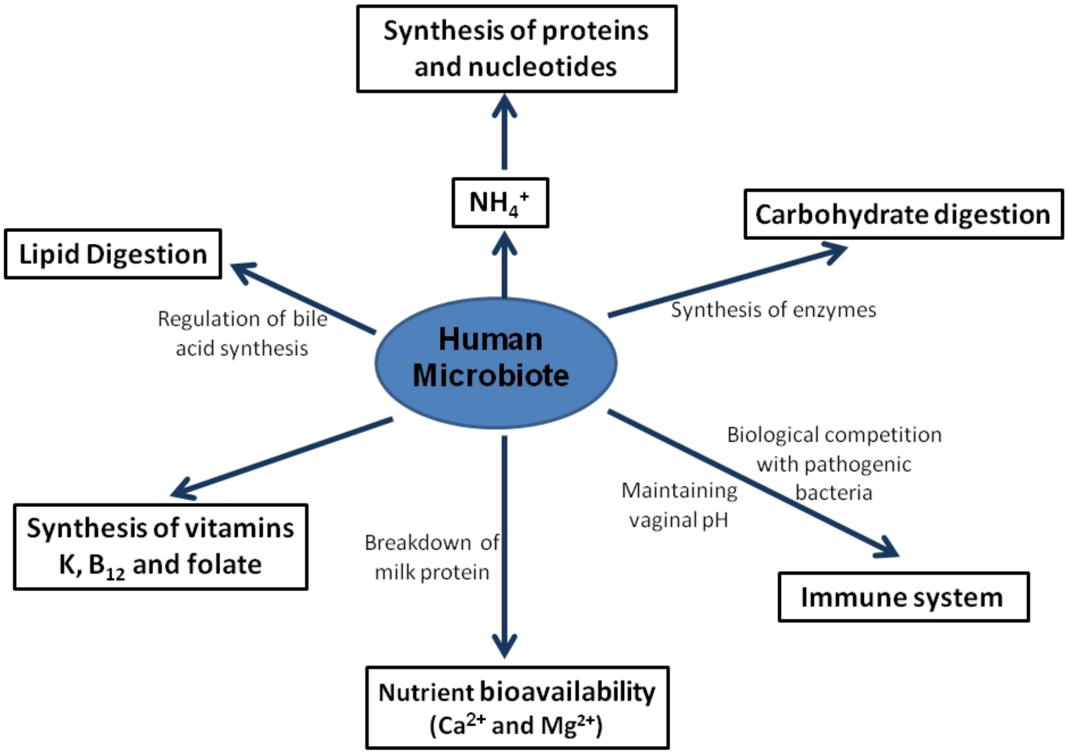

Fig. 3. Benefits of human microbiote

Probiotics can be used as biological control agents of other bacteria and fungi [29,30]. This function has been reported with lactic acid bacteria (*Lactobacillus* and *Pediococcus* genus) as biocontrol agents against the phytopathogenic and spoilage bacteria and fungi [31]. A bacterial strain (*Alteromonas haloplanktis*) isolated from the gonads of Chilean scallop displayed *in vitro* inhibitory activity against the pathogens *V. ordalii, V. parahaemolyticus, V. anguillarum, V. alginolyticus,* and *Aeromonas hydrophila* [32]. The exact modes of action of the probiotics are not well understood, but it is suggested that microbial populations may release chemical substances such as antibiotics, lysozymes, proteases, hydrogen peroxide and organic acids that have a bactericidal or bacteriostatic effects on other microbial populations. Rouse et al. [33] reported that the lactic acid bacteria *Pediococcus pentosaceous* produced antifungal peptides (not completely characterized), with potential applications in the food industry to prevent fungal spoilage of food. Other modes of action are by competition for nutrients as iron or adhesion sites on gut or other tissue surfaces, or by enhancement of the immune systems of animals against infections by viruses, bacteria, fungi and parasites [29].

Some bacteria may play an important role in the control of harmful algae blooms. Bacteria such as *Pedobacter* spp can act on many species of microalgae of red tide plankton such as, for example, *Microcyctis aeruginosa* [34]. Further studies will provide new insights into its role in water environment with prospects to use these algicidal bacteria as microbial pesticides.

Bacteria of microflora from mollusks such as bivalve are important in the digestive process, metabolism and metamorphosis [35]. Bacteria in the aquatic environment are used as food by adults and larvae of bivalve, providing nitrogen and carbon and recycling organic and mineral matter released by these aquatic organisms. Furthermore, marine bacteria, such as cyanobacteria, excrete various substances, including amino acids, carbohydrates, and vitamin B12. Prieur et al. [36] isolated cellulolytic bacteria from the digestive tract of the bivalve *Teredo navalis* that had the ability to degrade mannose and galactose. Belkin *et al*. [37] showed that certain bacteria can associate with the gill tissues of a mussel in deep ocean - *Bathymodiolus thermophilus* and help to fix CO_2 and thus aid autotrophic metabolism. Bivalve bacteria that live in sulphide-enriched habitats are important in the degradation of the organic matter through anaerobic metabolism [36].

Among the environmental factors that induce or influence metamorphosis of many marine invertebrates, the occurrence of bacterial films and organic particles trapped within the films could also be used as food by larvae ready to metamorphose. Alternatively, bacteria living in the biofilms could synthesize certain compounds such as low and high molecular weight polysaccharides, low molecular weight peptides and neurotransmitters, diffusible into the environment, which could induce metamorphosis. Water-soluble chemical compounds produced by the biofilms of two bacterial strains *Macrococcus sp*. and *Bacillus* sp. induced larval settlement of the green-lipped mussel, *Perna canaliculus* [38].

4. PARASITIC BACTERIA

Parasitic bacteria occur in the body of animals and plants and obtain their organic food or release poisonous secretions called toxins. Many of these toxins act specifically on some organisms. Thus, the majority of bacterial pathogens are highly specialized for a limited number of eukaryotic host organisms. Plant pathogenic bacteria (Fig. 4) are responsible for some of the most devastating losses of major agricultural crops and vital fruit trees, at a cost price of millions of dollars annually [39]. *Ralstonia solanacearum* is a soil borne bacterium, capable of inducing disease on more than 250 plant species by invading their roots, colonizing the xylem vessels and causing a lethal wilting known as bacterial wilt disease [40]. Seeds of cashew, cocoa, coffee, pumpkin and tomato are protected from this bacterial phytopathogen because they produce oligo- and poly-saccharides that block the pathogen lectins from binding to xylem cell wall glycans [41].

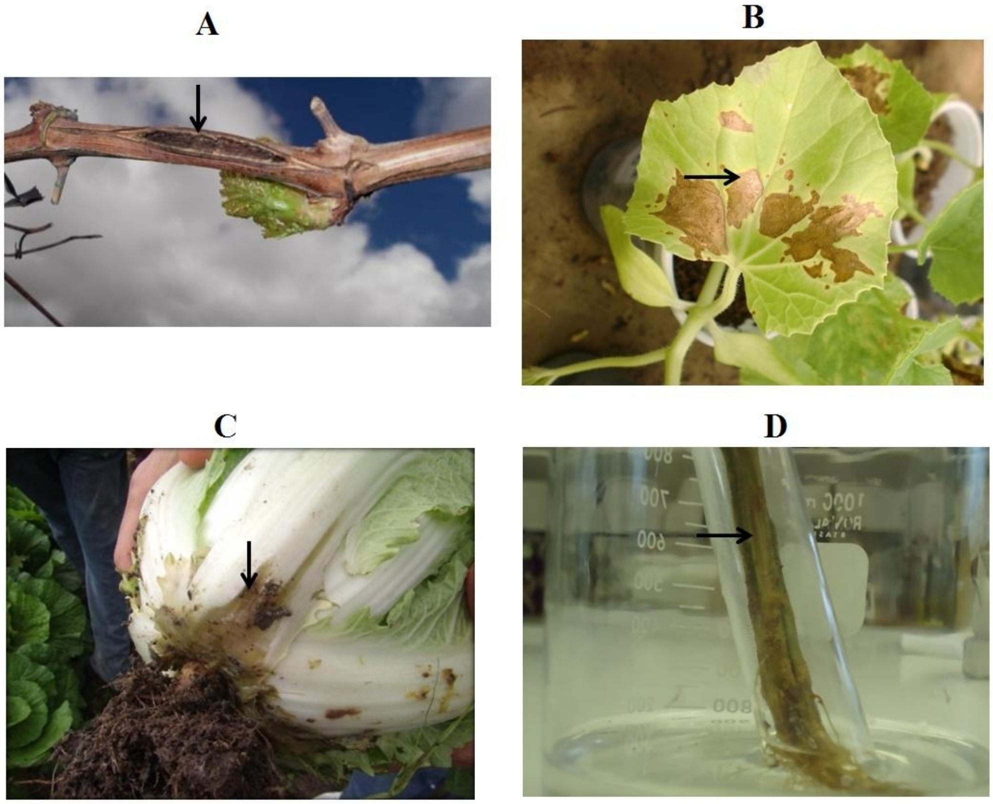

Fig. 4. Diseases caused by phytopathogenic bacteria. Bacterial canker of grapevine caused by *Xanthomonas campestris* pv. *viticola* (A); blotch of melon caused by *Acidovorax citrulli*, showing reddish-brown lesions on leaves (B); rooting of *Brassica pekinensis* by *Pectobacterium carotovorum* subsp. *carotovorum* (C); tomato wilt disease caused by *Ralstonia solanacearum*, showing colonization of xylem vessels (D)

Bacterial canker is another disease caused by a phytopathogen that has negative economic impact. Bacterial canker of grapevine caused by *Xanthomonas campestris* pv. *viticola* can manifest in various parts of the plant. In leaves, the symptoms are small, dark and angular leaf spots that may coalesce and dry up, causing necrotic areas and leaf blight. Cankers were often observed on petioles, stems and rachis and were also observed in grapes [42]. Blackleg, a major bacterial disease of potato, is caused by bacterial organism - *Pectobacterium carotovorum* subsp. *carotovorum*. This bacterium can cause rotting of potato tubers (soft rot) during storage. Control of potato blackleg is hampered by the absence of effective tools and strategies and by the dispersing ability of the bacterium, being spread via surface and rain water, by aerosols and also, by insects [43].

Acidovorax citrulli is the bacterial causal agent of bacterial fruit blotch, a devastating disease of melon (*Cucumis melo*) and other plants from the same family. Its destructive potential stems from the fact that, under favorable conditions to bacterial growth, infection spreads rapidly throughout the field [44]. Symptoms of bacterial fruit blotch including water-soaking and coalescing reddish-brown lesions on cotyledons and reddish-brown lesions on leaves that developed along the venation [45].

Among pathogenic bacteria to humans, there is *Staphylococcus aureus*, which is a coccus (spherical) microorganism usually with irregular distribution in clusters like bunches of grapes that is responsible for many infections in humans such as endocarditis, acute hematogenous osteomyelitis, meningitis or pulmonary infection. *E. coli*, which is a rod-shaped (a bacillus) organism, is part of the normal flora but can opportunistically cause diseases (such as urinary tract infection, diarrhea, meningitis and septicemia). *P. aeruginosa*, a mobile aerobic bacillus organism widely distributed in nature, is found in small groups of normal intestinal flora and on human skin. *P. aeruginosa* rarely causes disease in a healthy immune system, but in individuals with compromised immune systems, this bacterium infects the respiratory tract, urinary tract, burns, and also causes other blood infections [4].

5. ANTIBACTERIAL LECTINS

Antimicrobial peptides and polypeptides are promising candidates for use as raw materials for producing new antibiotics. The carbohydrate recognizing proteins known as lectins are noteworthy since they are able to interact with carbohydrates on bacterial cellular walls [46-48]. Lectins can agglutinate cells and precipitate polysaccharides, glycoproteins or glycolipids, without structural modifications [49]. The presence of lectins in a sample can be evaluated in a microtiter plate through incubation with erythrocytes. The linkage between lectins and glycoconjugates from erythrocyte surface maintains the cells agglutinated and suspended in solution.

Gomes et al. [50] isolated an antimicrobial chitin-binding-lectin from the leaves of the medicinal plant *Schinus terebinthifolius*. The authors reported that this lectin showed antibacterial activity against *E. coli* (MIC, minimal inhibitory concentration, of 28.5 µg⁄ml; MBC, minimal bactericidal concentration, of 115 µg⁄ml), *K. pneumoniae* (MIC of 3.59 µg⁄ml; MBC of 115 µg⁄ml), *Proteus mirabilis* (MIC of 3.59 µg⁄ml; MBC of 14.37 µg⁄ml), *P. aeruginosa* (MIC of 1.79 µg⁄ml; MBC of 14.37 µg⁄ml), *Salmonella enteritidis* (MIC of 0.45 µg⁄ml; MBC of 115 µg⁄ml), and *S. aureus* (MIC of 1.79 µg⁄ml; MBC of 7.18 µg⁄ml).

Lectins can also promote agglutination of bacterial cells [47]. Fig. 5 shows the agglutination of *S. aureus* promoted by *S. terebinthifolius* leaf lectin (SteLL) in assay tubes. The agglutination occurs through linkage between the carbohydrate binding sites of lectin and glycoconjugates from bacterial surface as schematized in Fig. 5A. The bacterial agglutination was inhibited in the presence of the carbohydrate inhibitor of SteLL (N-acetyl-glucosamine) as shown in Fig. 5B. The inhibition of bacterial agglutination by lectins after incubation with free carbohydrates or glycoconjugates ensures that the binding of lectins to bacteria involves the carbohydrate-binding sites.

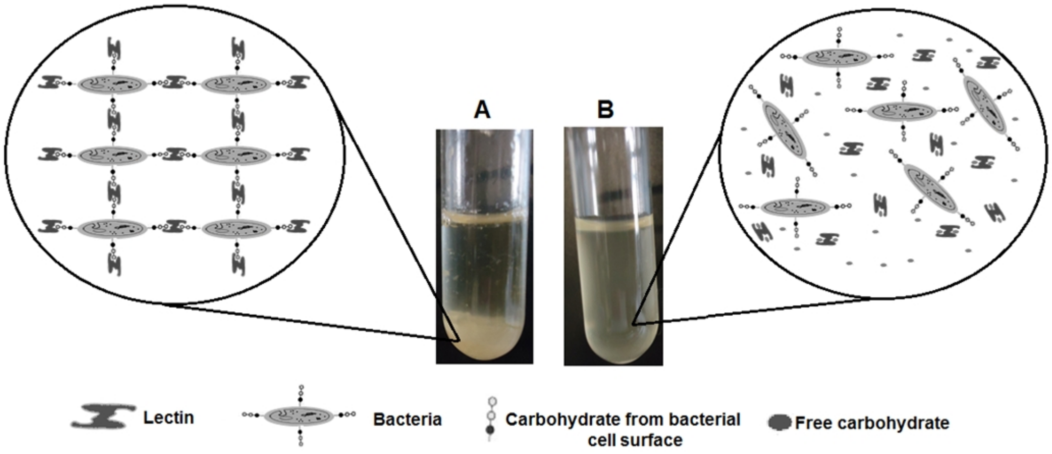

Fig. 5. (A) Agglutination of *Staphylococcus aureus* by incubation with the *Schinus terebinthifolius* leaf lectin (SteLL). (B) Inhibition of agglutination in the presence of the carbohydrate inhibitor of SteLL (N-acetyl-glucosamine). The circles show schematizations of the phenomena occurring in the assay tubes

Oliveira et al. [51] isolated an antibacterial lectin from *Eugenia uniflora* seeds (EuniSL), which inhibited the growth of *S. aureus*, *P. aeruginosa* and *Klebsiella* spp with MIC of 1.5 µg⁄ml. Additionally, EuniSL also inhibited the growth of *Bacillus subtilis*, *Streptococcus* spp and *E. coli*, although less efficiently (MIC of 16.5 µg⁄ml). Additionally, EuniSL was able to agglutinate *S. aureus*, *Streptococcus* spp, *Klebsiella* spp and *P. aeruginosa*.

MuHL, a chitin-binding-lectin isolated from *Myracrodruon urundeuva* heartwood, was able to inhibit the growth and agglutinate the gram-positive bacteria *S. aureus* (MIC of 0.58 µg⁄ml; MAC, minimal agglutinating concentration, of 2.34 µg⁄ml), *Enterococcus* (*Streptococcus*) *faecalis* (MIC of 2.34 µg⁄ml; MAC of 4.68), *B. subtilis* (MIC of 2.34 µg⁄ml; MAC of 4.68 µg⁄ml), and *Corynebacterium callunae* (MIC of 1.17 µg⁄ml; MAC of 4.68 µg⁄ml), as well as the gram-negative bacteria *E. coli* (MIC of 9.37 µg⁄ml; MAC of 9.37 µg⁄ml), *K. pneumoniae* (MIC of 9.37 µg⁄ml; MAC of 9.37 µg⁄ml) and *P. aeruginosa* (MIC of 4.68 µg⁄ml; MAC of 9.37 µg⁄ml) [52]. *M. urundeuva* heartwood is very resistant to the deteriorative biological agents and according to Sá et al. [52], the antibacterial activity of MuHL may be involved in this resistance.

A lectin isolated from the leaf of *Phthirusa pyrifolia* also showed antibacterial potentials being active against gram-positive bacteria such as *Staphylococcus epidermidis*, *Enterococcus* (*Streptococcus*) *faecalis* and *B. subtilis* and the gram-negative bacterium, *K. pneumoniae* with the MIC values ranging from 250 µg⁄ml to >2000 µg⁄ml [53]. WSMoL, a water-soluble lectin purified from seeds of *Moringa oleifera*, reduced the growth of *S. aureus* and *E. coli* and was also active against ambient lake water bacteria [54].

Antimicrobial lectins have also been isolated from animals. Nunes et al. [55] purified a lectin from *Bothrops leucurus* snake venom, which inhibited the growth of the gram-positive bacteria *S. aureus*, *E. faecalis* and *B. subtilis* with MIC of 31.25, 62.25 and 125 µg/ml, respectively. Table 1 lists antibacterial lectins and species against which they are active.

Table 1. Antimicrobial activity of lectins

Lectins	**Sources**	**Antibacterial activities**
Lectins from plants		
EuniSL	Seeds of *E. uniflora*	*S. aureus*, *P. aeruginosa* and *Klebsiella* sp
MuHL	Heartwood of *M. urundeuva*	*S. aureus*, *E. faecalis*, *B. subtilis*, *C. callunae*, *E. coli*, *K. pneumoniae* and *P. aeruginosa*
PpyLL	Leaves of *P. pyrifolia*	*S. epidermidis*, *E. faecalis*, *B. subtilis* and *K. pneumonia*
WSMoL	Seeds of *M. oleifera*	*S. aureus*, *E. coli* and bacteria from ambient lake water
SteLL	Leaves of *S. terebinthifolius*	*E. coli*, *K. pneumonia*, *P. mirabilis*, *P. aeruginosa*, *S. enteritidis* and *S. aureus*
Lectin from animal		
BIL	*B. leucurus* snake venom	*S. aureus*, *E. faecalis* and *B. subtilis*

References: [50-52,54,55]

Moura et al. [56] overviewed the processes involved in biofilm formation and in biocorrosion of pipes used for oil transportation, which occurs due to fixation of bacteria that release metabolites and form biofilms thus inducing or accelerating corrosion. The authors highlighted five groups of bacteria (EPS-producing bacteria, acid-producing bacteria, sulfur-oxidizing bacteria, iron-precipitating bacteria and sulfate-reducing bacteria) as promoters of biocorrosion. In addition, authors pointed out the use of biocides, protective coatings (antifouling) and corrosion inhibitors as the main methods applied by industries to prevent corrosive bacteria from spreading. It was then suggested that plant compounds, including lectins should be used for controlling biocorrosion.

6. BACTERIA AS BIOLOGICAL CONTROL AGENTS

Pesticides are used to control organisms that are considered harmful [57]. However, the main problem with the use of chemical pesticides is the development of resistance, resulting in reduced efficiency of the product and increased environmental risk. Pesticides are one of the causes of water pollution and some pesticides are persistent organic pollutants which contribute to soil contamination [58].

Bacteria have been studied as safer and more eco-friendly alternatives for the control of postharvest decays caused by fungi. The bacteria used for this purpose usually act as antagonistic microorganisms probably through competition for nutrients and space as well as by production of antibiotics, direct parasitism, and possibly induced resistance in the harvested commodity. *B. subtilis* has been used as an antagonist for phytopathogenic fungi that attack fruits [59].

Investigations carried out by Yoshiyama and Kimura [60] showed that seven bacterial strains belonging to *Bacillus* genus, isolated from the digestive tract of the Japanese honeybee (*Apis cerana japonica*), inhibited the development of the gram-positive bacterium *Paenibacillus larvae*, the causal agent of American foulbrood. This disease is contagious and affects the larval and pupal stages of honeybees. The authors suggested that these *Bacillus* strains can be used for control of this disease by acting as antagonists of *P. larvae*.

An alternative is the use of *Bacillus thuringiensis*, a bacterium that produces toxins with hemolytic and cytolytic activities. This versatile pathogen is capable of infecting protozoans, nematodes, flatworms, mites and insects [61]. *B. thuringiensis* is characterized by the production of crystals composed of proteins known as deltaendotoxins that are toxic to insect pests [62].

B. thuringiensis (Bt), before 1976, was used exclusively for the control of insect pests in agriculture. The discovery of a pathogenic strain against Diptera, called Bt israelensis (Bti) initiated the use of this bacterium in the control of the vector disease. Insects such as *Aedes aegypti* (of the Culicidae family) - vector of dengue and yellow fever- and *Simulium* spp. (of Simuliidae family), transmitters of filariasis, are included in the Diptera order. The use of bacteria for biological control of insect larvae from Culicidae and Simuliidae family has been highlighted by having more kinds of formulation (granules, powder or liquid), genetic stability, not toxic to humans, besides being more advantageous considering social and environmental costs of using non-selective insecticides in aquatic ecosystems [63].

A strategy used in Brazil as part of the National Program of Dengue Control is the biological control with *Bacillus thuringiensis* serovar *israelensis* (Bti). The endotoxin Cry1AC, produced during Bti sporulation, is digested by enzymes of larvae midgut releasing larvicidal toxins; tablet containing spore and crystals (15%, w/w) of *B. thuringiensis* was able to cause 100 % mortality of larvae and was suggested for use in programs to control dengue vector [64]. Cry1AC has an *N*-acetylgalactosamine-specific lectin domain that binds glycoconjugates at insect midgut [65,66]. Another example of larvicidal protein produced by bacterial strains is that from *Bacillus sphaericus*, which was lethal to the 3rd instar larvae of *Culex pipiens*, the vector of the West Nile fever and the Rift Valley fever [67].

7. CONCLUSION

The purpose of this review was to re-evaluate the biological importance of bacteria to the environments, how they are used as biological control agents and the importance of lectins in controlling pathogenic bacteria that affect animals (including humans) and plants. Moreover, this review re-emphasizes biotechnological applications of bacteria in many areas of human interest. This review was motivated by the lack of adequate knowledge about the ecology of bacteria and use of plant lectins as antimicrobial agents.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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