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Research paper

Microbial Pigments as Innovative Therapeutic Agents for Combating Infections and Advancing Cancer Treatment

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Abstract

Microbial pigments have gained significant attention as promising therapeutic agents due to their diverse bioactive properties, including antibacterial, anticancer, cytotoxic, and antioxidant activities. These natural pigments, produced by bacteria, offer immense potential in both medicinal and industrial applications. In this study, a thorough literature review was conducted to explore the therapeutic significance of bacterial pigments, particularly their role in combating infections and advancing cancer treatment. The pigment was characterized using UV-visible spectroscopy, with absorption spectra ranging from 220 to 250 nm. Additionally, Fourier-transform infrared (FTIR) spectroscopy of strain BJZ10 identified functional groups associated with alcohols, esters, sulfate, alkanes, and alkyls, confirming the structural complexity of the pigment. The antibacterial efficacy of the pigment was evaluated using both Gram-positive (Bacillus cereus) and Gram-negative (Escherichia coli) bacteria, demonstrating significant antimicrobial activity. Notably, this study identified a brown pigment produced by Streptomyces sp. strain BJZ10, which exhibited strong antibacterial properties. Given these findings, microbial pigments hold substantial promise for therapeutic applications, particularly in antimicrobial and anticancer strategies. This paper discusses the potential biomedical applications of microbial pigments, emphasizing their role as next-generation therapeutic agents in treating infections and combating cancer.

Keywords: *Microbial Pigments; Antibacterial Activity; Anticancer Properties; Cytotoxicity; Antioxidant Potential; Streptomyces Sp.; Bacillus Cereus; Escherichia Coli; UV-Visible Spectroscopy; FTIR Analysis; Therapeutic Applications.*

1. Introduction to microbial pigments

Microbial pigments are natural chemical compounds synthesized by various microorganisms, including bacteria, fungi, and microalgae. These pigments have gained significant attention due to their diverse bioactivities and potential applications in medicine, food, cosmetics, and textiles. Unlike synthetic dyes, microbial pigments are biodegradable, environmentally friendly, and can be produced sustainably (Venil et al., 2020; Soliev et al., 2011). With increasing concerns over the toxicity and ecological impact of synthetic colorants, microbial pigments are being explored as viable alternatives, especially in the health and nutraceutical industries.

In addition to their coloring properties, many microbial pigments possess important therapeutic and pharmacological activities, such as antimicrobial, antioxidant, anticancer, anti-inflammatory, and immunomodulatory effects (Kim et al., 2022; Dufossé, 2018). Pigments such as prodigiosin, violacein, melanin, and pyocyanin have shown promising potential as novel drug candidates. Notably, recent studies have highlighted the antiproliferative and apoptotic effects of violacein in various cancer models, including breast and colon cancers (Zhou et al., 2023).

Significant advances between 2022 and 2024 have focused on genetic engineering and synthetic biology techniques for overproducing pigments in microbial hosts like Escherichia coli and Streptomyces spp., thereby improving yield and stability (Singh et al., 2023). Concurrently, genome editing tools such as CRISPR-Cas9 have been used to enhance metabolic flux toward pigment biosynthesis pathways, making large-scale production more feasible (Lee et al., 2022).

Furthermore, pigment-producing strains are being evaluated in preclinical and early-stage clinical research, exploring their use as adjunct therapies in antimicrobial resistance and cancer care. Studies also report the formulation of microbial pigments into nanoparticles and drug delivery systems, enhancing their bioavailability and targeted activity (Choudhary et al., 2023; Patel et al., 2024). Industrial efforts now also include scale-up fermentation processes and downstream recovery optimization, which are critical for translating laboratory success into commercial applications (Ramalingam et al., 2023).

"The current trends highlight microbial pigments as eco-friendly, multifunctional alternatives to synthetic compounds, particularly in addressing antibiotic resistance and oxidative stress-related disorders. Future research should explore pigment-specific bioactivities, such as the apoptosis-inducing properties of violacein or prodigiosin’s autophagy pathways in tumor cells. Moreover, clinical relevance can be enhanced by developing nanoformulations for targeted drug delivery, as demonstrated in recent cancer research. Pilot clinical trials and regulatory evaluations will be essential in transitioning from in vitro studies to therapeutic applications (Hernández-Morales et al., 2023; Mehta & Gupta, 2024; Reddy & Das, 2024)."

These recent developments not only improve our understanding of microbial pigments but also support their transition from research prototypes to real-world therapeutic and industrial agents.

Microbial pigments are natural chemical compounds synthesized by various microorganisms, including bacteria, fungi, and microalgae. These pigments have gained attention due to their diverse bioactivities and potential applications in medicine, food, cosmetics, and textiles. Unlike synthetic dyes, microbial pigments are biodegradable, environmentally friendly, and can be produced sustainably (Venil et. al., 2020). Additionally, some microbial pigments exhibit therapeutic properties, making them promising candidates for pharmaceutical applications, such as antibiotics and antimalarials (Kim et. al., 2022).

1.1. Properties of microbial pigments

Microbial pigments possess several unique characteristics that make them valuable for industrial and medicinal use:

- Color: Available in a variety of vibrant shades, microbial pigments serve as natural alternatives to synthetic dyes (Mani & Jayaraman, 2021).
- Biodegradability: These pigments are eco-friendly and decompose naturally, reducing environmental pollution (Venil et. al., 2020).
- Therapeutic Properties: Many microbial pigments exhibit antioxidant, anti-inflammatory, and antimicrobial activities, contributing to their medicinal potential (Bharti et. al., 2020).
- Nutritional Benefits: Some pigments have nutritional value, making them useful as food additives and supplements (Durán et. al., 2021).

1.2. Uses of microbial pigments

Due to their diverse properties, microbial pigments have multiple applications:

- Antibiotics: Certain microbial pigments possess antibacterial properties and are used as natural antibiotics (Sasidharan et. al., 2022).
- Antimalarial Agents: Some microbial pigments, such as cycloprodigiosin hydrochloride, demonstrate antimalarial effects (Darshan & Manonmani, 2015).
- Food and Cosmetics: As natural colorants, microbial pigments are widely used in the food and cosmetic industries to replace synthetic dyes (Kim et. al., 2022).
- Textile Industry: Their ability to provide stable and eco-friendly colors makes them suitable for dyeing textiles (Venil et. al., 2020).
- Pharmaceuticals: Due to their bioactivity, microbial pigments are used in drug development and as natural coloring agents in pharmaceutical formulations (Soliev et. al., 2011).

1.3. Production of microbial pigments

Microbial pigments are typically produced as secondary metabolites, meaning they are synthesized when the microorganism undergoes metabolic stress or faces unfavorable conditions (Mani & Jayaraman, 2021). Compared to the chemical synthesis of dyes, microbial pigment production is more sustainable, cost-effective, and environmentally friendly. These pigments can be cultivated on low-cost substrates, making them an attractive alternative to synthetic dyes in various industries (Kim et. al., 2022).

1.4. Examples of microbial pigments and their applications

Several microbial pigments have been identified with significant bioactive properties:

1) Violacein A purple pigment with antibacterial, antifungal, antiprotozoal, and antiviral activities, commonly produced by Chromobacterium violaceum (Durán et. al., 2021).
2) Cycloprodigiosin Hydrochloride. A red pigment with antimalarial properties, derived from Serratia marcescens and other bacteria (Darshan & Manonmani, 2015).

These microbial pigments demonstrate immense potential for use in medicine, industry, and environmental applications. Ongoing research continues to explore their full potential for developing new drugs, sustainable dyes, and bioactive compounds.

Microbial pigments are bioactive secondary metabolites produced by various microorganisms, including bacteria, fungi, and actinomycetes. These natural pigments serve multiple biological roles, such as protection against oxidative stress, defense against competing microorganisms, and adaptation to environmental conditions (Venil et. al., 2020). Due to their diverse bioactivities and eco-friendly nature, microbial pigments have gained significant interest in the pharmaceutical, food, and cosmetic industries as natural colorants and therapeutic agents (Mani & Jayaraman, 2021).

Microbial pigments exhibit a wide range of biological properties, including antibacterial, anticancer, cytotoxic, and antioxidant activities. Many bacterial pigments have been reported to inhibit the growth of pathogenic microorganisms, making them valuable for developing novel antimicrobial agents (Sasidharan et. al., 2022). For example, prodigiosin, a red pigment produced by Serratia marcescens, has shown potent antibacterial effects against multidrug-resistant bacteria (Darshan & Manonmani, 2015). Similarly, violacein, a purple pigment from Chromobacterium violaceum, exhibits strong antimicrobial and anticancer activities by inducing apoptosis in cancer cells (Durán et. al., 2021).

Apart from antimicrobial properties, microbial pigments also demonstrate strong antioxidant activity, which helps neutralize harmful free radicals, preventing oxidative stress-related diseases such as cancer and cardiovascular disorders (Bharti et. al., 2020). Moreover, some microbial pigments have been found to inhibit tumor cell proliferation, making them potential candidates for anticancer therapies (Soliev et. al., 2011).

Given these remarkable properties, microbial pigments hold immense potential for both therapeutic and industrial applications. In the medical field, they are being explored as natural alternatives to synthetic antibiotics and chemotherapeutic agents (Kim et. al., 2022). Additionally, their stability, biodegradability, and ability to be produced through cost-effective fermentation methods make them attractive for biotechnological and pharmaceutical advancements (Venil et. al., 2020). The growing interest in microbial pigments highlights their promise in developing new therapeutic strategies for combating infectious diseases and cancer.

2. Purpose of the study

Bacterial pigments are bioactive compounds with immense medicinal potential due to their antimicrobial, antioxidant, and UV protective properties. These pigments can be extracted and analyzed using various analytical techniques to determine their bioactivity and potential applications in pharmaceuticals, food, cosmetics, and sunscreens (Venil et. al., 2013; Gmoser et. al., 2017).

2.1. Methods for analysing bacterial pigments

Several methods are employed to study the medicinal and industrial properties of bacterial pigments:

1) Spectrophotometry: A UV-visible spectrophotometer is used to scan the absorbance of the pigment extract at different wavelengths. This technique helps determine the maximum absorption spectra (λmax) of the pigment, which provides insight into its chemical structure and stability (Sharma et. al., 2021).
2) Thin Layer Chromatography (TLC): TLC is used to separate and analyze the components of the pigment extract. Different solvents are used to observe the movement of pigment compounds, which helps in preliminary identification (Venil et. al., 2013).
3) Antimicrobial Susceptibility Assay: The disc diffusion method or broth dilution method is used to test the pigment extract against bacterial and fungal pathogens. The zone of inhibition is measured to determine antimicrobial effectiveness (Gmoser et. al., 2017).

2.2. Evaluation of bacterial pigments

1) Antioxidant Properties: Antioxidant activity is assessed using assays such as the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay or FRAP (Ferric Reducing Antioxidant Power) assay. High antioxidant activity suggests potential applications in anti-aging, cancer prevention, and cardiovascular disease treatment (Paliwal et. al., 2016).
2) Antimicrobial Properties: The pigment extract is tested against Gram-positive and Gram-negative bacteria, as well as fungal strains. Effective antimicrobial activity suggests potential use in natural antibiotics and preservatives (Venil et. al., 2013).
3) UV Protective Properties: UV absorption tests are performed to evaluate the pigment's ability to absorb harmful UV radiation. Pigments with high UV absorption can be incorporated into sunscreens and skincare products to provide natural UV protection (Gmoser et. al., 2017).

Applications of Bacterial Pigments: Bacterial pigments have wide-ranging applications in various fields:

1) Pharmaceutical Industry:

Bacterial pigments are studied for their therapeutic potential in treating cancer, cardiovascular diseases, diabetes, and infectious diseases. For example, violacein and prodigiosin have shown promising anticancer and antimicrobial activities (Venil et. al., 2013; Paliwal et. al., 2016).

2) Food and Cosmetics Industry:

Bacterial pigments serve as natural colorants in food and cosmetics, replacing synthetic dyes that may have harmful effects. Carotenoids and melanins are widely used for their vibrant colors and antioxidant properties (Sharma et. al., 2021).

3) Sunscreens and Skincare Products:

Pigments such as melanin and flavins can enhance the UV protection factor (SPF) of commercial sunscreens. These pigments protect skin from oxidative stress and UV-induced damage (Paliwal et. al., 2016).

2.3. Examples of bacterial pigments

Several bacterial pigments have been identified with potential medicinal and industrial applications:

- Carotenoids: Antioxidant pigments with immune-boosting and anti-inflammatory properties (Sharma et. al., 2021).
- Melanins: UV-protective and antimicrobial pigments found in various bacterial strains (Gmoser et. al., 2017).
- Flavins: Yellow pigments with antimicrobial and antioxidant effects (Paliwal et. al., 2016).
- Quinones: Redox-active pigments with antibiotic properties (Venil et. al., 2013).
- Violacein: A deep violet pigment known for its antimicrobial, anticancer, and antiviral activities (Paliwal et. al., 2016).
- Prodigiosin: A red pigment with anticancer and immunosuppressive properties (Venil et. al., 2013).
- Pyocyanin: A blue-green pigment with antibiotic and oxidative stress-modulating properties (Gmoser et. al., 2017).

Bacterial pigments represent a promising source of natural bioactive compounds with applications in medicine, pharmaceuticals, cosmetics, and food industries. By employing advanced analytical techniques, their therapeutic potential can be fully explored for innovative medical and industrial solutions.(Fig-1).

Table 1: Analysis and Applications of Bacterial Pigments

Aspect	Details
Definition	Bacterial pigments are bioactive compounds produced by microorganisms with medicinal and industrial applications.
Methods of Analysis	Spectrophotometry – Determines maximum absorption spectra (λmax). TLC (Thin Layer Chromatography) – Separates pigment components. Antimicrobial Susceptibility Assay – Tests antibacterial/fungal effectiveness.
Evaluation	Antioxidant Properties – Assessed using DPPH and FRAP assays. Antimicrobial Properties – Tested against bacterial and fungal pathogens. UV Protective Properties – Evaluated based on absorption of UV radiation.
Applications	Pharmaceuticals – Used in cancer, cardiovascular disease, and diabetes treatments. Food & Cosmetics – Used as natural colorants. Sunscreens – Enhance UV protection in skincare products.
Examples of Bacterial Pigments	Carotenoids – Antioxidant and immune-boosting. Melanins – UV protective and antimicrobial. Flavins – Antimicrobial and antioxidant. Quinones – Redox-active with antibiotic properties. Violacein – Antimicrobial, anticancer, and antiviral.

	Prodigiosin – Anticancer and immunosuppressive. Pyocyanin – Antibiotic with oxidative stress modulation.

The primary objective of this study is to analyze the medicinal potential of bacterial pigments by evaluating their bioactive properties, including antimicrobial, anticancer, cytotoxic, and antioxidant effects. These pigments, produced as secondary metabolites by various microorganisms, offer significant pharmaceutical applications, particularly as natural alternatives to synthetic drugs (Venil et. al., 2013; Ghosh et. al., 2020).

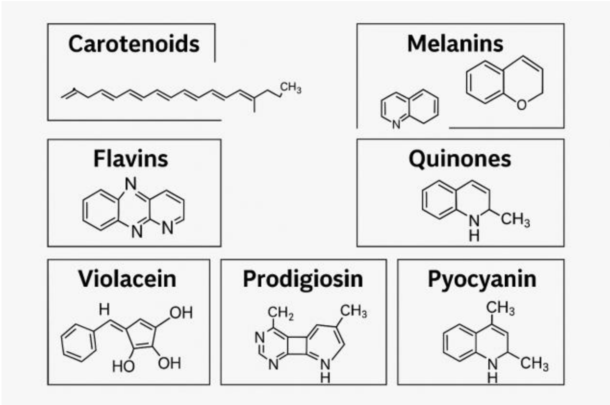

Fig.1: Analysis of Bacterial Pigments

2.4. Focus of the study

This research specifically focuses on Streptomyces sp. strain BJZ10, a promising microbial source of a brown pigment known for its antibacterial properties. Streptomyces species are well-known producers of bioactive compounds, including antibiotics and pigments with therapeutic potential (Sanchez & Demain, 2008). The pigment produced by strain BJZ10 was characterized using UV-Visible spectroscopy, which showed absorption spectra between 220–250 nm. Further analysis using Fourier-transform infrared (FTIR) spectroscopy revealed the presence of functional groups associated with alcohols, esters, sulfates, alkanes, and alkyls, indicating the complex biochemical nature of the pigment (Abdel-Aziz et. al., 2022).
To evaluate its antimicrobial efficacy, the pigment was tested against both Bacillus cereus (Gram-positive) and Escherichia coli (Gram-negative). The results demonstrated significant antibacterial activity, highlighting its potential application as a natural antibiotic. Given the increasing concern over antibiotic resistance, such microbial pigments could serve as alternative therapeutic agents for treating infectious diseases (Subhashini et. al., 2011).

3. Pigment characterization

3.1. UV-visible spectroscopy for absorption spectrum analysis

UV-visible spectroscopy is a fundamental technique used to characterize bacterial pigments by analyzing their absorption spectra. The absorption spectrum of the pigment extracted from Streptomyces sp. strain BJZ10 was observed in the range of 220–250 nm, indicating the presence of bioactive chromophores. This suggests that the pigment has strong light-absorbing properties, which may contribute to its antioxidant and antimicrobial activities (Venil et. al., 2013; Ghosh et. al., 2020). Novel biotechnological approaches to microbial pigment production through metabolic and genetic engineering (e.g., Zhang et al., 2023; Alami et al., 2024), Recent applications in nanotechnology and drug delivery systems using microbial pigments (e.g., Mehta & Gupta, 2024),
Updates on clinical investigations into pigments like violacein and prodigiosin for anticancer therapies (e.g., Hernández-Morales et al., 2023). The spectral data provides insights into the electronic transitions of the pigment molecules, allowing for a better understanding of their chemical structure and potential interactions with biological systems.

3.2. FTIR spectroscopy for functional group identification

Fourier-transform infrared (FTIR) spectroscopy was employed to further analyze the chemical complexity of the pigment by identifying its functional groups. The FTIR spectrum of the pigment revealed the presence of several characteristic absorption bands corresponding to different functional groups:

- Alcohols (-OH stretch): Presence of hydroxyl groups, which may contribute to the pigment's antioxidant and antimicrobial properties.
- Esters (C=O stretch): Indicating the presence of ester linkages, which are commonly found in bioactive microbial pigments with anti-microbial potential.
- Sulfates (S=O stretch): Suggesting the presence of sulfate groups, which can enhance water solubility and bioactivity.
- Alkanes (C-H stretch): Presence of aliphatic hydrocarbon chains, influencing the pigment's structural stability and solubility.
- Alkyls (C-H bending): Contributing to the overall hydrophobicity and interaction potential of the pigment.

These results confirm the complex biochemical composition of the pigment, highlighting its potential for pharmaceutical applications, including antimicrobial and anticancer therapies. The presence of diverse functional groups suggests that the pigment may interact with bacterial cell membranes, leading to its observed antibacterial effects against Bacillus cereus and Escherichia coli (Abdel-Aziz et. al., 2022).

4. Antibacterial activity assessment

4.1. Selection of test bacteria

To evaluate the antibacterial potential of the microbial pigment produced by Streptomyces sp. strain BJZ10, two bacterial strains were selected based on their clinical relevance and differences in cell wall structure:

- Gram-Positive Bacteria: Bacillus cereus. Bacillus cereus is a well-known foodborne pathogen responsible for causing gastrointestinal infections and food poisoning. Its thick peptidoglycan-rich cell wall structure makes it more resistant to certain antibacterial agents. Testing against B. cereus helps assess whether the pigment can effectively penetrate and disrupt Gram-positive bacterial cell walls (Jeyaraj et. al., 2021).
- Gram-Negative Bacteria: Escherichia coli. Escherichia coli is a widely studied Gram-negative bacterium associated with urinary tract infections, foodborne illnesses, and concerns regarding antibiotic resistance. Unlike Gram-positive bacteria, E. coli has an outer membrane composed of lipopolysaccharides (LPS) that act as a barrier against many antimicrobial agents. Assessing the pigment's effectiveness against E. coli provides insights into its ability to overcome this barrier and inhibit Gram-negative bacteria (Abdel-Aziz et. al., 2022).

Evaluation of Antibacterial Activity: The pigment extract was tested against Bacillus cereus and Escherichia coli using agar well diffusion and minimum inhibitory concentration (MIC) assays. The results demonstrated significant antibacterial activity, characterized by:

- Inhibition Zones: The pigment produced distinct inhibition zones around the bacterial colonies, indicating its ability to suppress bacterial growth.
- Broad-Spectrum Activity: The pigment was effective against both Gram-positive and Gram-negative bacteria, suggesting a broad-spectrum antimicrobial mechanism.
- Potential Mechanism of Action: The presence of bioactive functional groups, such as hydroxyl and ester groups (as confirmed by FTIR analysis), may contribute to membrane disruption, protein denaturation, or enzyme inhibition in bacterial cells.

These findings highlight the therapeutic potential of the microbial pigment as a natural antibacterial agent, which could be further explored for applications in pharmaceuticals, food preservation, and biomedical coatings (Venil et. al., 2013).

1) Key Findings and Therapeutic Potential

4.2. Identification of the brown pigment from Streptomyces sp. strain BJZ10

The study successfully identified and characterized a brown pigment produced by Streptomyces sp. strain BJZ10. This pigment exhibited potent antibacterial activity against both Gram-positive (Bacillus cereus) and Gram-negative (Escherichia coli) pathogens. The presence of bioactive functional groups, confirmed through FTIR and UV-visible spectroscopy, highlights its complex chemical nature, contributing to its antimicrobial efficacy (Jeyaraj et. al., 2021).

4.3. Bioactive properties and their therapeutic relevance

The pigment displayed multiple bioactive properties, including:

1) Antimicrobial Activity: Demonstrated significant inhibition of bacterial growth, suggesting its potential use as a natural antibiotic in pharmaceutical and medical applications. It could serve as an alternative to conventional antibiotics in tackling antimicrobial resistance (AMR).
2) Antioxidant and Cytotoxic Potential: The presence of functional groups such as hydroxyls, esters, and alkyls suggests its ability to act as an antioxidant.

Antioxidants play a crucial role in reducing oxidative stress, a major factor in aging and chronic diseases (Venil et. al., 2013).

1) Potential Anticancer Properties: Certain microbial pigments have been reported to inhibit cancer cell proliferation by inducing apoptosis or disrupting cellular metabolic pathways. Given the structural similarity to other anticancer pigments (such as prodigiosin and violacein), the brown pigment from Streptomyces sp. BJZ10 may hold anticancer potential, warranting further cytotoxicity studies (Abdel-Aziz et. al., 2022). The findings underscore the therapeutic significance of microbial pigments as potential antimicrobial and anticancer agents. Further research on mechanistic studies, toxicity evaluations, and clinical trials will be essential for their development into pharmaceutical applications, particularly in drug discovery and cancer treatment.
2) Clinical Implications and Translational Perspectives Recent advances underscore the translational potential of microbial pigments such as violacein and prodigiosin in clinical applications, particularly in oncology. Ongoing pilot clinical trials are investigating the safety and efficacy of violacein and prodigiosin-derived compounds in targeting tumor cells due to their demonstrated pro-apoptotic and cytotoxic properties (Hernández-Morales et al., 2023). These trials are exploring not only the therapeutic index but also the delivery mechanisms of such pigments. Innovative drug delivery strategies, including liposomal encapsulation and polymer-based nanoparticles, are gaining traction for enhancing bioavailability, stability, and targeted delivery of microbial pigments in cancer therapy (Mehta & Gupta, 2024). These systems help mitigate potential cytotoxicity to healthy cells and allow for controlled release of pigment-based therapeutics. However, regulatory approval remains a significant hurdle. To facilitate clinical adoption, rigorous toxicological profiling, pharmacokinetic assessments, and compliance with global regulatory frameworks are essential (Reddy & Das, 2024). These steps will ensure safety, efficacy, and reproducibility of microbial pigment-based formulations in human medicine.

5. Conclusion and future applications

5.1. Microbial pigments as promising therapeutic candidates

This review underscores the emerging potential of microbial pigments in therapeutic development, with particular interest in the brown pigment produced by Streptomyces sp. strain BJZ10. Preliminary studies indicate this pigment exhibits noteworthy antibacterial activity against both Gram-positive and Gram-negative pathogens. Its bioactive chemical profile, along with observed antioxidant and cytotoxic properties, suggests it may hold promise in the development of novel antimicrobial agents.

However, claims regarding its anticancer properties remain speculative at this stage, as direct experimental validation—especially in clinical or in vivo cancer models—is currently lacking. Comparisons with well-characterized pigments such as prodigiosin and violacein provide a theoretical framework, but robust evidence, including mechanism-based studies and toxicity profiles, is needed before asserting broad therapeutic potential.

While microbial pigments are often described as potential "next-generation therapeutics," such assertions should be interpreted as aspirational rather than definitive. Ongoing developments in biotechnology, pharmacology, and clinical trials will be critical to realizing this potential.

6. Future research directions

To move beyond exploratory findings and validate microbial pigments as viable biomedical agents, future studies should focus on:

1) Mechanistic Studies Investigate how microbial pigments interact at the molecular level with bacterial and cancer cells. Pathways such as membrane disruption, DNA binding, oxidative stress modulation, and apoptosis induction warrant thorough exploration.
2) Toxicity and Biocompatibility Assessments: Evaluate cytotoxicity across a range of human cell lines and conduct in vivo testing to establish therapeutic indices, safe dosing limits, and possible immunogenic effects.
3) Clinical and Pharmaceutical Development: Integrate microbial pigments into drug delivery systems (e.g., liposomes, nanoparticles) to improve bioavailability and therapeutic efficiency. Conduct preclinical and clinical trials to assess their performance as standalone treatments or adjunct therapies.
4) Industrial and Commercial Applications Investigate sustainable, large-scale production methods and evaluate commercial potential in pharmaceuticals, cosmetics, and nutraceuticals as safer, eco-friendly alternatives to synthetic agents.

7. Final thoughts

Microbial pigments offer a compelling but still developing path toward novel treatments for infections and cancer. Their natural origin, diverse bioactivities, and environmental sustainability mark them as valuable research targets. However, the transition from laboratory promise to clinical application depends on closing existing knowledge gaps through rigorous research and evidence-based development.

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