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Current Progress in *Bacillus* by Bibliographic Analysis

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Abstract: *Bacillus*, a versatile microorganism, has widespread industrial applications, particularly in the fields of biotechnology and environmental sustainability. This study uses bibliographic analysis through VOSviewer to explore key trends in *Bacillus* research, identifying significant keywords, organizations, and countries or regions leading the field. One notable discovery is the potential use of *Bacillus* in cement production, where its incorporation can enable self-healing of cracks in cement. This self-healing property can significantly reduce maintenance and labor costs in construction. Furthermore, the study highlights future opportunities for *Bacillus* research, particularly the integration of big data and machine learning. By leveraging large-scale data and advanced algorithms, *Bacillus* applications can be optimized for various industries, offering more efficient and sustainable solutions. This study provides insights into both current applications and future research directions for *Bacillus* in industrial settings.

Keywords: *Bacillus*; Bibliography; VOSviewer; Big Data; Machine Learning

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1. Introduction

Bacillus, a genus of microorganisms, is gaining increasing attention due to its diverse industrial applications [1,2]. This bacterium is known for its ability to survive in various harsh environments, making it a valuable asset in a range of sectors such as agriculture, environmental remediation, and biotechnology [3,4]. Its resilience and metabolic activities enable it to play pivotal roles in processes like biodegradation and waste treatment, offering solutions that are both cost-effective and sustainable [5,6]. In recent years, *Bacillus* has been explored for even more innovative uses, particularly in the field of materials science, where it holds the potential to revolutionize industries like construction and cement production [7,8].

To deepen our understanding of *Bacillus* and its industrial potential, this study utilizes bibliographic analysis, specifically through the use of VOSviewer, a powerful tool that enables the extraction and visualization of key data from scientific literature [9,10]. By analyzing a large corpus of research articles, we have identified the most prominent keywords, organizations, and countries or regions that are at the forefront of *Bacillus* -related studies. This bibliometric approach provides valuable insights into the trends and advancements in *Bacillus* research [11], offering a comprehensive overview of the current state of knowledge and highlighting emerging areas of interest for further exploration.

One particularly promising application of *Bacillus* is its integration into the cement production process [12,13], where it has been found to possess self-healing capabilities [14,15]. Cement, over time, is prone to cracking due to physical stress, chemical reactions, and environmental factors [16,17]. These cracks can significantly weaken the material, leading to costly repairs and reduced lifespan of structures [18,19]. *Bacillus*, however, offers an innovative solution by being incorporated into the cement mix, where its metabolic activity triggers the precipitation of calcium carbonate, effectively filling the cracks and preventing further damage [20,21]. This self-healing property not only reduces

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the need for external interventions but also holds the potential to cut down on labor and maintenance costs, making it an economically viable and sustainable alternative for the construction industry [22,23].

Looking forward, we also explore the exciting opportunities that lie in combining *Bacillus* research with the power of big data and machine learning [24]. These technologies have already shown great promise in various fields, such as facial recognition [25,26] and autonomous driving [27,28]. By applying them to *Bacillus* research, scientists can harness large-scale data sets to identify patterns and optimize its industrial applications [29,30]. For instance, by collecting data on factors like temperature, humidity, and the timing of *Bacillus* inoculation in concrete, machine learning algorithms could be trained to predict the ideal conditions for *Bacillus*-based self-healing cement. This combination of biotechnology with data-driven insights holds immense potential to advance *Bacillus* research, leading to more effective, sustainable, and cost-efficient solutions across a wide range of industries.

2. Materials and Methods

The bibliographic analysis method followed previous studies with slightly modifications [31,32]. On January 21, 2025, we performed a comprehensive bibliometric search in the Web of Science database using the keyword "*Bacillus*." This search returned a total of 224,918 articles, highlighting the extensive research conducted on *Bacillus* across various disciplines. To streamline our analysis, we downloaded the default 1,000 articles ranked as most relevant by the database. These articles provided a representative dataset for conducting bibliometric evaluations to uncover research trends, key contributors, and thematic focuses in the *Bacillus*-related literature. The data was then analyzed using VOSviewer [33,34], a powerful tool for visualizing and interpreting bibliometric networks.

For the keyword analysis, we applied a threshold of at least five occurrences for a keyword to be included in the network visualization. This ensured that only the most significant and frequently used terms were considered. The analysis revealed the central themes of *Bacillus*-related research, which likely included topics such as probiotics, biofilm formation, industrial applications, and environmental remediation. This approach allowed us to identify the key scientific domains where *Bacillus* plays a pivotal role, providing insights into its widespread utility in research and practical applications.

In analyzing organizational contributions, we set a minimum threshold of five documents per organization. This enabled us to identify the leading institutions actively engaged in *Bacillus* research. The results highlighted key academic and industrial organizations that are central to advancing this field, emphasizing their roles in knowledge generation and innovation. Such insights are invaluable for researchers seeking potential collaborators or institutions at the forefront of *Bacillus* research.

For the country and region analysis, we used a higher threshold of 20 documents to focus on the most prolific contributors on a national or regional scale. This analysis revealed the global distribution of *Bacillus* research, identifying countries and regions that are major players in the field. The results underscored the geographical hubs of scientific activity, providing a clear picture of where the most impactful *Bacillus* studies are conducted. Together, these analyses offer a holistic understanding of the current landscape of *Bacillus* research, guiding future studies and fostering global collaboration.

3. Results

Figure 1 showcases the most prominent keywords associated with research in the *Bacillus* domain, revealing the diverse areas of study and applications. Several keywords are directly related to environmental applications, highlighting *Bacillus*'s role in addressing ecological challenges. Keywords such as "degradation," "detoxification," "decontamination," and "removal" underscore the organism's utility in processes like breaking down pollutants, neutralizing toxins, and purifying contaminated environments. These findings reflect the significant interest in leveraging *Bacillus* for bioremediation and sustainable environmental solutions, showcasing its potential to combat pollution and promote ecological restoration.

Another set of keywords in Figure 1 pertains to molecular biology, illustrating the central role of *Bacillus* in advancing our understanding of genetic and molecular processes. Terms like "plasmid," "RNA," "16S rDNA," and "DNA" indicate a strong focus on genetic studies, gene expression, and evolutionary relationships. These keywords suggest that researchers frequently use *Bacillus* as a model organism to study molecular pathways, genetic transfer mechanisms, and the genetic diversity within microbial communities. Such studies have broad implications, including the development of genetic tools, biotechnology innovations, and a deeper understanding of microbial ecology and evolution.

Additionally, Figure 1 highlights several keywords associated with research methodologies, reflecting the tools and approaches commonly used in *Bacillus* studies. Words such as "classification," "conjugation," "extraction," and "sequence-analysis" point to the techniques employed for identifying and characterizing *Bacillus* strains and their genetic and functional attributes. These methods are integral to uncovering the potential applications of *Bacillus* in various fields, from industrial production to healthcare. The prominence of these methodological keywords underscores the importance of technical advancements in driving forward *Bacillus*-related research, enabling scientists to explore its capabilities and address both fundamental and applied scientific questions.

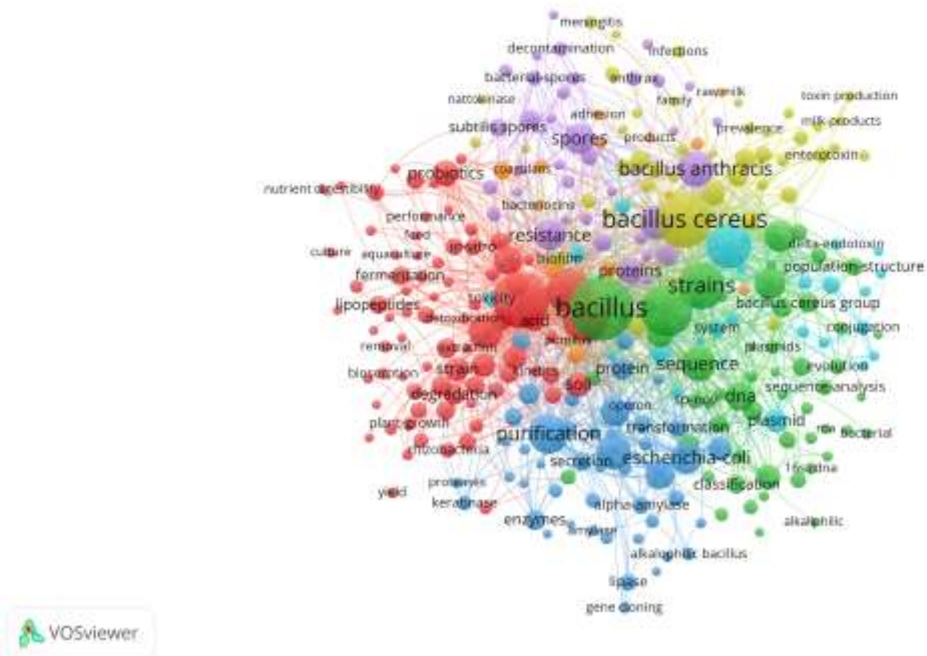

Figure 1. Keyword Analysis Visualized by VOSviewer. Lines represent connections between keywords.

Figure 2 highlights the key organizations involved in *Bacillus* research, with the University of Georgia occupying the most central position, underscoring its pivotal role in advancing the field. The prominence of this institution suggests a strong focus on *Bacillus*-related studies, likely encompassing a broad spectrum of topics such as environmental applications, molecular biology, and industrial uses. This central positioning also reflects the collaborative and influential nature of the University of Georgia in shaping the direction of global *Bacillus* research, including its connections with other leading institutions and contributions to high-impact publications.

In addition to the University of Georgia, Figure 2 reveals other significant contributors to *Bacillus* research, particularly institutions in South Korea. These include Seoul National University, Chung-Ang University, Korea University, Korea Food Research Institute, Kyung Hee University, and

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Kyungpook National University. The presence of multiple South Korean organizations in close proximity highlights the country's active involvement and leadership in this area of study. These institutions are likely focusing on a variety of applications, such as food safety, biotechnology, and environmental remediation, leveraging *Bacillus*'s unique properties to address regional and global challenges. The clustering of these organizations in the figure also suggests robust collaboration within the South Korean research community, as well as with international partners, driving innovation and knowledge exchange in the field of *Bacillus* research.

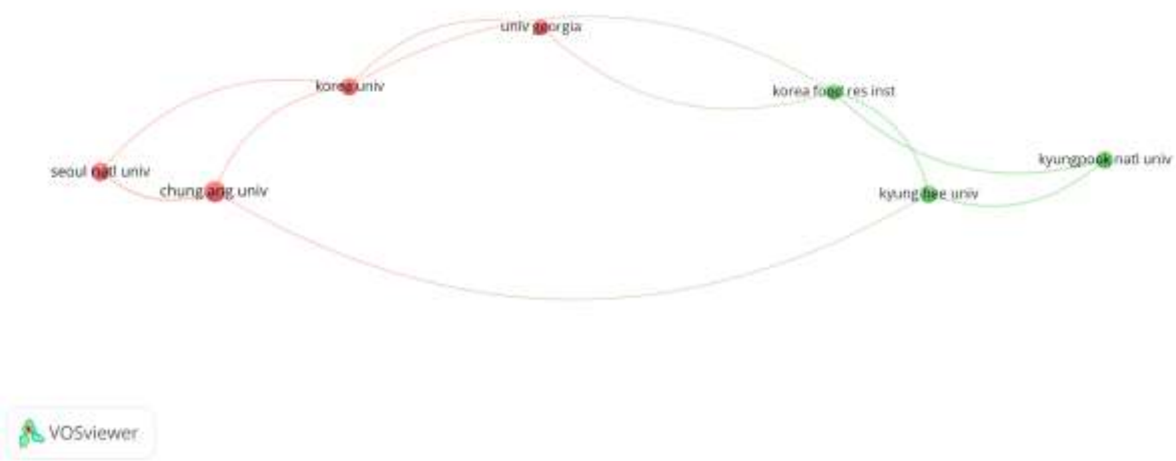

Figure 3. Organization Analysis Visualized by VOSviewer. Collaborative connections are shown by the linking lines.

Figure 3 highlights the major countries and regions contributing to *Bacillus* research, with China, the United States, India, and South Korea occupying central positions. These countries are pivotal in advancing the field, reflecting their extensive research output, significant funding, and collaborative networks. China's strong presence can be attributed to its investment in biotechnology and environmental sciences, while the United States, with its robust academic and industrial research framework, leads in innovation and applications of *Bacillus* in diverse areas. India and South Korea, known for their focus on agricultural biotechnology and industrial microbiology, further emphasize the global importance of *Bacillus* research.

Beyond the central contributors, other nations such as Japan, Poland, Germany, the United Kingdom, Italy, France, Russia, Brazil, and Iran also play essential roles in this field. These countries bring unique perspectives and expertise to *Bacillus* research, focusing on applications such as bioremediation, food safety, and medical microbiology. For instance, Japan and Germany are known for their technological advancements and precision in industrial applications, while countries like Brazil and India emphasize agricultural solutions to enhance crop yield and combat plant diseases. This diversity in research priorities reflects the multifaceted nature of *Bacillus* as a subject of study, encompassing molecular biology, environmental sustainability, and industrial innovation.

The global collaboration among these countries is a defining feature of *Bacillus* research. The interconnectedness seen in Figure 3 underscores the shared scientific goals and cooperative efforts that drive progress in this field. International partnerships facilitate knowledge exchange, technology transfer, and joint initiatives, ensuring that breakthroughs are not confined to individual regions but

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contribute to a broader understanding and utilization of *Bacillus*. This collaborative landscape highlights the importance of global networks in tackling challenges and optimizing *Bacillus* applications, showcasing a collective effort to address pressing issues such as environmental pollution, food security, and public health.

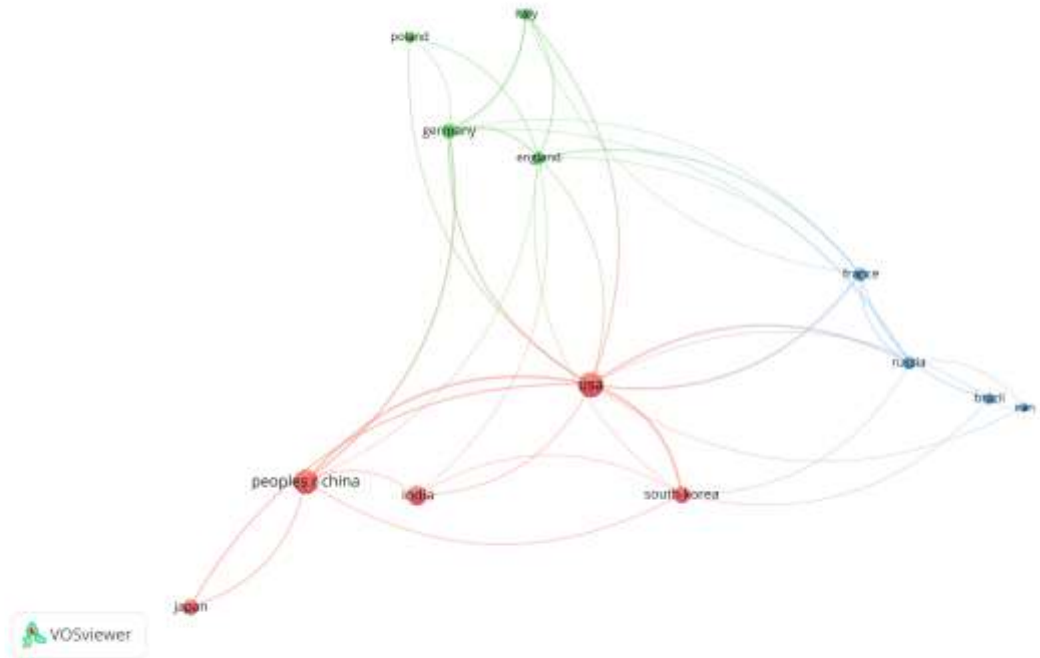

Figure 3. Country/Region Analysis Visualized by VOSviewer. Collaborative connections are shown by the linking lines.

4. Discussion

4.1. Bacillus and Its Industrial Potential

Through bibliographic analysis, we discovered that *Bacillus* has a wide range of industrial applications, with its potential to address various challenges in manufacturing and environmental sustainability [35,36]. One particularly fascinating industrial application is its use in the production of cement [37,38]. Cement, over time, is prone to cracking due to physical stress, weathering, and chemical reactions [39,40]. These cracks, if left untreated, can lead to the degradation of structures, shortening their lifespan and requiring costly repairs [41,42]. *Bacillus*, however, offers an innovative solution by being incorporated into the cement-making process [43,44]. The microorganism's metabolic activity plays a key role in filling these cracks with calcium compounds, effectively sealing them and reducing the need for external interventions [45,46].

This self-healing property of cement reinforced with *Bacillus* is a significant breakthrough in materials science [47]. As *Bacillus* bacteria metabolize within the cracks, they precipitate calcium carbonate, which solidifies and fills the voids in the concrete, preventing further deterioration [48]. This biological approach to healing cracks not only extends the life of the cement but also provides an eco-friendly alternative to traditional methods that rely on chemical treatments or manual repairs [49]. By using *Bacillus* in cement, the need for frequent maintenance is reduced, making it a cost-effective and sustainable solution for construction projects, especially in areas prone to environmental stress.

Moreover, this technology offers a complementary approach to human intervention in concrete maintenance. Traditional methods of crack repair, such as injecting epoxy or applying sealants, are labor-intensive and often require costly materials. *Bacillus*-based self-healing cement could significantly decrease the reliance on such manual repairs, thus offering a more efficient and less resource-intensive alternative [50,51]. The integration of *Bacillus* in cement not only helps with reducing repair costs but also contributes to a more sustainable construction industry by minimizing waste and the environmental impact associated with frequent repairs and replacements [52]. This promising application of *Bacillus* in cement demonstrates the growing potential of biotechnology in industrial sectors and highlights its role in advancing more resilient and sustainable materials [53,54].

Considering the applications of other bacterial species, such as *Shewanella*, which have been shown to have diverse industrial uses—including electricity generation through *Shewanella* biofilms [55,56], the removal of chromium pollutants via *Shewanella* biofilms [57], and the production of extracellular nanoparticles by *Shewanella oneidensis* [58]—it is worthwhile to explore expanding the applications of *Bacillus*. By broadening its scope of industrial applications, *Bacillus* could potentially demonstrate similar versatility and innovation in addressing a wider range of challenges across different sectors [59,60]. This expansion could unlock new opportunities for *Bacillus*-based technologies, further advancing its role in biotechnology and industrial sustainability [60,61].

4.2. Future Opportunities in Bacillus Research with Big Data and Machine Learning

We believe that the future opportunities for *Bacillus* research lie in its integration with big data and machine learning. The power of big data and machine learning has already been widely demonstrated in various fields such as facial recognition [62,63], autonomous driving [64,65], global species distribution prediction [66], educational outcome forecasting [67], and cancer estimation [68]. These technologies have revolutionized many industries, and we foresee a similarly transformative potential in the study and application of *Bacillus*. By combining these advanced tools with *Bacillus* research, we can unlock new avenues for optimizing its use, particularly in industrial applications such as cement production and environmental remediation.

One promising direction involves creating a large-scale database that includes a wide range of *Bacillus* applications, particularly in industries where its utility is growing [69,70]. This database could collect critical parameters such as temperature, humidity, rainfall, the timing of *Bacillus* inoculation, concentration levels, and the resulting effects. By aggregating this data, scientists can create comprehensive datasets that offer valuable insights into the optimal conditions for *Bacillus* application. Once this data is collected, machine learning models like neural networks can be trained using it to identify patterns and correlations that might otherwise go unnoticed [71,72], potentially leading to more efficient and targeted use of *Bacillus* in industrial settings.

In the future, these machine learning models could provide invaluable decision support in real-time situations. For example, if a concrete structure develops cracks, machine learning algorithms could analyze the available data and suggest whether *Bacillus*-based self-healing cement would be a viable solution. Such models, trained on large and diverse datasets, would have the potential to offer more accurate and practical recommendations than even experienced scientists could provide. This fusion of *Bacillus* research with big data and machine learning not only enhances the precision of industrial applications but also accelerates the development of more sustainable and effective solutions in biotechnology.

5. Conclusions

In conclusion, *Bacillus* presents significant potential for various industrial applications, particularly in cement production where it can enable self-healing of cracks, thus reducing labor costs. Through bibliographic analysis with VOSviewer, we identified key trends in *Bacillus* research, including prominent keywords, organizations, and countries/regions involved. The integration of *Bacillus* with big data and machine learning offers promising future opportunities for optimizing its applications across industries. By harnessing these advanced technologies, *Bacillus*-based solutions can be refined, making them more efficient, sustainable, and cost-effective in addressing industrial challenges. This research underscores the growing impact of *Bacillus* in biotechnology and industry.

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