

Chapter 11

Biotechnological Potential of Microbial Pigments: From Production to Application

Vaidegi Muthuvelraj^a, Pavithran Kumar^a, Manjunathan Jagadeesan^{a*}

^aDepartment of Biotechnology, School of Life sciences, Vels Institute of Science Technology and Advanced Studies, Chennai.

** Corresponding Author: jmanjunthan@gmail.com*

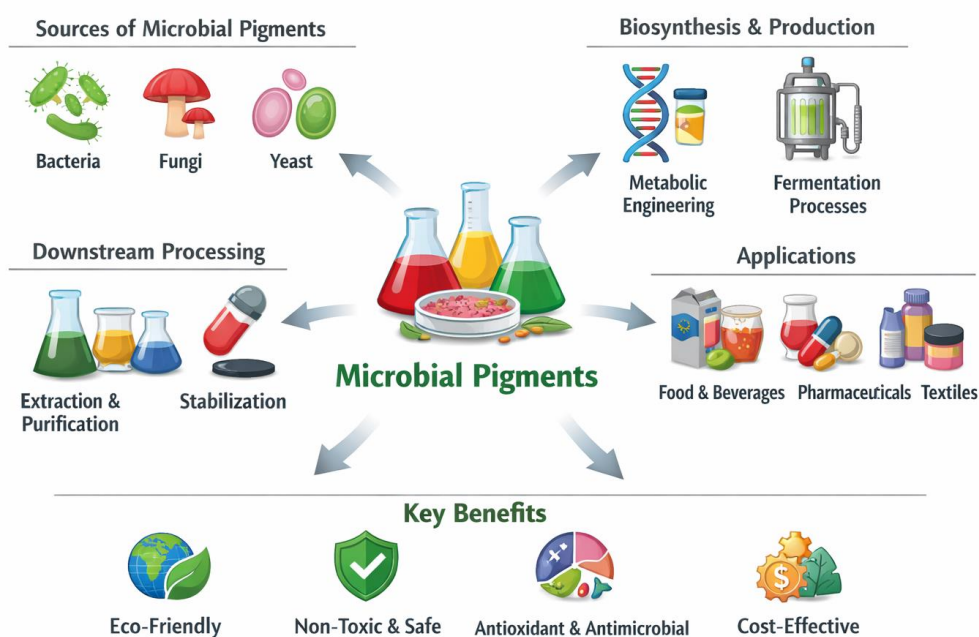
Abstract

Microbial pigments have gained considerable attention as sustainable and eco-friendly alternatives to synthetic colorants, driven by increasing environmental concerns and demand for natural products. These pigments are produced by bacteria, fungi, yeasts, and microalgae and display a wide range of colors along with bioactive properties such as antioxidant, antimicrobial, anticancer, and anti-inflammatory activities. Advances in biotechnology, including metabolic engineering, synthetic biology, and process optimization, have significantly improved pigment yield, stability, and scalability. The use of low-cost substrates and agro-industrial wastes further enhances economic feasibility and sustainability. Efficient downstream processing techniques ensure pigment purity, safety, and functional performance for diverse applications. Microbial pigments are increasingly utilized in food, pharmaceuticals, cosmetics, textiles, and agriculture due to their multifunctional nature. Despite these advantages, challenges such as large-scale production, stability, and regulatory approvals remain. This chapter presents a comprehensive overview of microbial pigment sources,

classification, biosynthesis, production technologies, downstream processing, applications, and future prospects, highlighting their importance in sustainable industrial biotechnology.

Keywords: Microbial pigments; Biopigments; Fermentation; Biosynthesis; Carotenoids; Industrial applications.

Graphical Abstract



1. Introduction

Color is a vital quality parameter that significantly influences consumer perception, product acceptance, and overall marketability across a wide range of industries, including food, pharmaceuticals, textiles, and cosmetics. The visual appeal imparted by color often determines consumer preference and purchasing decisions, making pigments an essential component in product formulation. Traditionally, pigments have been sourced either from natural plant materials or synthesized through chemical processes. While plant-

derived pigments are generally perceived as safe and natural, they are often limited by factors such as seasonal availability, geographical dependency, low extraction yield, and high processing costs. These limitations restrict their large-scale industrial application and consistent supply. Conversely, synthetic pigments have been widely adopted due to their low cost, high stability, and ease of production. However, increasing evidence of their adverse environmental and health effects, including toxicity, allergenicity, and potential carcinogenicity, has led to stringent regulatory controls and a growing shift in consumer preference toward safer, natural alternatives [1].

In this context, microbial pigments have emerged as a promising and sustainable alternative, attracting considerable attention in recent years. A diverse array of microorganisms, including bacteria, fungi, yeasts, and microalgae, are capable of producing pigments with varied chemical structures, colors, and functional properties. One of the key advantages of microbial systems is their ability to grow rapidly under controlled conditions, independent of climatic and seasonal constraints, ensuring a continuous and reliable production process. Additionally, these microorganisms can utilize a wide range of low-cost substrates, including agricultural residues, food waste, and industrial by-products, thereby reducing production costs and contributing to waste valorization and environmental sustainability [2]. Beyond their role as colorants, microbial pigments often possess significant bioactive properties, such as antimicrobial, antioxidant, anti-inflammatory, and anticancer activities, which enhance their applicability in high-value industries like pharmaceuticals and nutraceuticals. Consequently, the exploration and development of microbial pigments represent a major advancement in modern biotechnology, offering eco-friendly, economically viable, and

multifunctional alternatives to conventional pigments while supporting the transition toward sustainable industrial practices [3].

2. Diversity and Sources of Microbial Pigments

2.1 Bacterial Pigments

Bacteria are one of the most versatile producers of pigments, synthesizing a wide variety of compounds with distinct colors and biological functions. These pigments often play important roles in microbial survival, including protection against ultraviolet radiation, oxidative stress, and microbial competition. For instance, *Serratia marcescens* produces prodigiosin, a red pigment known for its anticancer and immunosuppressive properties. Similarly, *Chromobacterium violaceum* synthesizes violacein, a purple pigment with strong antimicrobial and antioxidant activity. Pigments such as pyocyanin produced by *Pseudomonas aeruginosa* also exhibit redox activity and contribute to microbial pathogenicity. Due to their bioactivity and ease of cultivation, bacterial pigments are widely studied for pharmaceutical and industrial applications [4,5].

2.2 Fungal Pigments

Fungi, particularly filamentous fungi, are well-known producers of industrially important pigments. Species belonging to the genus *Monascus* produce azaphilone pigments that range in color from yellow to red and are widely used as natural food colorants in Asian countries. Other fungi such as *Aspergillus* and *Penicillium* produce polyketide-derived pigments with potential applications in food and textile industries. Additionally, melanin pigments produced by fungi serve as protective agents against environmental stress and have applications in cosmetics and biomedicine. Fungal pigments are

particularly advantageous due to their high yield and compatibility with solid-state fermentation processes [6].

2.3 Yeast Pigments

Yeasts represent another important group of pigment-producing microorganisms, especially known for their ability to synthesize carotenoids. Species such as *Rhodotorula* and *Phaffia rhodozyma* produce valuable pigments like β -carotene and astaxanthin, which are widely used in aquaculture to enhance coloration in fish and crustaceans. These pigments also possess strong antioxidant properties, making them useful in nutraceutical and pharmaceutical industries. Yeasts are preferred in industrial production due to their rapid growth, ease of genetic manipulation, and Generally Recognized as Safe (GRAS) status [7].

2.4 Algal Pigments

Microalgae are rich sources of pigments such as chlorophylls, carotenoids, and phycobiliproteins. These pigments not only contribute to photosynthesis but also have significant commercial value. For example, astaxanthin produced by microalgae is widely used in food supplements and cosmetics, while phycobiliproteins are used as natural colorants and fluorescent markers in biomedical research. Algal pigments are gaining popularity due to their high nutritional value and potential health benefits, including antioxidant and anti-inflammatory properties [8].

3. Classification of Microbial Pigments

Microbial pigments can be broadly classified based on their chemical structure and biosynthetic origin, reflecting the remarkable diversity and functional complexity of these bioactive compounds. Among the most prominent groups are carotenoids, which are lipid-soluble

pigments responsible for a wide range of yellow, orange, and red hues. These compounds are synthesized through isoprenoid pathways and are well known for their strong antioxidant activity, as they scavenge free radicals and protect cellular components from oxidative damage. Additionally, certain carotenoids, such as β -carotene, serve as precursors of vitamin A, making them nutritionally significant in food and feed applications [9].

Melanins represent another important class of microbial pigments, characterized by their dark brown to black coloration. They are formed through the oxidative polymerization of phenolic or indolic compounds and are widely distributed among bacteria and fungi. Melanins play a crucial role in protecting microorganisms from environmental stresses, particularly ultraviolet (UV) radiation, extreme temperatures, and oxidative stress. Due to these protective properties, melanins have found applications in cosmetics, pharmaceuticals, and even in the development of UV-protective materials [10].

Polyketide pigments, such as those produced by *Monascus* species, are synthesized via the polyketide synthase (PKS) pathway and exhibit a range of colors from yellow to deep red. These pigments are extensively used as natural food colorants and have also demonstrated pharmacological activities, including antimicrobial and cholesterol-lowering effects. Flavins, including riboflavin (vitamin B₂), are yellow pigments that play essential roles in cellular metabolism, particularly in redox reactions and energy production. Their importance extends to their use as nutritional supplements and food additives [11].

Quinones and phenazines constitute another class of microbial pigments with significant biological activity. These compounds are often involved in electron transport chains and exhibit strong antimicrobial and redox properties, making them valuable in pharmaceutical and agricultural applications. Lastly, phycobiliproteins are water-soluble pigments primarily found in cyanobacteria and algae. These pigments, such as phycocyanin and phycoerythrin, are widely used as natural colorants in food and cosmetics, as well as fluorescent markers in biomedical research due to their high sensitivity and specificity [12].

Overall, this classification underscores the extensive chemical diversity and multifunctional nature of microbial pigments, highlighting their wide-ranging applications and importance in various biotechnological fields.

Table 1. Types, Sources, and Applications of Microbial Pigments

| Pigment Type | Major Microbial Sources | Color | Key Properties | Applications |
|-------------------------|--|---------------------------|--|---|
| Carotenoids | <i>Rhodotorula</i> , <i>Dunaliella</i> , <i>Blakeslea</i> | Yellow – Orange–Red | Antioxidant, provitamin A activity | Food colorants, nutraceuticals , cosmetics |
| Melanins | <i>Streptomyces</i> , <i>Aspergillus</i> , bacteria | Brown –Black | UV protection, antioxidant, metal chelation | Cosmetics, pharmaceuticals, radioprotection |
| Polyketides | <i>Monascus</i> spp. | Red– Orange | Antimicrobial, bioactive compounds | Food industry, pharmaceuticals |
| Flavins (Riboflavin) | <i>Ashbya</i> <i>gossypii</i> , <i>Bacillus</i> <i>subtilis</i> | Yellow | Vitamin B2 activity, redox reactions | Food fortification, pharmaceuticals |

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|-----------------------|--|----------------|--|--|
| Quinones | <i>Penicillium</i> , <i>Streptomyces</i> | Yellow -Red | Electron transport, antimicrobial | Medicine, biochemical applications |
| Phenazines | <i>Pseudomonas</i> spp. | Blue- Green | Antimicrobial, redox-active | Agriculture (biocontrol), pharmaceutica ls |
| Phycobiliprot eins | Cyanobacteri a, algae (<i>Spirulina</i>) | Blue- Red | Fluorescent, water-soluble | Food colorants, diagnostics, fluorescent markers |
| Violacein | <i>Chromobacter ium violaceum</i> | Purple | Anticancer, antimicrobial | Pharmaceutica ls, research |
| Prodigiosin | <i>Serratia marcescens</i> | Red | Antimicrobial, anticancer, immunosuppre ssive | Pharmaceutica ls, biomedical research |

4. Biosynthesis of Microbial Pigments

The biosynthesis of microbial pigments is a complex process involving multiple enzymatic reactions and regulatory mechanisms. Pigments are generally produced as secondary metabolites, synthesized during the stationary phase of microbial growth when primary nutrients become limited. Key biosynthetic pathways include the mevalonate and non-mevalonate pathways for carotenoid synthesis, the polyketide synthase (PKS) pathway for fungal pigments, and the shikimate pathway for aromatic pigments. These pathways involve a series of gene clusters that encode enzymes responsible for the stepwise conversion of precursor molecules into pigment compounds [13].

Environmental factors such as pH, temperature, light, and nutrient availability significantly influence pigment production by regulating gene expression. Recent advances in metabolic engineering and synthetic biology have enabled the manipulation of these pathways to enhance pigment yield. Techniques such as gene overexpression,

pathway optimization, and heterologous expression in suitable host organisms have greatly improved production efficiency, making microbial pigments more commercially viable [14].

5. Production Technologies

The industrial production of microbial pigments is fundamentally dependent on efficient and well-optimized fermentation technologies, which enable large-scale cultivation of pigment-producing microorganisms under controlled conditions. Among these, submerged fermentation (SmF) is the most widely employed method, particularly for bacteria and yeasts. In this system, microorganisms are grown in liquid nutrient media, allowing uniform distribution of nutrients, better control of environmental factors, and ease of monitoring process parameters. SmF offers significant advantages such as high productivity, reproducibility, and suitability for continuous processing, making it ideal for industrial-scale operations. The ability to precisely regulate parameters such as pH, temperature, dissolved oxygen, and nutrient concentration ensures consistent pigment yield and quality. Moreover, automation and process control systems further enhance the efficiency and reliability of submerged fermentation [15].

In contrast, solid-state fermentation (SSF) is predominantly used for filamentous fungi and involves the growth of microorganisms on solid substrates with little to no free water. This method closely mimics the natural habitat of many fungi, often resulting in higher pigment yields and improved product characteristics. SSF is particularly advantageous due to its low operational cost, reduced energy requirements, and ability to utilize agro-industrial residues such as rice bran, wheat bran, and fruit peels as substrates. This not only

reduces production costs but also supports sustainable waste management through the conversion of low-value materials into high-value pigments [16].

Modern bioreactor systems are integral to both SmF and SSF processes, providing a controlled environment that optimizes microbial growth and metabolite production. Advanced bioreactors are equipped with sensors and control units that continuously monitor and regulate critical parameters such as temperature, pH, aeration, agitation, and oxygen transfer rates. Proper oxygen transfer is especially crucial for aerobic pigment-producing microorganisms, as it directly influences metabolic activity and pigment synthesis. Additionally, innovations in bioprocess engineering, including fed-batch and continuous fermentation strategies, have significantly improved productivity and scalability. These advancements enable efficient resource utilization, minimize production time, and ensure consistent product quality. Overall, the integration of advanced fermentation technologies and bioreactor design has greatly enhanced the industrial feasibility and commercial potential of microbial pigment production [17].

6. Optimization Strategies

Optimization of culture conditions is a crucial step in enhancing microbial pigment production, as it directly influences both yield and cost-effectiveness of the process. The selection and concentration of nutritional components, particularly carbon and nitrogen sources, play a fundamental role in regulating microbial growth and metabolic activity. Carbon sources such as glucose, sucrose, glycerol, and various agro-industrial wastes serve not only as energy sources but also as key precursors in pigment biosynthesis pathways. Similarly,

nitrogen sources—including organic forms like yeast extract and peptone, as well as inorganic forms such as ammonium salts—affect enzyme production and cellular metabolism, thereby influencing pigment synthesis. The carbon-to-nitrogen ratio is especially important, as it can shift microbial metabolism toward either biomass production or secondary metabolite (pigment) formation [18].

In addition to nutritional factors, environmental parameters such as pH, temperature, aeration, agitation, and light intensity significantly impact pigment production. Each microorganism has an optimal range of conditions under which pigment synthesis is maximized. For instance, slight variations in pH or temperature can alter enzyme activity and metabolic flux, thereby affecting both the quantity and quality of the pigment produced. Light can also act as an inducing or inhibitory factor for certain pigments, particularly in photosensitive microorganisms [19,20].

To systematically optimize these multiple variables, advanced statistical tools such as Response Surface Methodology (RSM) and Design of Experiments (DoE) are widely employed. These techniques allow simultaneous evaluation of several factors and their interactions, reducing the number of experimental trials while providing precise optimization results. By generating mathematical models, these approaches help in predicting optimal conditions for maximum pigment yield and process efficiency. Furthermore, modern strategies such as adaptive laboratory evolution and strain improvement through mutagenesis or genetic engineering are being explored to develop robust, high-yielding microbial strains. Collectively, these optimization strategies play a vital role in improving productivity, reducing production costs, and facilitating the large-scale industrial application of microbial pigments [21].

7. Downstream Processing

Downstream processing is a critical stage in the production of microbial pigments, encompassing a series of steps including extraction, purification, concentration, and stabilization to obtain a final product that meets industrial quality standards. The efficiency of downstream processing significantly influences the overall cost, yield, and commercial viability of microbial pigments. The selection of an appropriate extraction method largely depends on the physicochemical properties of the pigment—such as solubility, polarity, and stability—as well as the type of microorganism producing it. For intracellular pigments, which are retained within microbial cells, initial cell disruption is essential. Techniques such as sonication, bead milling, and high-pressure homogenization are commonly employed to rupture the cell wall and release the pigment into the extraction medium. Solvent extraction using organic solvents like ethanol, methanol, acetone, or ethyl acetate is widely used due to its simplicity and effectiveness; however, the choice of solvent must consider factors such as toxicity, selectivity, and environmental impact [22].

In recent years, advanced extraction technologies have gained attention for their ability to improve efficiency while reducing solvent consumption and processing time. Ultrasound-assisted extraction enhances mass transfer through cavitation effects, while microwave-assisted extraction accelerates the release of pigments by rapid heating of cellular components. Supercritical fluid extraction, particularly using carbon dioxide, offers a green and solvent-free alternative that yields high-purity pigments with minimal degradation. Following extraction, purification steps are necessary to remove impurities such as proteins, lipids, and residual solvents.

Techniques such as column chromatography, high-performance liquid chromatography (HPLC), membrane filtration, and crystallization are employed to achieve the desired purity and concentration [23,24].

Stabilization is another crucial aspect of downstream processing, as many microbial pigments are sensitive to environmental factors such as light, heat, oxygen, and pH fluctuations. Strategies such as encapsulation, use of stabilizing agents, and controlled storage conditions are implemented to preserve pigment integrity and extend shelf life. Overall, efficient downstream processing not only ensures the safety, stability, and functionality of microbial pigments but also plays a pivotal role in their successful application across industries such as food, pharmaceuticals, cosmetics, and textiles [25].

Table 2. Production, Optimization, and Downstream Processing of Microbial Pigments

| Process Stage | Key Factors/Methods | Description | Impact on Production |
|-----------------------------------|--|--|--|
| Microbial Strain Selection | Wild strains, genetically modified strains, high-yield mutants | Selection of efficient pigment-producing microorganisms | Determines yield, quality, and pigment type |
| Culture Media Composition | Carbon sources (glucose, sucrose, agro-waste), Nitrogen sources (yeast extract, peptone) | Provides essential nutrients for growth and pigment biosynthesis | Influences biomass and pigment productivity |
| Environmental Conditions | pH, temperature, aeration, light intensity | Controlled conditions for optimal microbial metabolism | Affects pigment synthesis rate and stability |
| Fermentation Type | Submerged fermentation (SmF), | SmF for bacteria/yeast; SSF for fungi | Determines scalability |

| | | | |
|--------------------------------|---|--|--|
| | Solid-state fermentation (SSF) | using solid substrates | and cost-effectiveness |
| Bioreactor Parameters | Agitation, oxygen transfer rate, incubation time | Maintains uniform growth and metabolic activity | Enhances yield and process efficiency |
| Optimization Techniques | Response Surface Methodology (RSM), Design of Experiments (DoE) | Statistical tools to optimize multiple variables simultaneously | Maximizes yield and reduces production cost |
| Cell Disruption Methods | Sonication, homogenization, bead milling | Breaks microbial cells to release intracellular pigments | Improves extraction efficiency |
| Extraction Methods | Solvent extraction (ethanol, methanol, acetone), supercritical fluid extraction | Separates pigments from biomass using suitable solvents or advanced techniques | Affects purity, recovery rate, and safety |
| Purification Techniques | Chromatography, membrane filtration, crystallization | Removes impurities to obtain high-quality pigment | Ensures product quality and industrial applicability |
| Stabilization Methods | Encapsulation, use of stabilizers, controlled storage conditions | Protects pigments from degradation (light, heat, oxygen) | Extends shelf life and functionality |

8. Applications of Microbial Pigments

Microbial pigments have a wide range of applications across multiple industries due to their functional and bioactive properties. In the food industry, they are used as natural colorants in beverages, dairy products, and confectionery, providing both aesthetic appeal and health benefits. In pharmaceuticals, microbial pigments are explored for their antimicrobial, anticancer, and antioxidant properties, contributing to drug development and therapeutic applications [26].

In the textile industry, microbial pigments serve as eco-friendly dyes, reducing the environmental impact associated with synthetic dyes. The cosmetic industry utilizes these pigments in skincare and makeup products due to their natural origin and beneficial properties such as UV protection and anti-aging effects. In agriculture, microbial pigments are used as biocontrol agents and plant growth promoters, enhancing crop productivity and protection. Additionally, they have applications in environmental biotechnology, including bioremediation and biosensing [27].

9. Advantages of Microbial Pigments

Microbial pigments offer numerous advantages over conventional plant-derived and synthetic pigments, making them highly attractive for modern industrial applications. One of their most significant benefits is sustainability, as they are produced using renewable biological systems and can be generated through controlled fermentation processes with minimal environmental impact. Unlike plant-based pigments, whose availability is often influenced by seasonal variations, climatic conditions, and land use requirements, microbial pigments can be produced consistently throughout the year under optimized laboratory or industrial conditions. This ensures a stable supply chain and reduces dependency on agricultural resources. Furthermore, microbial pigment production can utilize inexpensive substrates, including agro-industrial residues and waste materials, thereby contributing to waste management and promoting a circular bioeconomy [28].

Another major advantage is their eco-friendly and biodegradable nature. Synthetic pigments are often associated with toxic by-products and environmental pollution, whereas microbial pigments

are generally biodegradable and less harmful to ecosystems. In addition, most microbial pigments are considered non-toxic and safe for human consumption, especially when produced by Generally Recognized as Safe (GRAS) microorganisms, making them highly suitable for applications in the food and pharmaceutical industries. Their safety profile is further enhanced by the absence of hazardous chemical synthesis processes [29].

Beyond their coloring properties, microbial pigments exhibit a wide range of biological activities that significantly enhance their industrial value. Many of these pigments possess antioxidant properties, which help in neutralizing free radicals and preventing oxidative damage. Others exhibit antimicrobial, antifungal, anti-inflammatory, and even anticancer activities, opening new opportunities in the development of functional foods, nutraceuticals, and therapeutic agents. This multifunctionality allows microbial pigments to serve dual roles as both colorants and bioactive compounds, providing added value in diverse sectors such as food, healthcare, cosmetics, and agriculture. Collectively, these advantages position microbial pigments as a sustainable, safe, and versatile alternative to traditional pigments, supporting their increasing adoption in various industries [30].

10. Challenges and Limitations

Despite their potential, microbial pigments face several challenges that limit their widespread commercialization. High production costs, particularly during downstream processing, remain a significant barrier. Stability issues, such as sensitivity to light, heat, and pH, can affect pigment quality and shelf life. Regulatory approvals for food and pharmaceutical applications require extensive safety testing, which can be time-consuming and costly. Additionally, scaling up

production from laboratory to industrial levels presents technical challenges that need to be addressed.

11. Future Perspectives

The future of microbial pigments is exceptionally promising, fueled by rapid advancements in biotechnology and a growing global shift toward natural, safe, and sustainable products. Increasing consumer awareness regarding the harmful effects of synthetic dyes, along with stringent environmental regulations, has created a strong demand for eco-friendly alternatives, positioning microbial pigments as a viable solution. Modern biotechnological tools, particularly synthetic biology and metabolic engineering, are playing a transformative role in enhancing pigment production. Through targeted gene editing, pathway optimization, and heterologous expression, it is now possible to construct high-yielding microbial strains capable of producing pigments with improved quality, consistency, and novel functionalities. Additionally, omics-based approaches, including genomics, transcriptomics, proteomics, and metabolomics, provide deeper insights into cellular mechanisms, enabling precise control and regulation of pigment biosynthesis.

Another significant factor contributing to the future potential of microbial pigments is the utilization of low-cost substrates, such as agricultural residues, food waste, and industrial by-products. This not only reduces production costs but also supports waste valorization and circular bioeconomy concepts, thereby enhancing sustainability. Furthermore, advancements in fermentation technology and bioprocess optimization are expected to improve scalability and industrial feasibility.

Innovations in nanotechnology are opening new avenues for the application of microbial pigments by enabling the development of advanced delivery systems, such as nano-encapsulation, which enhances pigment stability, solubility, and bioavailability. These systems can protect pigments from environmental degradation caused by light, heat, and oxygen, thereby extending their shelf life and expanding their applicability in sensitive industries like food and pharmaceuticals. Moreover, interdisciplinary research integrating biotechnology, materials science, and process engineering is expected to accelerate the commercialization of microbial pigments.

Overall, as scientific research and technological innovations continue to progress, microbial pigments are poised to become integral components of green manufacturing and sustainable industrial practices. Their ability to combine functional properties with environmental benefits ensures their vital role in shaping the future of industries seeking safer and more sustainable alternatives.

12. Conclusion

Microbial pigments represent a highly versatile and sustainable alternative to conventional synthetic colorants, offering numerous advantages that align with current global priorities of safety, environmental protection, and functional efficiency. Unlike synthetic dyes, which are often associated with toxic by-products, environmental pollution, and potential health risks, microbial pigments are generally biodegradable, eco-friendly, and produced through natural biological processes. Their production relies on renewable resources and controlled fermentation systems, minimizing ecological impact and reducing dependence on petrochemical-based raw materials. Moreover, many microbial

pigments are derived from Generally Recognized as Safe (GRAS) microorganisms, making them suitable for applications in sensitive sectors such as food and pharmaceuticals, where safety and regulatory compliance are critical.

In addition to their environmental and safety benefits, microbial pigments exhibit a wide range of functional properties that enhance their industrial value. These pigments are not merely colorants but also bioactive compounds with antioxidant, antimicrobial, anti-inflammatory, and anticancer activities. Such multifunctionality enables their use in diverse industries, including food, where they serve as natural colorants and preservatives; pharmaceuticals, where they contribute to drug development and therapeutic formulations; textiles, where they provide eco-friendly dyeing alternatives; and cosmetics, where they are incorporated into skincare and personal care products for their protective and aesthetic properties. This broad spectrum of applications underscores their immense biotechnological potential and growing relevance in modern industry.

Despite these advantages, certain challenges such as high production costs, stability issues, and regulatory hurdles must be addressed to facilitate large-scale commercialization. Continued research and technological innovation are therefore essential to optimize production processes, improve pigment stability, and develop cost-effective downstream processing techniques. Advances in areas such as metabolic engineering, synthetic biology, and process optimization are expected to play a key role in overcoming these limitations. Furthermore, increasing consumer awareness and preference for natural, sustainable, and health-friendly products are driving market demand for microbial pigments. As industries continue to transition toward greener and more sustainable practices, microbial pigments

are poised to become a fundamental component of future industrial biotechnology, contributing significantly to the development of eco-conscious and value-added products.

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