WWW.IJRPR.COM

International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Microbial Pigmentation: Biosynthesis, Production, Optimization, Characterization, Applications and Future Perspectives

Srinivasan J., Hari S., and Tamilmozhi M

Department of Bioscience, School of Life Sciences, Sri Krishna Knowledge Foundation (Deemed to be University), Kuniamuthur, Coimbatore – 641008, Tamilnadu, India.
Email: jjsriniga@gmail.com; Ph. No.: 9894513472

ABSTRACT :

Microbial pigmentation refers to the formation, accumulation, secretion, or transformation of colored molecules by the microorganisms like bacteria, yeasts and filamentous fungi that can produce structural diverse pigments, including carotenoids, melanin, prodigiosin, riboflavin and polyketide-derived pigments. These compounds are studied because the visible color is often along with biological such as antioxidant activity, and antimicrobial effects. This may show that microbial pigment production depends on an interaction between the strain genetics and process conditions, including nutrient availability, pH, temperature, oxygen transfer, culture time and downstream recovery. Recent studies may show the value of low-cost substrates and agro-industrial residues, including cheese, for sustainable pigment production. Metabolic engineering and synthetic biology provide and improved productivity, but products may be toxic, pathway burdens, membrane limitations, pigment instability and purification costs remain the important barriers. Overall, microbial pigmentation is a multidisciplinary field like microbiology, biochemistry, fermentation technology, analytical chemistry, materials science and sustainable biotechnology.

Keywords: Microbial pigmentation, microbial pigments, carotenoids, melanin, violacein, prodigiosin, fungal pigments, fermentation, metabolic engineering, natural colorants, sustainable biotechnology.

Introduction

The color is one of the most recognizable properties of microbial culture. A colony may appear yellow, orange, red, pink, violet, blue, brown or black because the organism will produce one or more chromogenic metabolites. These compounds are not simple visual features. In many microorganisms, is associated with protection against environmental stress, oxidative damage, radiation, and other ecological pressures. Microbial pigments have gained attention as secondary metabolites due to their potential applications such as food, textiles, biomedical research, and environmental management. The microbial pigmentation has increased because of some conventional synthetic colorants and pigment sources. Microbial systems can be cultivated under controlled conditions, and they can use renewable substrates, may produce extracellular pigments, simplifying recovery. In contrast, 'natural' does not automatically mean safe. The diversity of microbial pigments, and the role of microorganisms as cell factories, production and downstream processing, challenges and future directions. [2,5, 6, 7, 8, 10]

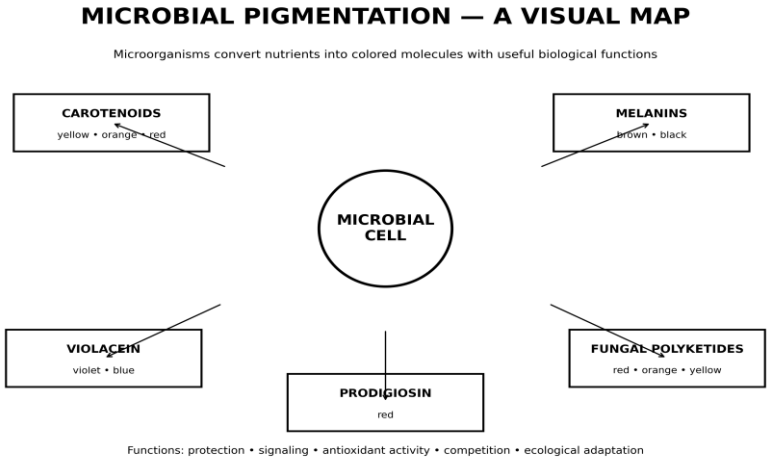


Figure 1. Major microbial pigment families and representative biological functions. Original educational schematic prepared for this review.

Table 1. Representative classes of biosynthesized microbial pigments.

Pigment class	Representative producers	Typical color	Important features
Carotenoids	Rhodotorula, bacteria, fungi	Yellow, orange, red	Antioxidant activity; some are provitamin A carotenoids [4,5,7,9]
Melanins	Streptomyces, fungi, bacteria	Brown, black	UV absorption, redox behavior, metal chelation [1,3,10,11]
Violacein	Chromobacterium and other bacteria	Violet/blue	Bioactive secondary metabolite; antimicrobial and anticancer research [2]
Prodigiosin	Serratia and other bacteria	Red	Bioactive chromogenic metabolite; antimicrobial and anticancer research [2]
Riboflavin	Fungi and bacteria	Yellow	Vitamin-derived pigment with nutritional relevance [5,7]
Polyketide pigments	Filamentous fungi and bacteria	Red/ orange/ yellow/ brown	Large structural diversity; food, textile and bioactive potential [5–8]

Major Pigment Families and Their Biology

Carotenoids

The carotenoids are highly unsaturated, and generally non-nitrogenous pigments built from isoprenoid precursors. Their highly conjugated double-bond systems generated yellow, orange and red colors. The previous studies have shown that microbial carotenoid production is attractive because microorganisms can be cultivated independently of season and it can be geography and can be engineered to redirect metabolic flux toward the products. Metabolic-engineering literature also highlights the difficulty of increasing pathway flux without creating new limitations. Precursor availability can, competing pathways, membrane capacity and toxicity can limit accumulation. Therefore, pathway engineering is the most effective when combined with system-level analysis and the process optimization rather than changing one gene in isolation. [4,7]

Melanin

The melanin are multifaceted, heterogeneous pigments formed using oxidative conversion and polymerization. The literature may ainclude eumelanin, pheomelanin, and neuromelanin as a key form and the microbial melanin is particularly noteworthy because it combines strong optical absorption with antioxidant, redox, and protective properties. Choi's bioprocess reviews compare melanin production using yield, productivity and reaction conditions. Recent Streptomyces work further demonstrates the value of extracellular melanin because a secreted product can reduce cell-disruption requirements and simplify recovery. [1,3,11]

Violacein and Prodigiosin

Violacein and prodigiosin are chromogenic bacterial secondary metabolites that have received considerable attention for antimicrobial and anticancer research. Choi et al. reviewed both their biological activities and production strategies, including native hosts, heterologous hosts and synthetic-biology approaches. Their strong coloration is also useful during screening because pigment formation provides a visible phenotype for identifying productive strains. The key lesson is that as a high laboratory titer does not automatically mean that a process is industrially viable. [2]

Fungal Pigments

Filamentous fungi and yeasts are major microbial pigment producers. The fungal pigment reviews describe carotenoids, riboflavin and polyketide-derived compounds such as important groups. Fungi can produce pigments through pathways involving acetyl-CoA, malonyl-CoA and polyketide synthases, and creating a wide range of aromatic structures. Fungal pigments are also investigated for textile applications because many fungal metabolites can bind to fiber. The textile-focused review highlights their potential as alternatives to conventional colorants. [5–8]

Biosynthesis and Regulation of Microbial Pigmentation

Biosynthesis involves three main stages are precursor supply, enzyme expression and metabolic flux. The Carbon sources are nitrogen availability, pH, temperature, oxygen, light and the growth phase. For the carotenoids and the central challenge is often increasing flux oxidation and polymerization determines pigment types and properties. For polyketide pigments organization of polyketide synthase systems strongly influenced by the chemical profile. Pigmentation is therefore a metabolic phenotype rather than a single biochemical reaction. [1,4,5,9,11]

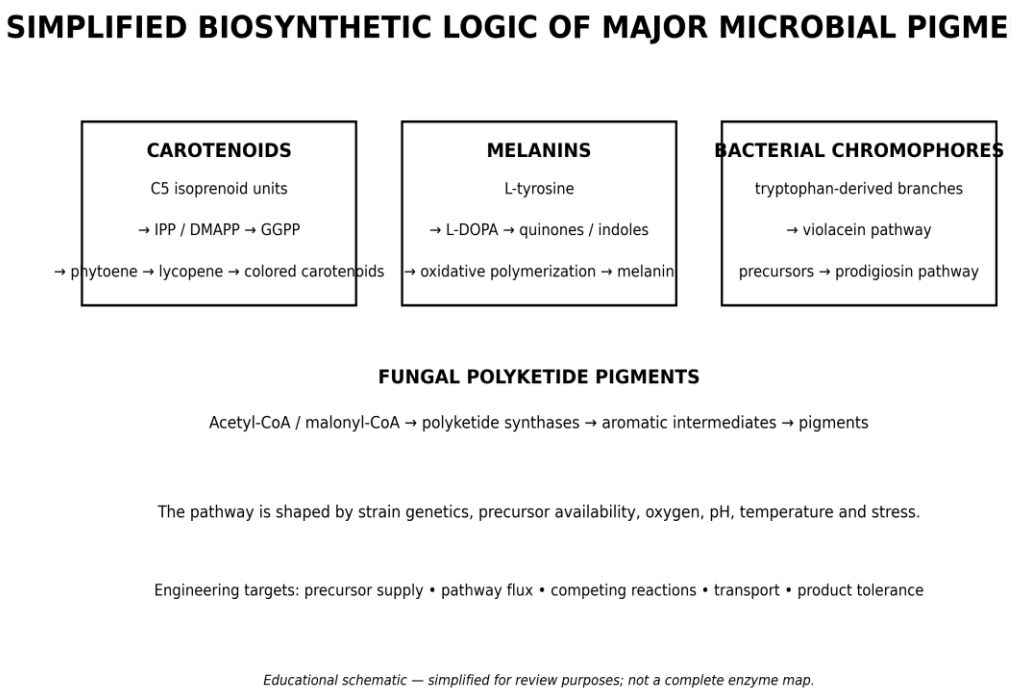


Figure 2. Simplified biosynthetic logic of major microbial pigment families. Original educational schematic; pathways are intentionally simplified.

Microorganisms as Cell Factories

The best way to understand microbial pigmentation is to treat microorganisms. The organism provides enzymes, cofactors, and transport systems that convert raw materials into a value-added pigment and why the strain selection matters are two organisms that produce the same pigment and may differ greatly in growth rate, pigment location. Streptomyces is the best example. Streptomycetes as versatile microbial cell factories and summarized strategies including medium optimization, use of raw substrates, fermentation design and downstream purification. The study of Streptomyces nashvillensis DSM 40314 provides an experimental example at 28 °C and pH 7.0, the strain reached 0.74 ± 0.01 g/L melanin in 96-hour shake-flask cultivation, with purification from the culture supernatant. [3,11]

Production and Fermentation Strategies

Microbial pigmentation can be produced in submerged fermentation, solid-state systems. The type of pigment produced depends on the microorganism and the specific pigment makes Submerged fermentation suitable for controlling pH, temperature, agitation and aeration. Testing one factor at a time experiments can be revealing obvious trends, but statistical designs can identify interactions between variables more efficiently. The Taguchi-based study using Rhodotorula glutinis P4M422 and goat cheese whey is a useful example and how a food-processing by-product can become a substrate for carotenoid synthesis. [3,9,11]

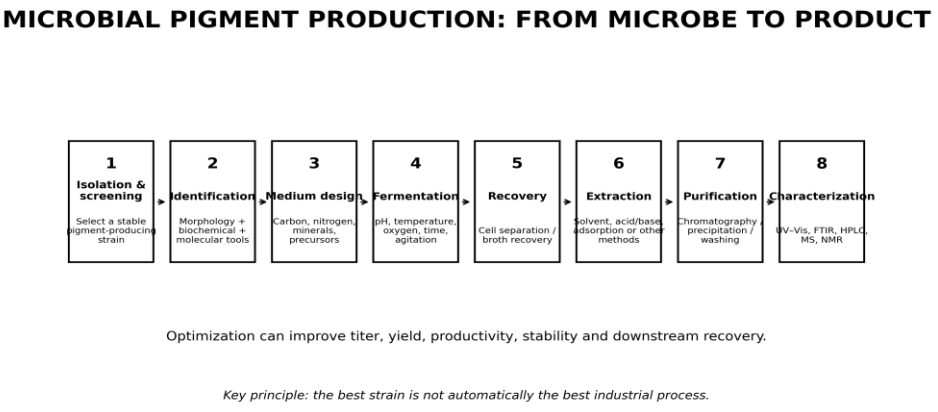


Figure 3. End-to-end workflow from pigment-producing microorganism to characterized pigment product. Original schematic.

Sustainable Substrates and Waste Valorization

Using inexpensive renewable substrates is one of the most practical ways to improve sustainability. The supplied literature discusses agro-industrial residues and other low-cost materials as carbon sources. Goat cheese whey is a clear example for lactose, proteins and other nutrients that can support microbial growth. his approach follows the principles of a circular bioeconomy, where waste materials are reused as resources for microbial growth and natural pigment production instead of being discarded. In contrast, waste substrates are variable, so industrial processes may require pretreatment, compositional monitoring and robust statistical control. Sustainability should therefore be evaluated across the whole process rather than only at fermentation. [5,6,9,11]

Downstream Processing, Purification and Characterization I

Downstream processing can determine whether pigment is economically useful. The intracellular pigments require cell harvesting and disruption before extraction and whereas extracellular pigments can often be recovered directly from culture broth. Depending on the pigment chemistry, downstream operations may include centrifugation, filtration, solvent extraction, acid/base treatment, precipitation, adsorption, chromatography and drying. Characterization may involve UV–Visible spectroscopy, FTIR, HPLC, mass spectrometry, elemental analysis and NMR. Streptomyces nashvillensis study, UV–Visible, FTIR, elemental analysis. Then analytical confirmation is required particularly and when the pigment is intended for food, pharmaceutical, cosmetic or biomedical applications. [1,3,11]

Metabolic Engineering and Synthetic Biology

Metabolic engineering seeks to redesign the cell so that more carbon reaches the desired pigment. Strategies discussed in the carotenoid literature include increasing precursor availability, balancing pathway enzymes, reducing competing reactions, modifying membrane properties and using heterologous pathways. Synthetic biology can also place pigment pathways into hosts with better growth characteristics or easier industrial handling. Engineering introduces trade-offs. The strong expression can burden the host, intermediates may be toxic, cofactors may become limiting. Successfully engineering therefore usually requires an interactive cycle of design, construction, measurement, analysis and redesign. [4,11]

Applications for Microbial Pigments

The supplied reviews collectively described a wide application spectrum. The microbial pigments can act as colorants, but many also possess biological or physicochemical properties that add value beyond color. [2,5–8,10]

Food and Nutraceutical Applications

It is investigated as natural food colors and as sources of compounds with antioxidant or nutritional value. The Carotenoids are particularly important because some have provitamin A activity. The Rhodotorula glutinis study links microbial carotenoid production with the development of value-added products from renewable substrates. For Food applications, stability, purity, toxicological safety and regulatory acceptance are essential. [4,9,10]

Textile Applications

Fungal pigments have been investigated for dyeing and finishing textiles. Their appeal lies in the possibility of reducing dependence on some synthetic dyes and using renewable biological production systems. The textile review nevertheless identifies practical limitations including extraction efficiency, shade reproducibility, fastness and compatibility with textile-processing conditions. [5,6]

Cosmetics and Pharmaceutical Research

Melanins are of interest for UV-absorbing and antioxidant properties, while carotenoids and bacterial pigments are investigated for antioxidant, antimicrobial or other biological activities. These findings are promising but should be interpreted carefully: in vitro biological activity is research finding, not automatic evidence of clinical effectiveness. [1,2,4,10]

Packaging and Advanced Materials

The melanin is attractive for functional materials because it can absorb light and participate in redox processes and interact with metal ions. The Streptomyces literature discusses possible applications in food packaging, environmental systems and bioelectronic materials. These uses depend on stability, processing compatibility, mechanical properties and safe integration into the final material. [1,3,10,11]

Environmental Applications

Microbial pigments can promote environmental technology through metal chelation, adsorption, and antioxidant behavior. Melanin is particularly interested in heavy-metal interaction and environmental remediation research. The broader public health review also emphasizes potential applications while identifying safety, standardization and scale-up as important requirements. [1,3,10]

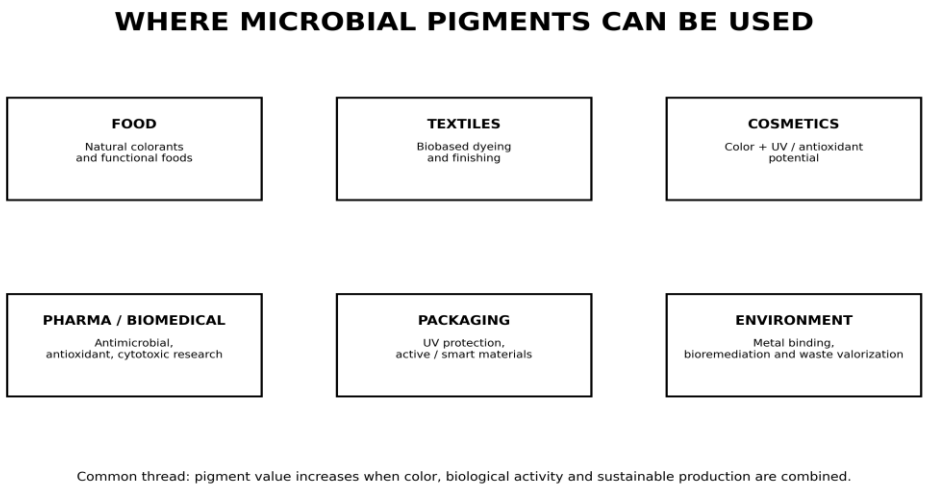


Figure 4. Application landscape of microbial pigments. Original educational infographic synthesized from the supplied literature.

Challenges Limiting Industrial Translation

- **Strain instability:** Pigment production can vary with culture history, mutation, contamination and environmental conditions. [1,4,5,9,11]
- **Low productivity:** A pigment may be chemically interesting but produced at a concentration too low for economical recovery. [1,4,9,11]
- **Product inhibition:** Some pigments or intermediates can stress the producing cell and limit pathway flux. [2,4]
- **Downstream cost:** Extraction and purification may represent a major fraction of total process cost. [1,3,5,9]
- **Batch variability:** Biological systems and waste substrates can vary between batches. [5,9,11]
- **Stability:** Light, heat, oxygen, pH and processing conditions can change pigment structure or color. [1,5,6]
- **Safety and regulation:** Food, cosmetic and biomedical uses require appropriate toxicological and quality assessment. [2,5,10]
- **Scale-up:** Oxygen transfer, mixing, heat removal and process control change substantially with bioreactor size. [3,9,11]

Future Directions

Future progress will likely come from combining strain discovery with quantitative bioprocess engineering. Genome mining and comparative genomics can identify silent or poorly characterized pigment pathways. At the process level, statistical experimental design, real-time monitoring and digital bioprocess control could make fermentation more predictable. Another promising direction is integrated biorefinery design. Instead of producing only one pigment, a microbial process could valorize a low-cost substrate into several products, for example pigment plus biomass, enzymes or other metabolites. This approach is particularly relevant for fungal and yeast systems using agro-industrial residues. [4,5,8,11]

Future studies should report standardized performance metrics. The titer, yield, volumetric productivity, recovery percentage, purity, substrate consumption. Such reporting would make studies easier to compare and help bridge the gap between laboratory-scale pigment discovery and industrial biotechnology. [1,3,4,9]

Conclusion

The microbial pigmentation is an important area of biotechnology where a microorganisms produce natural pigments that have many uses of color supplied literature demonstrates that bacterial, yeast and fungal, and including carotenoids, melanin, violacein, prodigiosin, riboflavin and polyketide-derived compounds. Their value comes from the combination of color, biological activity and the possibility of controlled microbial production. The strongest opportunities will arise when microbiology is integrated with process engineering. The strain selection, medium formulation, statistical optimization, metabolic engineering, efficient recovery and rigorous characterization must be considered as one connected process. For examples of Streptomyces melanin production and Rhodotorula carotenoid synthesis. Sustainable substrates such as food-processing by-products may further improve the environmental and economic profile of pigment production. Industrial translation still requires caution. The biological activity reported in laboratory studies is not established in safety or therapeutic efficacy by itself. The future research should emphasize reproducible production, standardized analytical characterization and life cycle thinking, safety evaluation. With these improvements, microbial pigmentation can contribute to sustainable colorants, functional biomaterials and value-added bioprocesses. [1–11]

REFERENCES

1. Choi, K.-Y. (2021). Bioprocesses of Microbial Melanin Production and Isolation. Frontiers in Bioengineering and Biotechnology, 9, 765110. https://doi.org/10.3389/fbioe.2021.765110
2. Choi, S. Y., Lim, S., Yoon, K.-H., Lee, J. I., & Mitchell, R. J. (2021). Biotechnological Activities and Applications of Bacterial Pigments Violacein and Prodigiosin. Journal of Biological Engineering, 15, 10. https://doi.org/10.1186/s13036-021-00262-9
3. Restaino, O. F., Manini, P., Kordjazi, T., Alfieri, M. L., Rippa, M., Mariniello, L., & Porta, R. (2024). Biotechnological Production and Characterization of Extracellular Melanin by Streptomyces nashvillensis. Microorganisms, 12, 297. https://doi.org/10.3390/microorganisms12020297
4. Wang, C., Zhao, S., Shao, X., Park, J.-B., Jeong, S.-H., Park, H.-J., Kwak, W.-J., Wei, G., & Kim, S.-W. (2019). Challenges and tackles in metabolic engineering for microbial production of carotenoids. Microbial Cell Factories, 18, 55. https://doi.org/10.1186/s12934-019-1105-1
5. Toma, M. A., Rahman, M. H., Rahman, M. S., Arif, M., Nazir, K. H. M. N. H., & Dufossé, L. (2023). Fungal Pigments: Carotenoids, Riboflavin, and Polyketides with Diverse Applications. Journal of Fungi, 9, 454. https://doi.org/10.3390/jof9040454
6. Venil, C. K., Velmurugan, P., Dufossé, L., Devi, P. R., & Ravi, A. V. (2020). Fungal Pigments: Potential Coloring Compounds for Wide Ranging Applications in Textile Dyeing. Journal of Fungi, 6, 68. https://doi.org/10.3390/jof6020068
7. Rao, M. P. N., Xiao, M., & Li, W.-J. (2017). Fungal and Bacterial Pigments: Secondary Metabolites with Wide Applications. Frontiers in Microbiology, 8, 1113. https://doi.org/10.3389/fmicb.2017.01113
8. Kalra, R., Conlan, X. A., & Goel, M. (2020). Fungi as a Potential Source of Pigments: Harnessing Filamentous Fungi. Frontiers in Chemistry, 8, 369. https://doi.org/10.3389/fchem.2020.00369
9. Mata-Gómez, L. C., Mapelli-Brahm, P., Meléndez-Martínez, A. J., Méndez-Zavala, A., Morales-Oyervides, L., & Montañez, J. (2023). Microbial Carotenoid Synthesis Optimization in Goat Cheese Whey Using the Robust Taguchi Method: A Sustainable Approach to Help Tackle Vitamin A Deficiency. Foods, 12, 658. https://doi.org/10.3390/foods12030658
10. Ramesh, C., Vinithkumar, N. V., Kirubagaran, R., Venil, C. K., & Dufossé, L. (2019). Multifaceted Applications of Microbial Pigments: Current Knowledge, Challenges and Future Directions for Public Health Implications. Microorganisms, 7, 186. https://doi.org/10.3390/microorganisms7070186
11. Kordjazi, T., Mariniello, L., Giosafatto, C. V. L., Porta, R., & Restaino, O. F. (2024). Streptomycetes as Microbial Cell Factories for the Biotechnological Production of Melanin. International Journal of Molecular Sciences, 25, 3013. https://doi.org/10.3390/ijms25053013