Lysinibacillus Species: Their Potential as Effective Bioremediation, Biostimulant, and Biocontrol Agents

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ABSTRACT

The use of synthetic chemicals has increased drastically due to industrialization and urbanization. However, the long-term and indiscriminate use of these chemicals has a negative impact on environment and human health; thus, public concerns about the hazardous effects of such synthetic chemicals are increasing day by day. To solve these problems, the exploitation of potential alternatives has become a major challenge, and the admiration of beneficial microbes is increasing due to their safe and environment-friendly nature. Microbes can mitigate the hazardous effects of synthetic chemicals by reducing their use and toxicity. Lysinibacillus species are gram-positive, spore-forming, motile bacteria. This genus was previously designated as Bacillus spp. under the family Bacillaceae of the phylum Firmicutes. For a long period of time, Lysinibacillus is well-known for its insecticidal activity against various insects, including mosquitoes, which are the vector of several human diseases. In addition, some Lysinibacillus species have a potential for heavy metal remediation. In recent years, Lysinibacillus spp. are attracting the researchers’ attention as plant growth-promoting and disease control agents, which would be used as alternatives to agrochemicals. This study gives an overview of the entomopathogenic, bioremediation, plant growth-promoting, and biological disease control abilities of the genus Lysinibacillus.

Keywords

biocontrol, bioremediation, entomopathogen, lysinibacillus, plant growth promotion

1. Introduction

Industrialization and urbanization considerably increased the living standard of the people. However, due to several industrial developments, huge quantities of industrial wastes are produced. Many kinds of pollutants are also discharged to the environment. For example, mining operations are conducted to collect several metals which are used in metal industries. However, during the operations, the surrounding environment gets contaminated with heavy metals. In agricultural industries, chemical fertilizers and pesticides are widely used to enhance food production and meet the global food demand. However, the indiscriminate use of agricultural chemicals deteriorates the soil quality and pollute the air, water, and soil. On the other hand, due to urbanization, the cities become overcrowded, which provides suitable conditions for the vectors to transmit infectious diseases, causing several health problems. Various chemical insecticides are used to control these insect vectors and they also pollute the environment. In recent years, public concerns about the long-term effects of synthetic chemicals on the environment and human health are increasing. Therefore, the reduction of synthetic chemical use and pollutants becomes a major challenge. There are certain types of microbes that can be used to mitigate the hazardous effects of synthetic chemicals. Due to their safe and environment-friendly nature, the admiration for microbes is increasing day by day. Microbes can be found in any part of the biosphere, and their ecological functions are still widely used to control various diseases and vectors.
largely unknown [1]. *Bacillus thuringiensis*, a well-known entomopathogenic bacterium, can control a wide range of insect vectors which transmit infectious diseases in humans [2]. *Bacillus* and some other bacteria have the ability to remediate heavy metal-contaminated sites [3]. Nowadays, *Bacillus, Pseudomonas*, and *Rhizobium*-based commercial products to improve crop production are available in the market. Moreover, a wide range of microbes, such as *Agrobacterium, Bacillus, Pseudomonas*, and *Trichoderma*, are used for the formulation of biocontrol products which can efficiently suppress different types of plant pathogens [4]. Among these bacteria, the genus *Bacillus* is the common active ingredient of most microbe-based products, because it produces endospores which are highly resistant, specialized structures that can withstand different environmental conditions and make commercial formulation easier [5]. Thus, *Bacillus*-based products have gained the trust of the growers. To increase the repertory of microbe-based products, researchers have been searching for such type of promising agents. *Lysinibacillus*, a new genus which was recently reclassified from *Bacillus*, have been reported to have the potential to control pests, remediate heavy metal-contaminated environments, and increase crop yields. Because *Lysinibacillus* has the ability to produce endospores, it can be considered as a suitable agent for microbial products. This review gives an overview of the entomopathogenic, bioremediation, plant growth-promoting, and biological disease control abilities of the genus *Lysinibacillus* based on the information collected from previous studies.

2. Taxonomy

*Lysinibacillus* species were previously classified as members of the genus *Bacillus*. Along with a novel species (*Lysinibacillus boronitolerans*), two previously classified species, *Bacillus sphaericus* and *Bacillus fusiformis*, were reclassified to the new genus *Lysinibacillus* based on their unique peptidoglycan composition, physiology, and molecular phylogenetic position based on 16S rRNA gene sequences [6]. In cell wall peptidoglycan, lysine and aspartic acid are present as the diagnostic amino acids, representing the A4a (Lys-Asp) type of cell wall peptidoglycan [7, 8]. Due to the presence of the Lys-Asp type of peptidoglycan in the cell wall, it was named *Lysinibacillus*. Diphosphatidylglycerol, phosphatidylglycerol, and ninhydrin-positive phosphoglycolipid are the major polar lipids, and menaquinone MK-7 is the dominant respiratory lipoquinone system of the genus. Iso-C15:0 is the major cellular fatty acid. The G+C content is 35–38 mol%. They are positive for oxidase and catalase tests, and negative for indole and H2S production, nitrate reduction, and β-galactosidase (ONPG) tests. The cells are motile, rod-shaped, and produce spherical or ellipsoidal endospores [9].

Another 26 species were identified as new members of *Lysinibacillus*, which are enlisted in LPSN-bacterio-net (http://www.bacterio.net/lysinibacillus.html) and NCBI (http://www.ncbi.nlm.nih.gov/) (Table 1).

| Species                  | References         |
|--------------------------|--------------------|
| *Lysinibacillus acetophenoni* | Azmatunnisa et al., 2015 [10] |
| *Lysinibacillus alkaliphilus* | Zhao et al., 2015 [11] |
| *Lysinibacillus alkalisoli* | Sun et al., 2017 [12] |
| *Lysinibacillus antri Narsing* | Rao et al., 2019 [13] |
| *Lysinibacillus boronitolerans* | Ahmed et al., 2007 [9] |
| *Lysinibacillus capsici* | Burkett-Cadena et al., 2019 [14] |

(Continued)
Table 1: List of validly published species of *Lysinibacillus* (Continued)

| Species                                 | References                  |
|-----------------------------------------|-----------------------------|
| *Lysinibacillus chungkukjangi*          | Kim et al., 2013 [15]       |
| *Lysinibacillus composti*               | Hayat et al., 2014 [16]     |
| *Lysinibacillus contaminans*            | Kämpfer et al., 2013 [17]   |
| *Lysinibacillus cresolivorans*          | Ren et al., 2015 [18]       |
| *Lysinibacillus endophyticus*           | Yu et al., 2016 [19]        |
| *Lysinibacillus fusiformis*             | Ahmed et al., 2007 [9]      |
| *Lysinibacillus halotolerans*           | Kong et al., 2014 [20]      |
| *Lysinibacillus louembei*               | Ouoba et al., 2015 [21]     |
| *Lysinibacillus macroides*              | Coorevits et al., 2012 [22] |
| *Lysinibacillus manganicus*             | Liu et al., 2013 [23]       |
| *Lysinibacillus mangiferihumi corrig.*  | Yang et al., 2012 [24]      |
| *Lysinibacillus massiliensis*           | Jung et al., 2012 [25]      |
| *Lysinibacillus meyeri*                 | Seiler et al., 2013 [26]    |
| *Lysinibacillus odysseyi*               | Jung et al., 2012 [25]      |
| *Lysinibacillus pakistanensis*          | Ahmed et al., 2014 [6]      |
| *Lysinibacillus parviboronicapiens*     | Miwa et al., 2009 [27]      |
| *Lysinibacillus sinduriensis*           | Jung et al., 2012 [25]      |
| *Lysinibacillus sphaericus*             | Ahmed et al., 2007 [9]      |
| *Lysinibacillus tabacioli*              | Duan et al., 2013 [28]      |
| *Lysinibacillus telephonicus*           | Rahi et al., 2017 [29]      |
| *Lysinibacillus varians*                | Zhu et al., 2014 [7]        |
| *Lysinibacillus xylanilyticus*          | Lee et al., 2010 [30]       |
| *Lysinibacillus yapensis*               | Yu et al., 2019 [31]        |

3. Beneficial effect as bioinsecticide

Insect pests and vectors of important human diseases are controlled primarily through the use of chemical pesticides. However, the indiscriminate use of chemicals to kill the pests will also kill beneficial insects, such as honeybee, hover flies, and parasitic wasps [32]. Moreover, the overuse and misuse of insecticides result in the development of high resistance of insect pests to various insecticides [33]. These problems drive the demand for alternative methods of pest control. Recently, microbial insecticides are acquiring the admiration of researchers due to their safe and ecofriendly nature. Various entomopathogenic microbes are used as active ingredients of microbial insecticides.

*L. sphaericus* is well-known for its entomopathogenic activity [34]. This bacterium was first reported as a pathogen of mosquito in 1965 [35]. Since then, an intensive isolation and screening program was organized by
WHO [36, 37]. *L. sphaericus* strain 1593, which exhibited a strong larvicidal activity against mosquito, was isolated from dead mosquito larvae in Indonesia [37]. Since *L. sphaericus* is a potential agent for controlling malaria vector mosquito, it became a matter of interest for researchers. Today, various *L. sphaericus*-based vector control products, such as GRISELESF® (LABIOFAM, Habana, Cuba), Sphaerus SC (Bthek Ltda, Santa Maria, Brazil), VextoLex FG (Valent Biosciences, Illinois, USA), and Spherimos (Novo Nordisk, Bagsværd, Denmark) [38], are commercially available worldwide. Regis et al. [39] reported that the application of Spherimos controlled the southern house mosquitoes (*Culex quinquefasciatus*), which is the vector of filariasis. After the application of Spherimos, the population density of mosquitoes was significantly lowered for at least five months, and infective bites were reduced by approximately 60%. Another commercial formulation of *L. sphaericus*, Vectolex CG®, was effective in controlling Saint Louis encephalitis vector mosquitoes (*Aedes triseriatus, Culex pipiens*, and *Culex restuans*) and malaria vector (*Anopheles gambiae sensu lato*) [40, 41]. The formulation provided 100% larval mortality against Giles mosquitoes within 24 h of application, and its effectiveness lasted for up to 11 days [40].

*L. sphaericus* is pathogenic not only against mosquitoes, but also to other insect pests, such as German cockroach (*Blattella germanica*), common cutworm (*Spodoptera litura*), and nematodes [38, 42], which indicates that *L. sphaericus* may be useful for controlling a wide range of insect and animal pests. Entomopathogenic *L. sphaericus* produces various insecticidal toxins, such as sphaericolysin, mosquitocidal toxins, binary (Bin) toxin, Cry48/Cry49 toxin, and S-layer protein [38]. The pathogenicity of the bacterium against insects is attributed primarily to Bin toxin, which is produced in the final stages of sporulation [43]. Bin toxin-producing strains of *L. sphaericus* display a strong insecticidal activity against mosquitoes [44].

### 4. Potential as a metal bioremediation agent

In the past few decades, the world is facing the problem of various environmental pollution due to the increasing human activities [45]. Soil and water pollution with heavy metals, fuels, synthetic compounds, and petroleum industry products are the serious ecological threats we face today. Heavy metals are commonly used in agriculture and industries to manufacture pesticides, alloy, and electric and electronic products. On the other hand, toxic heavy metals discharged from those products, industrial effluents, and mining operations often pollute the environment [46].

For the treatment of industrial effluents, precipitation, ion exchange, electrochemical processes, and membrane processes are commonly used. However, due to technical or economic constraints, the application of these processes is sometimes incompetent [47]. Bioremediation offers efficient, cost effective, and ecofriendly techniques over traditional methods [48]. Bioremediation is a technique which uses microbes to clean up the contaminants in the environment. It is an important tool for environmental remediation of non-biodegradable heavy metals.

Four *Lysinibacillus* species (*L. sphaericus, L. fusiformis, L. xylanilyticus*, and *L. macrolides*) were reported to have bioremediation potential [49, 50]. Generally, two mechanisms are involved in the bioremediation process of *Lysinibacillus*. The first one is an enzymatic reduction by which toxic heavy metals are converted into non-toxic forms. Gupta et al. [51] reported that the mercury-tolerant strain of *L. fusiformis* can transform the toxic HgCl₂ to HgCl through enzymatic reduction. Similarly, two *Lysinibacillus* strains (*L. xylanilyticus* and *L. marcoide*) showed promising results in reducing toxic Se oxyanions into elemental Se nanoparticles [52]. In addition, Bafana et al. [53] reported that *L. sphaericus* can detoxify Cr and Hg by reducing them. The second mechanism is biosorption, which is the binding of metal ions with metal-binding proteins present on the bacterial cell wall. Some *Lysinibacillus* spp. accumulate or remove toxic metals through biosorption process [54, 55, 56, 57, 58, 59].
structural components of the cell wall of *Lysinibacillus* spp., such as hydroxyl, carbonyl, carboxyl, amide, imidazole, phosphate, phosphodiester groups, and paracrystalline surface layer (S-layer) protein play a vital role in biosorption [50, 60, 61, 62]. The metal ions get attached to the functional groups or protein layer, followed by binding of metal ions to the reactive groups present on bacterial cell wall; the internalization of metal ions occurs inside the cell [63].

5. Emerging research in the field of crop production

In the last few decades, plant-beneficial bacteria have drawn special attention from the scientific communities and agriculture industries due to their potential to enhance crop productivity in an environment-friendly manner. Hence, there is an ongoing search for beneficial microbes. The rhizospheric and endophytic strains of *Lysinibacillus* have been increasingly investigated for their beneficial effects on plants. While the studies are still minimal, many reports have highlighted the possible contribution of *Lysinibacillus* spp. to plant growth and health.

### 5.1 Plant growth promotion by *Lysinibacillus* spp.

It is well-known that certain plant-associated bacteria can enhance plant growth. These beneficial bacteria are generally known as plant growth-promoting rhizobacteria (PGPR) or plant growth-promoting bacteria (PGPB). Genera such as *Pseudomonas*, *Bacillus*, *Azospirillum*, *Azotobacter*, and *Rhizobium* are some of the most prominent PGPR or PGPB. PGPR/PGPB can directly and indirectly stimulate plant growth through various mechanisms, such as mineral solubilization, nitrogen fixation, phytohormone production, and so on [64].

**Table 2: *Lysinibacillus* species with different plant growth-promoting traits**

| (Expected) effects | Species | Origin | Traits | References |
|--------------------|---------|--------|--------|------------|
| Increase in plant biomass | *L. sphaericus* Epiphytic bacteria | Spinach | P solubilization, IAA production, NH₃ production | Sharma and Shaharan, 2015 [65] |
| Endophytic bacteria | *L. fusiformis* | Ginseng | P solubilization, IAA production, siderophore production | Vendan *et al.*, 2010 [66] |
| | *L. fusiformis* | Citrus | P solubilization, IAA production, N fixation, siderophore production, ACC deaminase production | Trivedi *et al.*, 2011 [67] |
| | *Lysinibacillus* sp. | Banana | P solubilization | Andrade *et al.*, 2014 [68] |
| | *L. xylanilyticus* | Rice | P solubilization, IAA production, N fixation, K solubilization | Tan *et al.*, 2015 [69] |
| | *L. fusiformis, L. changkukjangi* | Corn | IAA production | Yu *et al.*, 2016 [70] |
| | *L. sphaericus* | Rice | Nitrogenase activity, IAA production, GA production, CK production, ACC deaminase production | Shabanamol *et al.*, 2018 [71] |
| | *Lysinibacillus* sp. | Undescribed | P solubilization, IAA production | Sahu *et al.*, 2018 [72] |
| | *Lysinibacillus* sp. | Tea | P solubilization, IAA production, siderophore production, ACC deaminase production | Borah *et al.*, 2019 [73] |
| | *L. fusiformis* | Apple | IAA production, siderophore production | Passera *et al.*, 2020 [74] |

(Continued)
Table 2: *Lysinibacillus* species with different plant growth-promoting traits (continued)

| (Expected) effects | Species                    | Origin          | Traits                                                                 | References                                      |
|--------------------|----------------------------|-----------------|----------------------------------------------------------------------|------------------------------------------------|
| Increase in plant biomass | Rhizobacteria             |                 |                                                                      |                                                 |
|                     | *L. fusiformis*            | Soybean, rice   | Nitrogenase activity, IAA production                                  | Park *et al*., 2005 [75]                        |
|                     | *Lysinibacillus* sp.      | Rice            | IAA production, ACC deaminase production, SA production              | Islam *et al*., 2013 [76]                      |
|                     | *L. xylanilyticus*        | Wheat           | NH₃ production, ACC deaminase production, Zn solubilization          | Verma *et al*., 2014 [77]                      |
|                     | *L. sphaericus*           | Wheat           | N fixation, IAA production, P solubilization, K solubilization, Zn solubilization | Verma *et al*., 2016 [78]                      |
|                     | *Lysinibacillus* sp.      | Maize           | P solubilization, IAA production                                      | Abiala *et al*., 2015 [79]                     |
|                     | *L. sphaericus*           | Undescribed     | N fixation                                                           | Labuschagne *et al*., 2015 [80]                |
|                     | *L. fusiformis*           | Tomato          | No data                                                              | Rahmoune *et al*., 2017 [81]                   |
|                     | *L. sphaericus*           | Maize           | IAA production, siderophore production, P solubilization, K solubilization, Si solubilization | Naureen *et al*., 2017 [82]                    |
|                     | *L. sphaericus*           | Pumpkin         | P solubilization                                                    | Sule *et al*., 2020 [83]                       |
|                     | *L. fusiformis*           | Wheat           | IAA production                                                       | Akinrinlola, 2018 [84]                        |
| Others              | *L. fusiformis, L.        | Forest          | P solubilization, IAA production                                      | De Mandal *et al*., 2018 [85]                  |
|                    | *xylanilyticus*            |                 |                                                                      |                                                 |
| Growth promotion under salt stress conditions | Endophytic bacteria |                 |                                                                      |                                                 |
|                     | *L. fusiformis*           | Argentine screwbean | N fixation, IAA production, GA production, ABA production | Sgroy *et al*., 2009 [86]                      |
|                    | *Lysinibacillus* spp.     | Various plants  | P solubilization, IAA production, extracellular enzymes production   | Kumar *et al*., 2017 [87]                      |
| Others              | *Lysinibacillus* sp.      | Compost         | Increase in chlorophyll contents of plants, enhancement of antioxidant enzymes in plants | Duo *et al*., 2018 [88]                        |
| Growth promotion under metal stress conditions | Rhizobacteria            |                 |                                                                      |                                                 |
|                     | *L. varians*              | Waste contaminated soil | Cd and Pb bioaccumulation, NH₃ production, IAA production, P solubilization, siderophore production | Pal and Sengupta, 2019 [89]                    |
|                     | *Lysinibacillus* sp.      | Giant bulrush   | Pb tolerance, NH₃ production, IAA production                          | Kamaruzzaman *et al*., 2020 [90]               |
| Others              | *L. sphaericus*           | Culture collection | N fixation, nitrification, IAA production                             | Martinez and Dussán, 2018 [91]                 |
|                     | *L. fusiformis, L.        | Soil            | IAA production, K solubilization, siderophore production             | Jinal *et al*., 2019 [92]                      |
|                    | *mangiferithumi*          |                 |                                                                      |                                                 |
|                     | *Lysinibacillus* spp.     | Zn polluted soil | Zn tolerance, K solubilization, IAA production, siderophore production | Jinal *et al*., 2020 [93]                      |
In recent studies, it was demonstrated that *Lysinibacillus* spp. (e.g., *L. sphaericus*, *L. fusiformis*, *L. chungkukjangi*, and *L. xylanilyticus*) also possess diverse beneficial traits related to plant growth promotion (Table 2). Phosphorus, one of the three macromolecules essential for plant growth, is required in various metabolic pathways [94]. Many *Lysinibacillus* spp. were reported to exhibit the capacity to solubilize fixed inorganic phosphorus compounds into soluble P form that can be easily assimilated by plants. Moreover, several *Lysinibacillus* strains can solubilize other important insoluble minerals, such as potassium, iron, zinc, and silicate [66, 78, 82]. The secretion of organic acids, hydrolytic enzymes, and metal chelator compounds from these *Lysinibacillus* spp. was reported to facilitate the conversion of insoluble minerals into bioavailable forms [67, 82].

Nitrogen is the most limiting primary element for plant growth and productivity. Plants absorb nitrogen from the soil through their roots, but the amount of bioavailable nitrogen is limited in the rhizosphere. Although nitrogen gas makes up about 80% of the earth’s atmosphere, plants are not able to use it in that form [95]. Some *Lysinibacillus* can fix nitrogen as ammonia [65, 69, 96]. Nitrogen fixation by bacteria is accomplished through the catalytic action of complex enzyme system known as nitrogenase encoded by *Nif* genes. Studies showed that *Lysinibacillus* spp. harbor the *Nif* genes and produce nitrogenases [71, 75, 91].

Phytohormones play important roles in plant growth and development as well as various biotic and abiotic stress tolerance [97]. The ability to synthesize indole-3-acetic acid (IAA), gibberellin, and cytokinin is associated with plant growth promotion by PGPR/PGPB [98, 99]. Some *Lysinibacillus* spp. also produce these hormones [70, 71, 88, 100].

Remarkable improvement in crop growth and yield in response to *Lysinibacillus* inoculation was reported by several research groups. Sule *et al.* [83] recently reported that soil drenching with phosphate-solubilizing *L. sphaericus* strain isolated from the pumpkin rhizosphere significantly improved the shoot growth of maize plants. Similarly, root inoculation with endophytic IAA-producing strains of *L. fusiformis* and *L. chungkukjangi* increased the root and shoot biomass of soybean and wheat plants [70]. Moreover, root inoculation with IAA- and siderophore-producing strain of *L. fusiformis* enhanced the shoot growth of various crop plants, including sweet pepper, hot pepper, chicory, green bean, and leak, and significantly increased the fruit weight of Zucchini under commercial greenhouse conditions [74].

Abiotic stress has had a persistent negative impact on the plant growth, leading to significant crop losses in agriculture. *Lysinibacillus* spp. were also reported to enhance plant tolerance to different abiotic stresses and improve plant growth under adverse stress conditions [86, 87, 92]. Salinity is one of the major problems affecting crop production worldwide [101]. Kumar *et al.* [87] reported that seed bacterization with salt-tolerant *Lysinibacillus* sp. effectively enhanced the growth of rice seedlings under salinity stress. Moreover, the contamination of agricultural lands with trace metals, such as Al, Mn, Cu, Pb, and Zn, negatively affects plant growth and causes crop yield reduction [102]. *Lysinibacillus* spp. can promote plant growth under metal stress condition [91, 92, 93]. For example, the growth of jack bean in Pb-contaminated soil was significantly improved by soil inoculation with Pb-tolerant *L. sphaericus* strains [91]. Zn-tolerant *Lysinibacillus* spp. were also reported to show growth-promoting effect on maize planted in Zn-contaminated soil [93]. Although the detailed mechanisms of plant growth promotion by *Lysinibacillus* are not fully understood, the accumulation of antioxidant molecules (proline, phenol, and ascorbic acid) and enzymes (peroxidase, superoxide dismutase, and catalase) in the plant may play a vital role in plant growth improvement under different stress conditions [83, 85].
5.2 Biocontrol potential of *Lysinibacillus*

Plant diseases caused by pathogenic microbes pose significant and persistent threat to agricultural production [103]. The estimated potential yield loss due to plant disease is up to 16% globally [104]. Chemical pesticides are widely used to control of plant diseases. However, the long-term and indiscriminate use of chemical pesticides frequently resulted in the development of resistant pathogens. Moreover, it has also been causing several negative effects in the environment and natural ecology. Therefore, the application of beneficial microbes is suggested as an alternative to chemical pesticides for an effective environment-friendly approach to control the plant diseases [105].

| Species       | Origin      | Target pathogens/disease                                 | Traits                                                                 | References |
|---------------|-------------|----------------------------------------------------------|------------------------------------------------------------------------|------------|
| *L. fusiformis* | Apple       | *Aspergillus niger*, *Botrytis cinerea*, *Phomopsis viticola*, and *Rhizoctonia solani* | Production of antifungal compounds                                     | Passera et al., 2020 [74] |
| *L. sphaericus* | Rice        | *Rhizoctonia solani*                                      | Mycolytic activity                                                      | Shabanamol et al., 2018 [71] |
| *L. sphaericus* | Rice        | Rice sheath blight (*Rhizoctonia solani*)                 | Induction of systemic resistance, production of antifungal volatile compounds, biosurfactant, HCN, and siderophore | Shabanamol et al., 2017 [96] |
| *L. fusiformis* | Citrus      | *Candidatus Liberibacter asiaticus*                       | Production of salicylic acid and chitinase                             | Trivedi et al., 2011 [67] |
| *L. sphaericus* | Maize       | *Alternaria alternata*, *Curvularia lunata*, *Aspergillus sp.*, *Sclerotinia sp.*, *Bipolaris spicifera*, and *Trichophyton sp.* | Production of antifungal metabolites, hydrolytic enzymes, and siderophore | Naureen et al., 2017 [82] |
| *Lysinibacillus* sp. | Maize   | *Fusarium verticillioides*                                | Chitinase production                                                    | Abiala et al., 2015 [79] |
| *L. fusiformis* | Chickpea    | *Fusarium oxyzorum*, *Fusarium solani*, and *Macrophomina phaseolina* | Production of chitinase, protease, and β-endoglucanase                  | Singh et al., 2013 [106] |
| *L. sphaericus* | Culture collection | *Meloidogyne incognita*                                        | Chitinase production                                                   | Abdel-Salam et al., 2018 [107] |

*Lysinibacillus* species were reported to have a biocontrol potential against a wide range of plant pathogens (Table 3). Among the 28 species of *Lysinibacillus*, only two species, *L. sphaericus* and *L. fusiformis*, were reported as potential agents that control several plant diseases. Different types of antimicrobial compounds are produced by *Lysinibacillus* spp., which may be associated with disease control activity. *Bacillus* spp., which have a biocontrol ability against plant diseases, were reported to produce a wide variety of antimicrobial compounds, such as...
hydrogen cyanide, chitinase, volatile compounds, and biosurfactants [108]. *Lysinibacillus* spp. also produce some of these antimicrobial compounds. The production of cell wall-degrading enzymes, such as chitinase, glucanase, and protease, are well-known mechanisms for biocontrol. Cell wall-degrading enzyme-producing *Lysinibacillus* can suppress the hyphal growth of fungi. These antimicrobial *Lysinibacillus* strains effectively control the diseases caused by fungi and nematodes [74, 79, 107]. Additionally, the inoculation of *Lysinibacillus* can suppress viral diseases [74]. In this case, disease suppression is attributed to plant immunity activated by *Lysinibacillus*. The plant immunity enhanced by *Lysinibacillus* is also effective against fungal disease caused by *Rhizoctonia solani* in rice plants [96].

6. Conclusions

Industrialization and urbanization have promoted the economic growth and improved the quality of our lives. However, numerous chemical pollutants have also been discharged into the environment, leading to various problems, such as environmental degradation, ecological disturbance, and health consequences. Therefore, the challenge that we face is to maintain the benefits of industrialization and urbanization while minimizing their negative impacts.

Several strategies are used to reduce the pollutant load generated by human activities and chemical pollutants concentrated in the environments. One of the strategies is the use of beneficial microbes residing in natural ecosystem. Microbes can mitigate the hazardous effect of synthetic chemicals by reducing their use and toxicity. As reviewed in this paper, *Lysinibacillus* have multifarious abilities, such as entomopathogenic, bioremediation, plant growth-promoting, and biocontrol abilities; thus, it was thought to be a good source of biopesticide, plant biostimulant, and bioremediation agent. In the future, *Lysinibacillus* based microbial products could be promising to mitigate the hazardous effect of chemical pollutants.

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