

International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(7): 1465-1471
www.biochemjournal.com
Received: 10-04-2026
Accepted: 13-05-2026

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Microbial melanin production from agro-residues: Biosynthetic pathways, bioprocess optimization and industrial applications

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i7Sr.9249>

Abstract

Melanin is a multifunctional natural biopolymer produced by diverse microorganisms that exhibits remarkable antioxidant, photoprotective, antimicrobial, metal-chelating, and biocompatible properties, making it an attractive biomaterial for pharmaceutical, cosmetic, food, environmental, agricultural, and bioelectronic applications. Conventional melanin production, however, is constrained by the high cost of fermentation media, limiting its commercial feasibility. Recent advances in microbial biotechnology have demonstrated that agro-industrial residues and lignocellulosic biomass can serve as sustainable, low-cost substrates for microbial melanin production while simultaneously promoting waste valorization and supporting circular bioeconomy initiatives. This review summarizes current knowledge on microbial melanin biosynthesis, emphasizing the major biosynthetic pathways, including L-3,4-dihydroxyphenylalanine (L-DOPA), 1,8-dihydroxynaphthalene (DHN), and pyromelanin pathways, together with the key enzymes and regulatory mechanisms governing pigment synthesis. The review further highlights the utilization of diverse agro-residues, such as molasses, wheat bran, rice bran, sugarcane bagasse, carrot peel, and huangjiu lees, for economical melanin production through optimized fermentation strategies. Recent developments in metabolic engineering, synthetic biology, statistical process optimization, and systems biology have significantly enhanced pigment yield, substrate utilization, and process efficiency, facilitating the development of robust microbial cell factories. The expanding industrial applications of microbial melanin in healthcare, biodegradable packaging, environmental remediation, smart materials, and sustainable agriculture are also discussed. Finally, the review outlines existing challenges, including substrate variability, downstream processing, and scale-up limitations, and identifies future research priorities focusing on integrated biorefineries, advanced strain engineering, and sustainable bioprocess development to enable economically viable and environmentally responsible microbial melanin production.

Keywords: Microbial melanin, agro-industrial residues, biosynthetic pathways, lignocellulosic biomass, bioprocess optimization, industrial biotechnology

1. Introduction

Melanin is a ubiquitous, heterogeneous biopolymer synthesized by diverse organisms, including bacteria, fungi, plants, and animals. It serves as a natural protective pigment against ultraviolet (UV) radiation, oxidative stress, extreme environmental conditions, and toxic metals owing to its exceptional antioxidant, photoprotective, free radical scavenging, metal-chelating, and electrical conductive properties (Tran-Ly *et al.*, 2020; Tsouko & Sarris, 2023)^[27, 29]. These multifunctional characteristics have expanded the industrial relevance of melanin in cosmetics, pharmaceuticals, food packaging, biomedical engineering, bioelectronics, environmental remediation, and agriculture (Fatima, 2023; Sundararajan & Ramasamy, 2024)^[6, 26]. As consumer preference shifts towards sustainable and naturally derived biomolecules, microbial melanin has emerged as an environmentally friendly alternative to chemically synthesized pigments because of its biodegradability, biocompatibility, and renewable production potential (Martínez *et al.*, 2019; Tsouko & Sarris, 2023)^[14, 29].

Microorganisms represent highly attractive platforms for melanin production because of their rapid growth, genetic manipulability, and ability to utilize a wide range of inexpensive substrates. Unlike extraction from animal or plant tissues, microbial fermentation enables controlled production with consistent quality and reduced environmental impact (Tran-Ly *et al.*, 2020)^[27].

Depending on the producing organism, microbial melanin is synthesized through three principal biosynthetic pathways, namely the L-3,4-dihydroxyphenylalanine (L-DOPA), 1,8-dihydroxynaphthalene (DHN), and pyromelanin pathways. These pathways are regulated by key enzymes such as tyrosinase, laccase, polyketide synthase, and homogentisate dioxygenase, which collectively determine pigment composition and biological functionality (Oh *et al.*, 2021; Xie *et al.*, 2024; Lorquin *et al.*, 2022) [20, 32, 13]. Recent advances in genomics, transcriptomics, and metabolic engineering have considerably improved our understanding of microbial melanogenesis, enabling the development of high-yield microbial cell factories with enhanced pigment production (Walker *et al.*, 2024; Tschirhart *et al.*, 2023) [31, 28].

Despite significant progress, large-scale commercialization of microbial melanin remains economically challenging because conventional fermentation media often rely on costly carbon and nitrogen sources. Consequently, increasing attention has been directed towards the utilization of agro-industrial residues and lignocellulosic biomass as economical and sustainable feedstocks. Agricultural by-products such as wheat bran, rice bran, sugarcane bagasse, molasses, fruit and vegetable wastes, corn stover, carrot peel, brewery residues, and huangjiu lees have been successfully explored as substrates for microbial pigment production (Korumilli, 2014; Arian *et al.*, 2020; Lin *et al.*, 2024) [9, 2, 12]. These renewable substrates are rich in fermentable carbohydrates and nutrients and simultaneously contribute to waste valorization, pollution reduction, and circular bioeconomy initiatives (Arruda *et al.*, 2024; Tsouko & Sarris, 2023) [3, 29].

Several bacterial and fungal species have demonstrated remarkable capability to convert these low-cost substrates into melanin. Members of the genera *Streptomyces*, *Pseudomonas*, *Vibrio*, *Aspergillus*, *Aureobasidium*, *Thermothelomyces*, and *Amorphotheca* have been extensively investigated owing to their high pigment productivity and adaptability to diverse fermentation systems (Eskandari & Etemadifar, 2021; Pandey *et al.*, 2024; Restaino *et al.*, 2024) [5, 21, 24]. Furthermore, optimization of fermentation variables, including pH, temperature, aeration, precursor supplementation, and carbon-to-nitrogen ratio, together with statistical optimization techniques such as response surface methodology and Taguchi experimental design, has substantially enhanced melanin yield and process efficiency (Müjdeci, 2022; Mathew & Bhat, 2022) [18, 15]. More recently, synthetic biology and metabolic engineering strategies involving heterologous expression of tyrosinase genes, pathway engineering, and recombinant microbial hosts have enabled gram-scale melanin production and improved product consistency (Martínez *et al.*, 2019; Larroude *et al.*, 2021; Tschirhart *et al.*, 2023) [14, 11, 28].

Beyond pigment production, microbial melanin possesses immense commercial value due to its broad spectrum of biological activities. Its antioxidant, antimicrobial, anti-inflammatory, UV-protective, and metal-binding properties have facilitated applications in drug delivery systems, wound dressings, biodegradable food packaging, biosensors, conductive biomaterials, and environmental detoxification (Tran-Ly *et al.*, 2020; Koch *et al.*, 2023) [27, 7]. In agriculture, microbial melanin has recently attracted interest for its potential roles in plant protection, biocontrol formulations,

and sustainable crop production, providing new opportunities for eco-friendly agricultural technologies (Muñoz *et al.*, 2024) [19].

Although substantial progress has been made in elucidating melanin biosynthesis and improving microbial production systems, information concerning microbial diversity, substrate utilization, metabolic engineering, process optimization, and industrial applications remains dispersed across the literature. Therefore, a comprehensive synthesis of recent developments is necessary to identify emerging trends, knowledge gaps, and future research priorities. This review summarizes recent advances in microbial melanin biosynthesis, highlights the utilization of agro-industrial residues and lignocellulosic biomass as sustainable substrates, discusses recent innovations in fermentation and metabolic engineering, and examines the expanding industrial applications of microbial melanin with emphasis on developing economically viable and environmentally sustainable production systems.

2. Microbial melanin biosynthesis

Melanin is a heterogeneous group of high-molecular-weight pigments synthesized through the oxidative polymerization of phenolic or indolic compounds. In microorganisms, melanin biosynthesis serves as an adaptive mechanism that enhances survival under adverse environmental conditions by protecting cells against ultraviolet radiation, oxidative stress, desiccation, heavy metals, and antimicrobial agents (Tran-Ly *et al.*, 2020; Fatima, 2023) [27, 6]. Unlike animal melanins, microbial melanins exhibit remarkable structural diversity because different microorganisms employ distinct metabolic pathways and precursor molecules. Based on their biosynthetic origin, microbial melanins are broadly classified into DOPA-melanin (eumelanin), DHN-melanin (allomelanin), pyromelanin, and, less frequently, pheomelanin (Tsouko & Sarris, 2023; Qin & Xia, 2024) [29]. Among these, the L-3,4-dihydroxyphenylalanine (L-DOPA) pathway is the most extensively studied. This pathway predominates in many bacteria, yeasts, and fungi, where the amino acid L-tyrosine is initially hydroxylated to L-DOPA by tyrosinase (EC 1.14.18.1). Subsequently, L-DOPA undergoes oxidation to dopaquinone, followed by a series of spontaneous cyclization, oxidation, and polymerization reactions that ultimately generate eumelanin (Martínez *et al.*, 2019; Oh *et al.*, 2021) [14, 20]. Tyrosinase is regarded as the key rate-limiting enzyme because it possesses both monophenolase and diphenolase activities, catalyzing the conversion of monophenols to o-diphenols and subsequently to o-quinones. The availability of L-tyrosine, copper ions, and molecular oxygen strongly influences tyrosinase activity and melanin yield (Eskandari & Etemadifar, 2021; Medeiros *et al.*, 2022) [5].

The 1,8-dihydroxynaphthalene (DHN) pathway represents another major route of melanin biosynthesis, particularly in filamentous fungi. Unlike the DOPA pathway, DHN melanin is synthesized from acetyl-CoA through the polyketide pathway. Polyketide synthase (PKS) catalyzes the formation of pentaketide intermediates that are subsequently converted into 1,3,6,8-tetrahydroxynaphthalene (T4HN), scytalone, vermeline, and finally 1,8-dihydroxynaphthalene, which polymerizes to form DHN melanin (Xie *et al.*, 2024; Qin & Xia, 2024) [32]. Several fungal pathogens, including species of *Aspergillus*, *Alternaria*, *Magnaporthe*, and *Metarhizium*, rely on DHN

melanin for structural integrity, pathogenicity, environmental adaptation, and stress tolerance (Strycker *et al.*, 2021; Xie *et al.*, 2024) [32]. The discovery of divergent DHN biosynthetic pathways in entomopathogenic fungi has further highlighted the metabolic diversity underlying fungal melanogenesis.

A third important pathway is the pyomelanin pathway, which originates from the catabolism of L-tyrosine via homogentisic acid (HGA). In this pathway, tyrosine is converted to 4-hydroxyphenylpyruvate and subsequently to homogentisic acid by 4-hydroxyphenylpyruvate dioxygenase. Accumulation and extracellular oxidation of homogentisic acid result in the formation of pyomelanin polymers (Lorquin *et al.*, 2022) [13]. Pyomelanin-producing microorganisms, including *Pseudomonas aeruginosa*, *Yarrowia lipolytica*, and several recombinant bacterial strains, exhibit enhanced resistance to oxidative stress, heavy metals, and radiation, making pyomelanin an attractive candidate for biomedical and environmental applications (Larroude *et al.*, 2021; Koch *et al.*, 2023) [11, 7]. Recent metabolic engineering approaches have successfully redirected aromatic amino acid metabolism towards homogentisic acid accumulation, substantially increasing pyomelanin productivity (Larroude *et al.*, 2021) [11].

Although less frequently encountered in microorganisms, pheomelanin is synthesized through the incorporation of sulfur-containing amino acids such as cysteine into dopaquinone intermediates. Compared with eumelanin and DHN melanin, microbial pheomelanin has received relatively little attention because it is produced by only a limited number of microbial species and exhibits lower stability under environmental stress conditions (Fatima, 2023) [6]. Nevertheless, understanding its biosynthesis may provide opportunities for developing pigments with novel physicochemical properties.

The diversity of melanin-producing microorganisms has expanded considerably over the past decade. Bacterial genera such as *Streptomyces*, *Pseudomonas*, *Vibrio*, *Bacillus*, and *Aeromonas* have demonstrated high melanin productivity owing to their rapid growth rates and amenability to genetic manipulation (Tschirhart *et al.*, 2023; Kordjazi *et al.*, 2024) [28]. Similarly, fungal species including *Aspergillus*, *Aureobasidium*, *Thermothelomyces*, *Amorphotheca*, *Gliocephalotrichum*, and *Auricularia* possess efficient melanogenic systems capable of producing substantial quantities of extracellular or intracellular pigments under optimized fermentation conditions (Pandey *et al.*, 2024; Restaino *et al.*, 2024; Anjaneya *et al.*, 2024) [21, 24, 1]. Comparative studies indicate that fungal systems generally produce structurally complex melanins with higher molecular weights, whereas bacterial systems offer advantages in rapid fermentation, ease of genetic engineering, and process scalability (Tran-Ly *et al.*, 2020) [27].

Recent advances in systems biology have substantially improved the understanding of microbial melanogenesis. Whole-genome sequencing, transcriptomic profiling, proteomics, and metabolomics have enabled the identification of key regulatory genes and biosynthetic enzymes involved in pigment synthesis. Furthermore, synthetic biology approaches involving heterologous expression of tyrosinase genes, promoter engineering, CRISPR-based genome editing, and metabolic pathway optimization have significantly enhanced melanin

production while reducing fermentation time and production costs (Walker *et al.*, 2024; Tschirhart *et al.*, 2023) [31, 28]. These developments provide a strong foundation for engineering robust microbial cell factories capable of sustainable, large-scale melanin production using renewable feedstocks.

3. Agro-residues as sustainable substrates for microbial melanin production

The economic feasibility of microbial melanin production is largely influenced by the cost of fermentation substrates, which can account for a significant proportion of the overall production expenses. Conventional fermentation media containing purified glucose, peptone, yeast extract, and other refined nutrients increase production costs and limit commercial-scale applications. Consequently, recent research has focused on replacing expensive substrates with low-cost agro-industrial residues and lignocellulosic biomass, which are abundant, renewable, and nutrient-rich. The utilization of these residues not only reduces production costs but also promotes waste valorization and aligns with the principles of sustainable bioprocessing and the circular bioeconomy (Tsouko & Sarris, 2023; Arruda *et al.*, 2024) [3, 29].

Agro-residues generated during agricultural production and food processing contain substantial quantities of cellulose, hemicellulose, lignin, starch, proteins, minerals, and soluble sugars that support microbial growth and secondary metabolite production. Commonly investigated substrates include wheat bran, rice bran, sugarcane bagasse, corn stover, molasses, fruit peels, vegetable wastes, brewery residues, oilseed cakes, carrot peel, and cereal processing by-products (Korumilli, 2014; Ramesh *et al.*, 2022) [9, 23]. These substrates provide an economical carbon source while simultaneously addressing environmental concerns associated with agricultural waste disposal.

Among these substrates, molasses has received considerable attention because of its high sucrose content, essential minerals, and vitamins. As a by-product of the sugar industry, molasses supports rapid microbial growth without extensive pretreatment. *Pseudomonas koreensis* cultured in molasses-based medium produced up to 5.5 g L⁻¹ melanin following optimization of fermentation conditions using response surface methodology, demonstrating the suitability of this substrate for industrial pigment production (Eskandari & Etemadifar, 2021) [5]. Similarly, sugarcane-derived residues have been explored as economical feedstocks for bacterial fermentation due to their widespread availability in tropical countries.

Fruit and vegetable processing wastes have also emerged as promising substrates because they are rich in fermentable carbohydrates, organic acids, and micronutrients. Carrot peel extract has been successfully utilized for melanin production by *Aureobasidium pullulans*, producing approximately 4.22 g L⁻¹ pigment under optimized fermentation conditions (Müjdeci, 2022) [18]. Likewise, fruit pulp residues and vegetable wastes have demonstrated comparable efficiency while significantly lowering production costs and reducing organic waste accumulation (Arikan *et al.*, 2020) [2].

Lignocellulosic biomass represents one of the largest renewable carbon reservoirs available for microbial bioprocesses. Agricultural residues such as wheat straw, rice straw, corn stover, sugarcane bagasse, and forestry wastes

consist primarily of cellulose, hemicellulose, and lignin. Following physical, chemical, or enzymatic pretreatment, these polymers are hydrolyzed into fermentable sugars that serve as substrates for microbial metabolism (Arruda *et al.*, 2024) [3]. Recent studies have highlighted the successful integration of lignocellulosic biomass into fungal biorefineries, where microbial melanin production is combined with the generation of other value-added bioproducts, thereby improving process sustainability and economic viability (Tsouko & Sarris, 2023) [29].

Several studies have demonstrated that enzymatic pretreatment substantially improves substrate utilization by increasing cellulose accessibility and reducing lignin recalcitrance. Lin *et al.* (2024) [12] reported that enzymatic hydrolysis of huangjiu lees, an abundant by-product of Chinese rice wine production, significantly enhanced nutrient availability and enabled *Aureobasidium melanogenum* to achieve melanin yields of approximately 19.07 g L⁻¹, among the highest reported for fungal systems. Adaptive laboratory evolution further improved substrate assimilation and fermentation efficiency, highlighting the importance of integrating substrate pretreatment with microbial strain improvement.

Solid-state fermentation (SSF) has gained increasing attention for agro-residue utilization because it closely mimics the natural habitat of many filamentous fungi and actinomycetes. SSF offers several advantages over submerged fermentation, including lower water requirements, reduced contamination risk, higher product concentration, and simplified downstream processing. These findings suggest that SSF could provide a cost-effective strategy for industrial-scale microbial melanin production using solid agricultural wastes.

The composition of agro-residues varies considerably depending on crop species, geographical origin, harvesting practices, and processing methods, influencing microbial growth and pigment synthesis. High lignin content may restrict substrate accessibility, whereas phenolic compounds released during pretreatment can inhibit microbial metabolism if present at elevated concentrations. Therefore, substrate selection, detoxification, nutrient supplementation, and pretreatment strategies remain critical determinants of process efficiency (Kraseas intra *et al.*, 2023; Arruda *et al.*, 2024) [10, 3]. Statistical optimization techniques, including response surface methodology (RSM) and Design of Experiments (DoE), have been widely employed to optimize substrate concentration, moisture content, carbon-to-nitrogen ratio, and mineral supplementation, resulting in significant improvements in melanin productivity (Mathew & Bhat, 2022) [15].

Beyond cost reduction, the utilization of agro-industrial residues contributes significantly to environmental sustainability. Large quantities of agricultural wastes are either burned or discarded annually, leading to greenhouse gas emissions and environmental pollution. Converting these residues into high-value bioproducts such as melanin supports waste minimization, resource recovery, and carbon recycling while generating additional income for agricultural industries. Such integrated biorefinery approaches are increasingly recognized as essential components of the circular bioeconomy, where renewable biomass is efficiently transformed into multiple value-added products with minimal environmental impact (Arruda *et al.*, 2024; Tsouko & Sarris, 2023) [3, 29].

Although substantial progress has been achieved, several challenges remain before agro-residue-based melanin production can be fully commercialized. Variability in substrate composition, seasonal availability, pretreatment costs, inhibitor formation during hydrolysis, and inconsistencies in fermentation performance continue to limit industrial implementation. Future research should therefore focus on developing robust microbial strains capable of directly utilizing complex lignocellulosic substrates, optimizing integrated biorefinery processes, and employing synthetic biology tools to enhance substrate conversion efficiency and pigment productivity.

4. Industrial applications of microbial melanin

The exceptional physicochemical and biological properties of microbial melanin have expanded its applications across diverse industrial sectors. As a naturally occurring biopolymer, melanin exhibits remarkable antioxidant, antimicrobial, UV-absorbing, metal-chelating, electrical conductive, and biocompatible properties, making it an attractive alternative to synthetic pigments (Tran-Ly *et al.*, 2020; Tsouko & Sarris, 2023) [27, 29]. One of the major applications of microbial melanin is in the cosmetic industry, where it is incorporated into sunscreens, anti-aging creams, and skin-protective formulations because of its ability to absorb ultraviolet radiation and neutralize reactive oxygen species. Compared with synthetic UV filters, microbial melanin offers superior biocompatibility and biodegradability while minimizing environmental toxicity (Fatima, 2023) [6].

In the pharmaceutical and biomedical sectors, microbial melanin has attracted considerable attention owing to its antioxidant, anti-inflammatory, antimicrobial, and radioprotective activities. Recent studies have demonstrated its potential as a drug delivery carrier, wound dressing material, tissue engineering scaffold, and photoprotective biomaterial. Owing to its excellent biocompatibility and ability to interact with various biomolecules, melanin nanoparticles have also been explored for targeted drug delivery and cancer therapy (Mattoon *et al.*, 2021; Koch *et al.*, 2023) [7]. The pigment has also found applications in the food industry, particularly in biodegradable food packaging materials. Melanin enhances UV protection and oxidative stability while extending the shelf life of packaged products. Its natural origin and non-toxic characteristics make it a promising additive for sustainable food packaging systems (Tran-Ly *et al.*, 2020) [27].

Environmental applications represent another rapidly expanding area of microbial melanin research. The polymer possesses numerous functional groups capable of binding heavy metals and organic pollutants, enabling its use in wastewater treatment and bioremediation. Melanin-based biosorbents have demonstrated high affinity toward lead, cadmium, mercury, copper, and other toxic metals, while simultaneously exhibiting excellent stability under harsh environmental conditions (Tsouko & Sarris, 2023) [29]. Recent advances have also highlighted the use of melanin in bioelectronics and advanced materials. The electrical conductivity, redox activity, and semiconducting nature of melanin have facilitated its incorporation into biosensors, flexible electronics, conductive coatings, batteries, and bio-inspired electronic devices. Engineered bacterial cellulose integrated with microbial melanin has shown considerable promise as a sustainable material for smart textiles and

wearable electronics (Walker *et al.*, 2023; Walker *et al.*, 2024) [30, 31].

In agriculture, microbial melanin is emerging as a promising biomolecule for sustainable crop production. Melanin-producing microorganisms exhibit enhanced tolerance to environmental stresses and may improve microbial survival during field application. Furthermore, melanin has been investigated for its role in biocontrol formulations, plant growth promotion, and eco-friendly crop protection strategies, although large-scale agricultural applications remain in the early stages of development (Muñoz *et al.*, 2024) [19]. Despite these promising applications, commercialization of microbial melanin is still constrained by production costs, downstream purification, and batch-to-batch variability. Continued improvements in fermentation technology, strain engineering, and purification strategies are expected to overcome these limitations and facilitate industrial-scale production.

5. Future perspectives

Recent developments in microbial biotechnology have significantly advanced sustainable melanin production; however, several scientific and technological challenges remain. Future research should focus on identifying high-yield microbial strains capable of directly utilizing untreated lignocellulosic biomass and diverse agro-industrial residues, thereby minimizing substrate pretreatment costs and improving process economics (Arruda *et al.*, 2024) [3]. Synthetic biology, metabolic engineering, and CRISPR-

based genome editing offer promising opportunities for constructing superior microbial cell factories with enhanced precursor availability, improved metabolic flux, and increased melanin productivity. Multi-omics approaches integrating genomics, transcriptomics, proteomics, and metabolomics will further facilitate the identification of regulatory networks controlling melanogenesis and enable rational strain improvement (Tschirhart *et al.*, 2023; Walker *et al.*, 2024) [28, 30].

Another important research direction involves developing integrated biorefineries in which microbial melanin is produced simultaneously with enzymes, organic acids, biofuels, or other high-value metabolites from a common biomass feedstock. Such integrated production systems would significantly improve resource utilization, reduce waste generation, and enhance overall economic feasibility. Downstream processing also requires considerable attention. The development of environmentally friendly extraction and purification methods, continuous fermentation systems, membrane-based recovery technologies, and process intensification strategies will be essential for reducing production costs while maintaining pigment quality. Finally, comprehensive life-cycle assessment, techno-economic analysis, and regulatory evaluation are required before microbial melanin can achieve widespread industrial adoption. Collaborative efforts among microbiologists, biochemical engineers, material scientists, and industrial stakeholders will accelerate the commercialization of sustainable microbial melanin production technologies.

Table 1: Representative microbial strains utilizing agro-residues for melanin production

Microorganism	Agro-residue/substrate	Melanin yield	Optimization strategy	Reference
<i>Aureobasidium melanogenum</i>	Huangjiu lees hydrolysate	19.07 g L ⁻¹	Enzymatic hydrolysis + adaptive evolution	Lin <i>et al.</i> (2024) [12]
<i>Pseudomonas koreensis</i>	Molasses	5.5 g L ⁻¹	Response Surface Methodology	Eskandari & Etemadifar (2021) [5]
<i>Aureobasidium pullulans</i>	Carrot peel extract	4.22 g L ⁻¹	Fermentation optimization	Müjdeci (2022) [18]
<i>Auricularia auricula</i>	Wheat bran extract	519.5 mg L ⁻¹	L-tyrosine supplementation	Zou <i>et al.</i> (2016) [33]
<i>Aspergillus nidulans</i>	Agro-industrial by-products	1.0 g L ⁻¹	Medium optimization	Campanhol <i>et al.</i> (2023) [4]
<i>Arthrospira platensis</i>	Residue hydrolysates	0.24 g L ⁻¹	Medium optimization (RSM)	Kraseasintra <i>et al.</i> (2023) [10]

6. Conclusion

Microbial melanin has emerged as a versatile and sustainable natural pigment with immense potential across pharmaceutical, cosmetic, food, environmental, agricultural, and bioelectronic industries. Advances in understanding biosynthetic pathways, microbial diversity, metabolic regulation, and fermentation technologies have substantially improved pigment production during the past decade. The utilization of agro-industrial residues and lignocellulosic biomass as low-cost substrates represents a major step toward economically viable and environmentally sustainable melanin production while supporting circular bioeconomy initiatives. Recent developments in metabolic engineering, synthetic biology, and systems biotechnology have further enhanced microbial productivity and process efficiency, enabling the development of robust microbial cell factories. Nevertheless, challenges associated with substrate variability, downstream processing, and large-scale commercialization continue to limit industrial implementation. Future research integrating strain engineering, bioprocess optimization, advanced

biorefineries, and sustainable downstream technologies will be critical for translating laboratory-scale production into commercially viable processes. Overall, microbial melanin derived from renewable agro-residues represents a promising platform for producing high-value bioproducts while contributing to sustainable waste valorization and green industrial biotechnology.

Acknowledgements

The authors also thank the AICRP on EAAI (Bioconversion Technology), University of Agricultural Sciences, Dharwad for providing institutional support and encouragement during the preparation of this review manuscript.

Conflict of interest: The authors declare that they have no conflict of interests to declare.

Funding: The authors received no specific financial support from any funding agency in the public, commercial, or not-for-profit sectors for the preparation of this review.

References

1. Anjaneya G, Chandrappa SB, Rudrappa M, SK M. Bioproduction and characterization of melanin pigment produced by the fungal strain *Gliocephalotrichum* sp. DSGB2. *Biomedicine*. 2024. doi:10.51248/v44i1.4117.
2. Arikan EB, Canli O, Caro Y, Dufossé L, Dizge N. Production of bio-based pigments from food processing industry by-products (apple, pomegranate, black carrot, red beet pulps) using *Aspergillus carbonarius*. *J Fungi*. 2020;6(4):240. doi:10.3390/jof6040240.
3. Arruda GL, Raymundo MTFR, Cruz-Santos MM, Shibukawa VP, Jofre FM, Prado CA, *et al*. Lignocellulosic materials valorization in second generation biorefineries: An opportunity to produce fungal biopigments. *Crit Rev Biotechnol*. 2024;1-20. doi:10.1080/07388551.2024.2349581.
4. Campanhol BS, Casellato F, Medina KJD, Sponchiado SRP. Improvement of DOPA-melanin production by *Aspergillus nidulans* using eco-friendly and inexpensive substrates. *J Fungi*. 2023;9(7):714. doi:10.3390/jof9070714.
5. Eskandari S, Etemadifar Z. Melanin biopolymers from newly isolated *Pseudomonas koreensis* strain UIS19 with potential for cosmetics application, and optimization on molasses waste medium. *J Appl Microbiol*. 2021;131(3):1331-1343. doi:10.1111/jam.15046.
6. Fatima M. Microbial melanin: Recent developments and challenges in the production, extraction, purification and application of microbial melanin. *Annu Res Rev Biol*. 2023. doi:10.9734/arrb/2023/v38i1030610.
7. Koch S, Freidank-Pohl C, Siontas O, Cortesao M, Mota A, Runzheimer K, *et al*. *Aspergillus niger* as a cell factory for the production of pyomelanin, a molecule with UV-C radiation shielding activity. *Front Microbiol*. 2023;14. doi:10.3389/fmicb.2023.1233740.
8. Kordjazi T, Mariniello L, Giosafatto CVL, Porta R, Restaino OF. *Streptomyces* as microbial cell factories for the biotechnological production of melanin. *Int J Mol Sci*. 2024;25. doi:10.3390/ijms25053013.
9. Korumilli T. Studies on pigment production by microorganisms using raw materials of agro-industrial origin. 2014.
10. Kraseasentra O, Sensupa S, Mahanil K, Yoosathaporn S, Pekkoh J, Srinuanpan S, *et al*. Optimization of melanin production by *Streptomyces antibioticus* NRRL B-1701 using *Arthrospira* (*Spirulina*) *platensis* residue hydrolysates as low-cost L-tyrosine supplement. *BioTech*. 2023;12(1):24. doi:10.3390/biotech12010024.
11. Larroude M, Onésime D, Rué O, Nicaud J, Rossignol T. A *Yarrowia lipolytica* strain engineered for pyomelanin production. *Microorganisms*. 2021;9(4):838. doi:10.3390/microorganisms9040838.
12. Lin C, Lu P, Ma J, Kan T, Han X, Liu S, *et al*. Investigation into the production of melanin from by-products of Huangjiu brewing. *Foods*. 2024;13(19):3063. doi:10.3390/foods13193063.
13. Lorquin F, Piccerelle P, Orneto C, Robin M, Lorquin J. New insights and advances on pyomelanin production: From microbial synthesis to applications. *J Ind Microbiol Biotechnol*. 2022;49(4). doi:10.1093/jimb/kuac013.
14. Martínez LM, Martinez A, Gosset G. Production of melanins with recombinant microorganisms. *Front Bioeng Biotechnol*. 2019;7:285. doi:10.3389/fbioe.2019.00285.
15. Mathew D, Bhat SG. Statistical design for biogenesis of melanin nanoparticles from producer strain *Pseudomonas stutzeri* BTCZ109 through Taguchi DoE. *Biocatal Agric Biotechnol*. 2022;42:102366. doi:10.1016/j.bcab.2022.102366.
16. Mattoon ER, Cordero RJB, Casadevall A. Fungal melanins and applications in healthcare, bioremediation and industry. *J Fungi*. 2021;7(6):488. doi:10.3390/jof7060488.
17. Medeiros WB, Medina KJD, Sponchiado SRP. Improved natural melanin production by *Aspergillus nidulans* after optimization of factors involved in the pigment biosynthesis pathway. *Microb Cell Fact*. 2022;21(1). doi:10.1186/s12934-022-02002-0.
18. Müjdeci GN. Experimental modeling and optimization of melanin production by *Aureobasidium pullulans* NBRC100716 in carrot peel extract. *Environ Prog Sustain Energy*. 2022;41(6). doi:10.1002/ep.13919.
19. Muñoz P, Cárdenas-Ninasivincha S, Aguilar Y. Exploring the agricultural applications of microbial melanin. *Microorganisms*. 2024;12(7):1352. doi:10.3390/microorganisms12071352.
20. Oh JJ, Kim YJ, Kim JY, Kwon SL, Lee C, Lee ME, *et al*. Genomic analysis and assessment of melanin synthesis in *Amorphotheca resinae* KUC3009. *J Fungi*. 2021;7(4):289. doi:10.3390/jof7040289.
21. Pandey S, Meshram V, Yehia HM, Alzahrani A, Akhtar N, Sur A. Efficient production and characterization of melanin from *Thermothelomyces hinnuleus* SP1 isolated from coal mines of Chhattisgarh, India. *Front Microbiol*. 2024. doi:10.3389/fmicb.2023.1320116.
22. Qin Y, Xia Y. Melanin in fungi: Advances in structure, biosynthesis, regulation, and metabolic engineering. *Microb Cell Fact*. 2024;23(1). doi:10.1186/s12934-024-02614-8.
23. Ramesh C, Prasastha VR, Venkatachalam M, Dufossé L. Natural substrates and culture conditions to produce pigments from potential microbes in submerged fermentation. *Fermentation*. 2022;8(9):460. doi:10.3390/fermentation8090460.
24. Restaino OF, Manini P, Kordjazi T, Alfieri ML, Rippa M, Mariniello L, *et al*. Biotechnological production and characterization of extracellular melanin by *Streptomyces nashvillensis*. *Microorganisms*. 2024;12(2):297. doi:10.3390/microorganisms12020297.
25. Strycker BD, Han Z, Bahari A, Pham T, Lin X, Shaw BD, *et al*. Raman characterization of fungal DHN and DOPA melanin biosynthesis pathways. *J Fungi*. 2021;7(10):841. doi:10.3390/jof7100841.
26. Sundararajan P, Ramasamy SP. A brief review on biosynthesis, extraction and purification of microbial melanin and its industrial applications. 2024. doi:10.58532/v3bjbt11p1ch4.
27. Tran-Ly AN, Reyes C, Schwarze FWMR, Ribera J. Microbial production of melanin and its various applications. *World J Microbiol Biotechnol*. 2020;36(11):170. doi:10.1007/S11274-020-02941-Z.
28. Tschirhart T, Compton J, Hennessa TM, VanArsdale E, Wang Z. Rapid, high-titer biosynthesis of melanin using

- the marine bacterium *Vibrio natriegens*. *Front Bioeng Biotechnol*. 2023. doi:10.3389/fbioe.2023.1239756.
29. Tsouko E, Sarris D. Microbial melanin: Renewable feedstock and emerging applications in food-related systems. *Sustainability*. 2023;15(9):7516. doi:10.3390/su15097516.
30. Walker KT, Keane J, Goosens VJ, Song WZ, Lee K, Ellis T. Self-dyeing textiles grown from cellulose-producing bacteria with engineered tyrosinase expression. *bioRxiv*. 2023. doi:10.1101/2023.02.28.530172.
31. Walker KT, Li IS, Keane J, Goosens VJ, Song W, Lee K, *et al*. Self-pigmenting textiles grown from cellulose-producing bacteria with engineered tyrosinase expression. *Nat Biotechnol*. 2024. doi:10.1038/s41587-024-02194-3.
32. Xie L, Liu Y, Zhang Y, Chen K, Yue Q, Wang C, *et al*. The divergence of DHN-derived melanin pathways in *Metarhizium robertsii*. 2024. doi:10.1101/2024.07.25.605210.
33. Zou Y, Hu W, Ma K, Tian M. Fermentative production of melanin by the fungus *Auricularia auricula* using wheat bran extract as major nutrient source. *Food Sci Technol Res*. 2016;23(1):23-29. doi:10.3136/FSTR.23.23.