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A Brief Review on the Emerging Role of Bacterial Pigments: From Industrial Uses to Novel Therapeutic Applications

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Authors' contributions

This work was carried out in collaboration among all authors. Author DNS wrote the first draft of the manuscript. Authors DNS, RM and AP managed the analyses of the study and managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Pigments produced by microorganisms are in high demand due to their safe, non-toxic, and biodegradable characteristics in both industrial and pharmaceutical fields. Using bacteria for pigment production offers several advantages, such as a short life cycle and ease of genetic modification. Numerous studies have highlighted that soil bacteria significantly contribute to the production of coloured pigments as secondary metabolites. Bacterial pigments are well-known for their antimicrobial, antioxidant, and anticancer properties, offering new therapeutic opportunities for the development of novel drugs. However, compared to fungal pigments, most bacterial pigments are still in the research and development stage. Hence, efforts to intensify bacterial pigment

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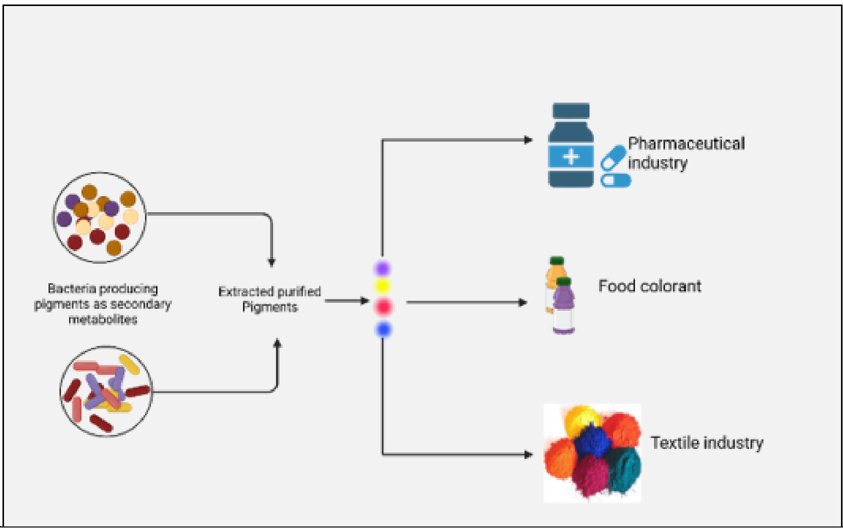
production are essential to make them readily available on the market at a low cost for various applications. This review article sheds light on bacterial pigments and their various applications based on the data available in the literature.

Graphical Abstract



Keywords: Bacterial pigments; secondary metabolites; antimicrobial properties; antibiotics; antibiotic resistance.

1. INTRODUCTION

Bacterial pigments exhibit diverse properties beyond their role as colourants, including antioxidant, anti-inflammatory, UV protection, antimicrobial, and anticancer activities [1]. Bacteria offer a readily available source of naturally derived pigments and present significant advantages over plant and fungal pigments, such as easy and rapid growth in low-cost media and straightforward processing [2,3].

These secondary metabolites have proved to be of great value in medicine, functioning as antibacterial, antifungal, anticancer, and immunosuppressant agents. Additionally, some secondary metabolites exhibit unexpected activities, offering potential solutions to diseases lacking effective treatments [4].

One of the most significant advantages of using bacterial pigments over traditional sources is the ease with which they can be produced. Bacteria have a short life cycle, can be cultured in large quantities using inexpensive media, and are relatively simple to genetically manipulate, which makes them the most suitable candidate for scalable pigment production [5].

There has been an increase in reports about the properties of microbial secondary metabolites in recent years. Researchers have highlighted that our understanding of how to increase the production of bioactive secondary metabolites is limited. Despite their promising applications, further research is necessary to address concerns about toxicity, resistance development, and human compatibility related to bacterial pigments [6].

As research progresses, the full potential of these pigments is being uncovered, and it is likely that they will play an increasingly important role in both the industrial and pharmaceutical sectors. This review aims to provide a brief overview of the current state of research on bacterial pigments and their diverse applications in different domains.

2. SOIL: A RICH SOURCE OF PIGMENTED BACTERIA

Pigment-producing bacteria are present in various ecological regions such as rhizosphere soil, desert sand, fresh water, marine samples and were reported in both low and high-temperature regions, they can persist in salt regions, and even as endophytes [7].

Throughout history, the majority of antibiotic molecules have been produced by soil bacteria that can be isolated and grown in a laboratory. However, there is still a large number of soil bacteria that cannot be isolated with current methods. These lesser-studied soil bacteria hold great potential for the discovery of new compounds [8].

According to the study of Narsing et al., (2017) various genera of actinomycetes such as *Streptomyces*, *Nocardia*, *Micromonospora*, *Thermomonospora*, *Actinoplanes*, *Microbispora*, *Streptosporangium*, *Actinomadura*, *Rhodococcus*, and *Kitasatospora* produce a wide variety of pigments. As per the results of their study, the genus *Streptomyces* was reported to have the highest pigment production. Many species of this genus, like *Streptomyces griseus*, *Streptomyces griseoviridis*, *Streptomyces coelicolor*, *Streptomyces cyaneus*, *Streptomyces vietnamensis*, *Streptomyces peucetius*, *Streptomyces echinoruber*, *Streptomyces shaanxiensis*, and *Streptomyces caeruleatus* were reported to produce pigments [9].

The study of Singh et al., (2016) says that "India has a unique asset of biodiversity, which can be used as a treasure for the search of novel isolates. With the variation in soil types due to geographical changes, soil provides a highly complex habitat for the microbes residing within it. This intricate environment allows soil microbes to play a crucial role in the discovery and isolation of novel drugs. In their study, researchers collected soil samples from six diverse habitats in India to isolate these microbes. The habitats included the rhizosphere of plants, agricultural soil, hospital surroundings, river mud, and preserved areas of forest soil [10].

Parmar et al. (2016) conducted a study at ITM University, Gwalior, Madhya Pradesh, India, with the objective of isolating, characterizing, and studying the biological activity of pigment-producing actinomycetes. For their research, they collected samples from the rhizosphere soil of the Chambal territory and other regions of Madhya Pradesh. The study's results revealed that a *Streptomyces* isolate exhibited notable antimicrobial activity against various pathogens. The Chambal territory of Madhya Pradesh was found to have a significant potential for producing potent actinomycetes with pigment-production and antimicrobial properties [11].

Similarly, a study conducted in the soils of the Kathmandu and Lalitpur districts isolated a total of 13 pigmented bacterial isolates. Among these soil pigment producers, the most notable were identified as *Staphylococcus aureus*, *Micrococcus luteus*, *Micrococcus roseus*, and *Pseudomonas aeruginosa*. Furthermore, their study demonstrated the antibacterial properties of the pigments produced by these bacteria, the antimicrobial activity of extracted carotenoid pigment was found to be more effective against Gram-positive than Gram-negative bacteria [12].

An interesting study on the mangrove ecosystem soil in Cochin, Kerala, isolated six yellow-orange pigment-producing bacterial strains. These isolates were identified as *Cellulosimicrobium funkei*, *Cytobacillus depressus*, *Bacillus aquimaris*, and *Halobacillus* sp. All of these isolates produced pigments that exhibited antibiofilm activity against food pathogens such as *Klebsiella* spp [13].

A soil sample collected from the exposed purple soil in Yanting County, Sichuan Province, People's Republic of China isolated actinomycin D-producing *Streptomyces parvulus* which produced yellow pigments [14].

In the last decade, there has been a noticeable increase in the number of studies focusing on the abilities of novel pigment producers from soil. This trend highlights the potential of soil as a rich source of pigment-producing microorganisms, whose pigments have significant applications across various industries [15].

2.1 Important Applications of Bacterial Pigments

2.1.1 In drug industries

Antimicrobial, anticancer, cytotoxic, and remarkable antioxidant properties of bacterial pigments make them popular in drug industries. Owing to the medicinal properties of bacterial pigments they were considered as the best choice for novel drugs [16].

Most of the studies in antimicrobial resistance concluded with the need for an urgent novel antimicrobial agent. "Never has the threat of antimicrobial resistance been more immediate and the need for solutions more urgent", said WHO Director-General Tedros Adhanom Ghebreyesus to The UN News in 2020. Marathe et al., (2019) and D'Andrea et al., (2019) have clearly described in their articles that the rise in antibiotic resistance is a serious growing problem for human health, hence they hope this extreme antimicrobial property of bacterial pigments can shed light as a solution to compete against antibiotic resistance [17,18].

Waghela and Khan (2019) in Mumbai India, conducted a study on the antibacterial properties of bacterial pigments isolated from food samples, they aimed to isolate the microorganisms from different food samples capable of producing pigments with antimicrobial activity. The antimicrobial activity of the pigments was tested against four human pathogens such as *Escherichia coli*, *Pseudomonas*, *Staphylococcus aureus*, and *Streptococcus species*, by the well diffusion method on nutrient agar plates. The results of their study showed that all three pigments one yellow and two orange pigments from the isolates were found to inhibit the growth of both Gram-positive as well as Gram-negative bacteria and thus these pigments could be designated as broad-spectrum antimicrobial agents [19].

Venil et al., (2013) reported that pigments such as pyocyanin and pyorubin obtained from *Pseudomonas aeruginosa*, pigments from *Micrococcus luteus* and *Monascus ruber*, prodigiosin, pigment produced from Vibrio sp., pigment of an endophyte fungal species *Monodictys castaneae*, shows good antibacterial property on various bacterial pathogens. In their study, Pigment obtained from Streptomyces hygroscopicus, even showed good antimicrobial activity against drug-resistant pathogens such as methicillin and vancomycin-resistant strains of *Staphylococcus aureus* and β-lactamase producing strains of *Escherichia coli*, *Pseudomonas aeruginosa*, and *Klebsiella sp.* [20].

2.1.2 In the textile and cosmetic industries

Textile industries are the largest consumer of natural dyes. Bacterial pigments are a very good natural colourant in the cosmetics and textile industries. Even though microbial pigments remain so costly, the value of these pigments is exponentially increasing in the international market of colour. These organic dyes are widely used as printing inks, paints, and coating agents [9]. The study by Choksi et al., in 2020 has suggested that bioactive pigment's antioxidant and sun-protective properties can be further developed and should be used as a main ingredient in cosmeceuticals [21].

2.1.3 Modern therapeutic aspects of bacterial pigments

The Nanomedicine technology and recombinant DNA technology offer another research opportunity for bacterial pigments for therapeutic purposes [22]. Nanomedicine is the application of nanotechnology in health care, and it is one of the most promising and worldwide accepted technologies that offers numerous promising possibilities to significantly improve medical diagnosis and therapy, leading to affordable higher-quality health care [23].

Rahul, et al., (2015) extracted and purified bioactive pigments from cultures of *Serratia marcescens* and *Chromobacterium violaceum*. These bioactive pigments, prodigiosin, violacein, and their combinations with photosynthesized silver and gold nanoparticles were studied for the growth inhibition of *Plasmodium falciparum* and *Trypanosoma brucei* gambiense. Prodigiosin was found to be more effective than violacein for inhibition of both parasites in vitro. Specifically, combinations of the microbial pigment prodigiosin with metal nanoparticles showed a significant reduction of both parasites without an increase in cytotoxicity toward mammalian cells. The data may be useful for the microbial pigment-based drug design [24].

Charkoudian et al., (2010) cultured *Streptomyces* and extracted their pigments then they modified the genomes and used engineered bacteria to make new pigments. The study proved that the metabolic engineering of microbial systems can scale up the production of bacterial metabolites by using large-scale bioprocessing techniques such as recombinant DNA technology [25].

Beyond the therapeutic applications, microbial pigments have great potential in biosensors, environmental remediation, and nanomaterial synthesis. These are the components of choice for drug delivery and tissue engineering due to their biocompatibility [26]. Due to their exceptional biocompatibility, a recent study referred to bacterial pigments as "Pandora's box against cancer" [27]. While this might seem exaggerated, it is worth noting that studies have consistently concurred with the common finding that these microbial pigments are poised to become key raw materials for future industries.

3. CONCLUSION

The demand for bacterial pigments is increasing due to their non-adverse effects on the environment and human health. Beyond their industrial uses in food, textiles, and cosmetics, their specific characteristics—such as antimicrobial, antioxidant, and anticancer properties—make them valuable in medical drug design. According to a compendium of reviewed articles, bacterial pigment production is emerging as a promising field of research with significant potential for various applications, particularly in drug design. Unexpected functions of known secondary metabolites continue to be discovered, filling gaps in current research on the medicinal use of bacterial pigments and holding great promise for the future of microbiology.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of manuscripts. For language correction and to improve readability, Curie was used.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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