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Review Article

Biotechnological Potential of Actinobacteria as a Solution to Global Challenges – A Mini Review

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Abstract

This review explores the biotechnological potential of actinobacteria, emphasizing their metabolic and genetic diversity. Widely distributed in terrestrial and aquatic habitats, these microorganisms are recognized for producing secondary metabolites with applications in health, agriculture, and industry. Key findings highlight their roles in antibiotic production, plant growth promotion, bioremediation, and the development of biosensors. Challenges, such as the activation of silent biosynthetic gene clusters and scaling up production, are also discussed. The integration of genomic and biotechnological approaches is underscored as essential for leveraging their potential to address global challenges, including antimicrobial resistance, environmental sustainability, and agricultural productivity.

Keywords: Actinobacteria; Agricultural biotechnology; Antibiotics; Bioremediation; Genomic approaches

Introduction

Actinobacteria, Gram-positive microorganisms, play a pivotal role in biotechnology due to their metabolic versatility (Silva *et al*. 2022; Almeida *et al*. 2024). Recent studies emphasize their ability to produce bioactive compounds in diverse ecological contexts (Fig. 1). For instance, Selim *et al.* (2021) investigated the biodiversity of secondary metabolites, while Bergeijk *et al.* (2020) explored genomic advancements for the discovery of natural products. Renowned for their production of bioactive compounds, actinobacteria are essential for developing solutions to antimicrobial resistance and environmental degradation. This review operates under the hypothesis that metabolic and genetic diversity of actinobacteria support their utility as tools to address critical challenges in health, environmental sustainability, and agriculture. The objectives of this study were to assess recent advancements in the biotechnological applications of actinobacteria, identify key challenges to optimizing their large-scale utilization, and propose strategies to integrate genomic and biotechnological methods into practical applications.

Biotechnological applications

The functional diversity of actinobacteria enables their application across multiple fields. These applications range from the production of bioactive compounds, such as antibiotics and pigments, to their use in agricultural and environmental biotechnologies. Table 1 illustrates the main applications discussed in this study, highlighting the strategic role of these microorganisms in various biotechnological contexts.

The metabolic versatility of actinobacteria results from their adaptability to different environments, where genetic mechanisms such as genomic islands, genome rearrangements, and post-translational modifications enable their survival under adverse conditions. This adaptability leads to the diversification and production of bioactive compounds with antibacterial, antifungal, and antiviral properties, as well as the production of industrial enzymes and biosensors (Martín *et al*. 2021; Mitra *et al*. 2022).

Antibiotics and therapeutic bioproducts

Actinobacteria, particularly the genus *Streptomyces*, are responsible for producing approximately 75% of clinically

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Table 1: Biotechnological applications of actinobacteria

	Application	Examples of Products	Main Genera	References
1	Antibiotic production	Erythromycin, Rifampin and Tetracycline	*Streptomyces, Amycolatopsis*	Simeis and Serra (2021)
2	Plant growth promotion	Nitrogen fixation, auxin production and phosphate solubilization	*Frankia, Arthrobacter*	Narsing *et al.* (2022)
3	Enzyme production	Amylases, cellulases and xylanases	*Streptomyces, Micromonospora*	Selim *et al.* (2021)
4	Natural pigments	Carotenoids and melanins	*Amycolatopsis, Rhodococcus*	Selim *et al.* (2021)
5	Natural pigments	Melanins for cosmetics and antioxidants	*Streptomyces, Amycolatopsis*	Celedón and Díaz (2021)
6	Natural pigments	Carotenoids for food and pharmaceuticals	*Rhodococcus, Actinomyces*	Venil *et al.* (2020)

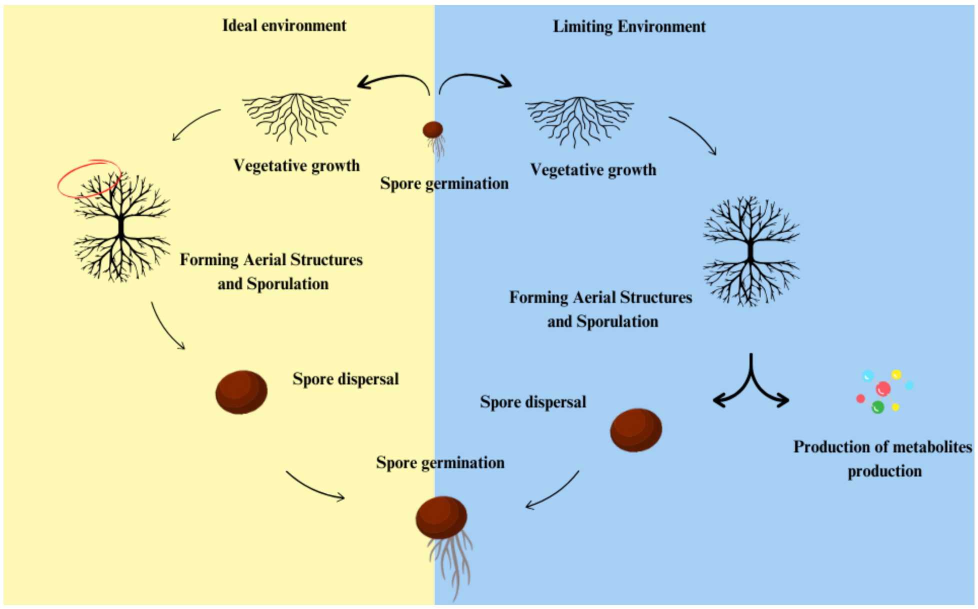

Fig. 1: Life cycle of actinobacteria in ideal and limiting environments

used antibacterial compounds, including macrolides, tetracyclines and glycopeptides (Selim *et al.* 2021; Abdelaziz *et al.* 2023; Rammali *et al.* 2024). Recent studies have highlighted advances in the discovery of novel antimicrobial compounds from unexplored habitats. For instance, Augustijn *et al.* (2024) identified metabolites with antimicrobial activity in marine species of the *Streptomyces* genus, while Selim *et al*. (2021) explored the potential of actinomycetes in alkaline soils. These efforts underscore the importance of extreme habitats as sources of novel bioactive molecules (Zhang *et al*. 2024). Furthermore, the combination of genomic and bioinformatics techniques has accelerated the identification of biosynthetic genes encoding previously untapped antibiotics (Bergeijk *et al.* 2020; Singh *et al*. 2021; Ruiz-Villafán *et al.* 2022). The discovery of new antimicrobial agents in unexplored habitats remains a critical focus in addressing microbial resistance.

Beyond antibiotics, secondary metabolites produced by actinobacteria have other significant applications in human health, including the production of natural pigments with antioxidant, anticancer, and antimicrobial properties. Melanins produced by *Streptomyces* have been investigated for their potential in treating degenerative diseases and protecting cells (Sarmiento-Tovar *et al.* 2022; Wibowo *et al.* 2022). These pigments, such as actinomycin D, also stand out in cancer treatment by interfering with DNA transcription and exhibiting antiproliferative activities. Actinomycin D, produced by *Streptomyces*, is widely used in chemotherapy to treat solid tumors and sarcomas by disrupting DNA transcription (Simeis and Serra 2021). Pigments like pyomelanin, also derived from actinobacteria, demonstrate significant anticancer activities, acting as antioxidants and antiproliferative agents (Wibowo *et al.* 2022). Other compounds with antiviral and immunomodulatory activities, such as those derived from *Amycolatopsis*, show promise in combating viral infections and in immunotherapy (Karimian *et al*. 2024).

Promoting plant growth

Actinobacteria enhance agricultural productivity through mechanisms such as the production of phytohormones (Boubekri *et al.* 2022) nitrogen fixation by genera like *Frankia* and *Arthrobacter* (Kumar *et al.* 2023) and phosphate solubilization mediated by *Streptomyces* and *Micromonospora* (Ebrahimi-Zarandi *et al.* 2022). For example, *Streptomyces albidoflavus* has been shown to promote drought stress resistance in plants (He *et al*. 2023), while *Micromonospora* spp. is known for increasing nutrient uptake in crops like wheat (Ebrahimi-Zarandi *et al.* 2022; Narsing *et al.* 2022; Khan *et al.* 2023). Genera such as *Streptomyces* and *Micromonospora* are widely utilized as biofertilizers and biopesticides, supporting sustainable agricultural practices (Bergeijk *et al.* 2020; Selim *et al.* 2021).

The phosphate solubilization process by actinobacteria occurs through the production of organic acids, such as gluconic acid and 2-ketogluconic acid, which acidify the rhizosphere, causing a pH drop. This acidification chelates the cations bound to phosphorus from their hydroxyl and carbonyl groups, increasing phosphorus availability in the soil (Soumare *et al*. 2021; Silva *et al.* 2023). Additionally, the production of phytohormones, such as indole-3-acetic acid (IAA), stimulates plant growth. When combined with phosphate solubilization, this process results in an overall increase in plant growth, including stem and root length as well as dry biomass weight (Fatmawati *et al.* 2023).

Bioremediation

The ability of actinobacteria to degrade environmental pollutants, including heavy metals and pesticides, underscores their significance in promoting environmental sustainability. Studies have shown that *Rhodococcus erythropolis* is effective in degrading aromatic compounds and hydrocarbons, while *Streptomyces rochei* removes heavy metals such as cadmium and lead from wastewater (Hamdan *et al.* 2021; Augustijn *et al.* 2024). Furthermore, consortia of actinobacteria have demonstrated synergy in the removal of pesticides such as atrazine and chlorpyrifos, as reported by Jain *et al.* (2022). These features make actinobacteria promising candidates for bioremediation applications in contaminated soils and water (Diagne *et al.* 2020; George *et al.* 2022). Species like *Rhodococcus* and *Streptomyces* have proven effective in detoxifying contaminants and improving soil health (Silva *et al.* 2022; Augustijn *et al.* 2024).

The bioremediation of heavy metals and pesticides by actinobacteria involves the production of enzymes such as Hexachlorocyclohexane Dehydrochlorinase (LinA), Haloalkane Dehalogenase (LinB) and Alcohol Dehydrogenase (LinC), which play crucial roles in the degradation of contaminants such as hexachlorocyclohexane (HCH) isomers, an organochlorine pesticide and other organochlorine compounds, transforming them into less toxic substances (Cuozzo *et al*. 2017). In the removal of heavy metals such as cadmium, lead, and zinc, the mechanisms utilized include the production of biosurfactants and the transformation of metals into less toxic forms (Mawang *et al*. 2021).

Biosensors and natural pigments

Advances in biosensors utilizing enzymes derived from actinobacteria enable precise detection of environmental pollutants. For instance, biosensors based on *Streptomyces* have been employed to monitor organic compounds in aquatic environments, while pigments derived from *Amycolatopsis* are used in optical devices for detecting heavy metals (Singh *et al.* 2021; Silva *et al.* 2022).

Moreover, natural pigments produced by actinobacteria offer eco-friendly alternatives for applications in food, cosmetics, and textiles. For example, pigments from *Streptomyces coelicolor* have demonstrated thermal stability and antimicrobial properties, making them suitable for use in food packaging and sustainable textiles (Selim *et al.* 2021; Sarmiento-Tovar *et al.* 2022).

Challenges and future perspectives

Despite their potential, several challenges hinder the broad application of actinobacteria:

- Activation of Silent Biosynthetic Genes: Many gene clusters remain inactive under laboratory conditions, limiting the production of bioactive compounds. Studies such as those by Karimian *et al.* (2024) highlight promising strategies, including co-culture and environmental stress, to stimulate the expression of these genes.
- Scaling up Production: Ensuring efficient large-scale production faces technical and economic barriers. According to Santos-Aberturas and Vior (2022), advances in bioprocesses and optimized fermentation techniques show potential to overcome these challenges.
- Environmental Integration: The introduction of actinobacteria into ecosystems may lead to unforeseen impacts. Rebai *et al.* (2024) emphasize the need for long-term studies to evaluate ecological interactions and mitigate potential environmental imbalances.

Future research should focus on optimizing cultivation techniques, leveraging metagenomics, and developing cost-effective biotechnological applications.

Conclusion

Actinobacteria offer unparalleled opportunities for innovation in medicine, agriculture, and environmental science. Addressing the challenges of gene activation, production scalability, and ecological impact will be crucial to realizing their full potential. Integrating genomic tools and biotechnological approaches is imperative for developing sustainable solutions to global challenges.

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Author Contribution

PCVS conceived and structured the study, conducted the literature search and selection, and drafted the initial version of the manuscript. JMS and GSAL contributed to the critical analysis of the literature and the revision of the manuscript. YCM, MELC and VDS assisted in data organization.

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability

The data supporting the findings of this review are entirely derived from peer-reviewed publications and publicly available databases, including PubMed, ScienceDirect, Scopus, and Web of Science. A comprehensive list of these sources is provided in the References section. No proprietary or unpublished data were used.

Ethical Approval

Not applicable to this study.

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