# NEW WAYS OF PRACTICAL APPLICATION OF ANTIMICROBIAL PHENAZINE PIGMENTS

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**Abstract**
*This article is devoted to analysis of relevant information about phenazine pigments, their properties, and novel directions of practical application. The main value of phenazines lies in their natural origin, ecological safety, and multifunctionality. Their practical use includes biocontrol in agriculture, integration into microbial fuel cells, and application in electrochemical sensors.*
**Keywords**: *phenazines, biocontrol, biosensors, Pseudomonas spp.*

**Introduction**. Phenazines are a class of heterocyclic nitrogen-containing compounds produced by various soil bacteria, including species from the genera *Pseudomonas, Streptomyces, Burkholderi*a, and others [1]. These pigments are well-known for their antimicrobial, antifungal, and antioxidant properties, which result from their redox activity and ability to generate reactive oxygen species [2]. Phenazine-1-carboxylic acid (PCA) has demonstrated high effectiveness in combating phytopathogens, particularly *Fusarium* spp., *Gaeumannomyces graminis*, and *Rhizoctonia solani* [3].

Traditionally, phenazines were considered natural antibiotics for biocontrol of plant diseases in agriculture [4]. However, in recent years, their applications have expanded significantly. Due to their unique electrochemical properties, phenazines are increasingly studied as components in biosensors, microbial fuel cells, and other electroactive biomaterials. Their ability to reversibly transfer electrons makes these compounds valuable for the development of sensor systems capable of monitoring environmental conditions [5, 8].

Recent studies have revealed that phenazines not only act as antimicrobial agents but also function as signaling molecules regulating gene expression, contribute to biofilm formation and structure, and serve as electron shuttles in energy-limited environments. These properties enhance bacterial survival and ecological fitness, especially under anaerobic or nutrient-deficient conditions [1]. Additionally, specific phenazine derivatives, such as pyocyanin and phenazine-1-carboxamide, have been shown to modulate host immune responses and iron availability, playing roles in both beneficial plant interactions and bacterial virulence in humans [1].

Particular interest lies in natural populations of phenazine-producing bacteria from arid regions, which are characterized by high adaptability to stress conditions (such as drought and low nutrient availability) and metabolic plasticity. These microorganisms may serve as the foundation for the development of environmentally safe biopreparations of the new generation.

The aim of our study is to analyze the current state of phenazine applications, assess the potential of natural producers, and explore new practical directions for using these pigments in various fields – from agriculture to bioelectronic devices and sustainable technologies.

**Materials and methods.** This study involved an analysis of scientific publications dedicated to the research of the antimicrobial properties of phenazine pigments, the genetic and metabolic diversity of their natural producers, as well as current practical applications of phenazines in biotechnology, agriculture, and biosensor systems.

For the collection and processing of sources, the scientific database ResearchGate and ScienceDirect was used, which includes open-access publications and peer-reviewed articles from leading international journals in the fields of microbiology, ecology, agrobiotechnology, and bioelectronics.

**Results and discussion**. A comprehensive study conducted by Parejko et al. examined 413 *Pseudomonas* spp. isolates collected from the rhizosphere of cereal crops grown in the arid regions of Washington State (USA). Using BOX-PCR profiling, the researchers identified four major genetic clusters among the isolates. These clusters were distinguished by their unique genomic fingerprints, levels of phenazine-1-carboxylic acid (PCA) production, metabolic capabilities, and patterns of adaptation to crop rotation systems. Notably, the largest group, Cluster 4, comprised strains with enhanced metabolic plasticity, allowing them to efficiently utilize a variety of root exudate compounds. This adaptability is particularly beneficial under arid and nutrient-poor soil conditions, making these strains prime candidates for sustainable biocontrol formulations.

Importantly, isolates within this cluster did not harbor genes responsible for the biosynthesis of other common bacterial antibiotics, such as *phlD* (responsible for 2,4-diacetylphloroglucinol), *prnC* (pyrrolnitrin), or *pltB* (pyoluteorin). The absence of these genes suggests a reduced risk of antagonistic side effects on non-target organisms, underlining the environmental safety and specificity of these phenazine-producing strains [3].

Additional research by Pierson et al. reinforces the ecological significance of phenazine-producing *Pseudomonas* in competitive root-associated environments. Strains such as *Pseudomonas chlororaphis* 30-84 were shown to produce a spectrum of phenazine derivatives, including PCA, 2-hydroxyphenazine-1-carboxylic acid (2-OH-PCA), and 2-hydroxyphenazine (2-OH-PHZ). These compounds are not only antimicrobial but also contribute to the structural integrity and function of bacterial biofilms, enhancing colonization and persistence in the rhizosphere. The production of phenazines is regulated by quorum sensing and environmental cues, which allows the bacteria to fine-tune their metabolic output in response to changing soil conditions and plant-derived signals [1].

Beyond agriculture, phenazines have garnered considerable interest in the field of bioelectrochemistry. Rabaey et al. demonstrated that phenazines produced by microorganisms – *especially Pseudomonas aeruginosa* – can significantly improve electron transfer efficiency in microbial fuel cells (MFCs). In these systems, PCA acts as a self-synthesized, redox-active mediator that facilitates the transfer of electrons from bacterial metabolism to an external electrode. This function eliminates the need for synthetic or externally supplied electron shuttles, enhancing the sustainability and autonomy of bioelectrochemical systems [5].

Complementary studies by Hernandez et al. and Wang et al. provided further insight into the physiological roles of phenazines in P. aeruginosa under anaerobic conditions. Phenazines such as pyocyanin (PYO) support alternative respiratory pathways by enabling the recycling of NADH, thus maintaining the intracellular redox balance necessary for cellular energy production. This redox cycling promotes long-term bacterial survival in oxygen-limited biofilms – an environment that closely mimics the anoxic conditions found in the anode chambers of MFCs [6, 7].

Recent advancements also suggest that genetically engineered phenazine-producing strains or synthetic analogs could further enhance the output of MFCs. By optimizing the structure and redox potential of phenazines, researchers aim to design more efficient electron shuttles tailored for specific electrochemical conditions. This line of research opens new doors to the development of next-generation biohybrid energy systems powered by microbial metabolism [1].

The utility of phenazines extends into optoelectronic and analytical applications. According to Banerjee, phenazine derivatives display strong potential as functional materials in chemosensors, owing to their ability to selectively interact with various metal ions. These interactions lead to noticeable spectral shifts – such as changes in absorbance or fluorescence – allowing for the design of highly sensitive and selective detection platforms for environmental and industrial monitoring.

Furthermore, phenazines stable redox behavior and electron-donating properties make them promising sensitizers in organic photovoltaic (OPV) systems. Their incorporation into light-harvesting layers enhances charge transfer efficiency and stability, critical factors for improving the performance of organic solar cells. Research is increasingly focused on the structural modification of phenazines to fine-tune their optical bandgaps and electron affinities, enabling better alignment with other components in photovoltaic architectures [8].

Pierson & Pierson also highlighted the long-standing use of phenazine-based compounds such as neutral red and phenazine methosulfate as redox indicators in colorimetric assays. Today, advancements in nanotechnology allow these molecules to be covalently anchored onto nanostructures like carbon nanotubes or graphene sheets. Such integration has led to the development of novel biosensors and light-emitting devices (LEDs) with enhanced sensitivity, miniaturization, and real-time monitoring capabilities [1].

In combination, these findings illustrate the broad versatility of phenazines – not only as natural antibiotics but as multifunctional redox-active molecules that bridge disciplines from plant science to energy technology and materials engineering. Their potential for cross-disciplinary innovation continues to grow, making phenazines one of the most exciting microbial metabolites in current biotechnological research.

**Conclusions.** Phenazines, especially phenazine-1-carboxylic acid (PCA), are natural antimicrobial metabolites with a well-documented ability to combat a wide range of soilborne phytopathogens. Their efficacy in promoting plant health is particularly notable under challenging abiotic conditions such as drought, salinity, and intense pathogenic pressure. This makes them promising agents for integrated crop management, especially in climate-resilient agricultural strategies. The genetic and metabolic diversity of phenazine-producing *Pseudomonas* spp. underscores their adaptive capabilities, allowing for the selection and engineering of specialized strains tailored to specific crop and soil needs.

However, the role of phenazines extends far beyond traditional biocontrol. They are increasingly recognized as key multifunctional molecules involved in microbial communication, redox homeostasis, and structural dynamics of microbial communities. Their function as electron shuttles in anaerobic and low-nutrient environments enhances the survival and ecological fitness of producing organisms, contributing to the stability and resilience of the rhizosphere microbiome.

From a technological standpoint, phenazines are valuable bioactive compounds with significant potential in bioelectronics and environmental diagnostics. In MFCs, they improve electron transfer efficiency and enable sustainable bioelectricity generation. In biosensor development, phenazine-based platforms allow for real-time, sensitive monitoring of microbial metabolism, environmental pollutants, and changes in bioprocesses.

From a biotechnological perspective, phenazines represent a unique convergence point between natural product chemistry, synthetic biology, and applied engineering. Their multifunctionality makes them highly adaptable tools across multiple domains – agriculture, renewable energy, materials science, and medicine.

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