Fungi as a Promising Source of Natural Pigments

Aparna S. Taware

Department of Botany, Deogiri College, Chhatrapati Sambhajinagar

DOI: https://doi.org/10.51584/IJRIAS.2025.100800016

Received: 26 July 2025; Accepted: 30 July 2025; Published: 29 August 2025

ABSTRACT

Due to environmental and health concerns associated with synthetic pigments, demand for natural colorants is growing. Fungal pigments can be promising alternative to synthetic pigments as they offer a sustainable and safe for use. This article comprehensively explores fungi's potential as a pigment source, detailing their significant advantages over traditional methods. Fungal pigments are biodegradable, offering a more sustainable option than toxic, poorly degrading synthetics. Plant based production has higher cost as compared to microbe-based production. Fungi's rapid, season-independent growth, ease of cultivation, and suitability for large-scale production makes it beneficial over plant-based production. Fungi produce a wide array of stable, soluble colors, and many pigments exhibit valuable antimicrobial, anticancer, and antioxidant properties, expanding their applications beyond simoly addition of coloration into pharmaceuticals and cosmetics. The article outlines diverse fungal pigment classes, including carotenoids, melanin, azaphilones, anthraquinones, and quinones. Specific commercially relevant examples, such as *Monascus* pigments for food, *Aspergillus niger* melanin for cosmetics, and Arpink Red from *Penicillium oxalicum*, demonstrate their broad industrial application. While challenges like pigment stability, efficient strain development, potential mycotoxin co-production, and purification difficulties persist, advanced biotechnological approaches are addressing these limitations. The robust growth observed in the natural and bio-based pigment markets, fueled by consumer demand for clean-label products and fermentation technology advancements, underscores a promising future for fungal-derived pigments as effective and sustainable colorant solutions.

Keywords: Natural pigments, Fungi, sustainable, applications, Global market

INTRODUCTION

The escalating global concern regarding the environmental and health implications of synthetic colorants has spurred a significant increase in the demand for natural, sustainable, and safe alternatives. This heightened interest has positioned natural pigments, particularly those derived from fungal sources, at the forefront of research and development efforts worldwide. Fungal source is a sustainable alternative to synthetic dyes offering a viable pathway to meet the growing global need for sustainable coloring solutions (Lagashetti & Dufossé, 2019).This article aims to provide a comprehensive exploration of the ability of fungi for production of pigments, encompassing their advantages over traditional methods, the diversity of pigments they produce, specific examples of commercially viable fungal pigments and their applications along with the present status of their commercialization and industrial utilization. Different challenges associated with their production, market size analysis in this increasingly important field.

Advantages of Fungal Pigments Over Traditional Methods

The utilization of fungal pigments presents a compelling set of advantages when compared to both synthetic and plant-based pigment production methods. Synthetic pigments, while possessing attributes like low production costs and superior coloring properties that initially contributed to their market dominance, are increasingly scrutinized for their detrimental environmental impact. These synthetic compounds often release toxic substances into the environment and exhibit poor degradation, leading to long-term ecological challenges (Downham & Collins, 2000; Lagashetti & Dufossé, 2019; Osman *et al.*, 2004). As compare to this, pigments produced by fungi are biodegradable and are sustainable alternative, mitigating the environmental hazards associated with synthetic colorants (Venil *et al.*, 2020).

Compared to plant-based pigments, fungi offer several key advantages in terms of production and consistency. Plant pigment production is often constrained by seasonal availability, a limitation that fungi readily overcome due to their capacity for season-independent growth. Furthermore, fungi exhibit rapid growth rates and can be easily cultivated in inexpensive culture media, rendering their production more efficient and cost-effective than the extraction of pigments from plant biomass. Fungal systems are particularly well-suited for large-scale production due to the well-established understanding of their cultural techniques, processing methodologies, and ease of handling. Moreover, fungi possess the remarkable ability to produce a wide spectrum of color shades and often yield pigments with enhanced stability and solubility compared to their plant-derived counterparts (Joshi & Attri, 2014).The processing of fungal pigments is generally simpler and more straightforward than the often complex extraction processes required for plant-based colorants (Lagashetti & Dufossé, 2019).

Economically, fungi present a highly viable platform for pigment production. They excel in terms of bioavailability, yield, cost-effectiveness, and the relative ease of large-scale cell culture and subsequent downstream processing (Lin & Xu, 2023). This inherent efficiency positions fungal pigments as a potentially competitive alternative to both synthetic and other natural sources. Beyond their coloring capabilities, many fungal pigments possess additional beneficial properties, including antimicrobial, anticancer, antioxidant, and cytotoxic activities (Narsing Rao *et al.*, 2017; Ramesh *et al.*, 2019; Sen *et al.*, 2019).These attributes expand their potential applications beyond mere coloration, opening avenues in sectors such as pharmaceuticals and cosmetics. Fungal pigments can also function as color intensifiers and additives in various industrial processes (Akilandeswari & Pradeep, 2016; Lagashetti & Dufossé, 2019; Narsing Rao *et al.*, 2017), and certain fungal pigments, such as carotenoids, serve as precursors to essential vitamins (Elkhateeb & Daba, 2023).

Diversity of Pigments from Fungal Sources

Fungi are prolific producers of a remarkable diversity of pigments, which can be broadly classified based on their underlying chemical structures. These classes encompass a wide spectrum of colors and functionalities, making fungi a versatile source for various applications.

Carotenoids represent a significant group of fungal pigments, typically exhibiting colors ranging from yellow to orange-red. Chemically, they are terpenoid compounds composed of 40 carbon atoms. Carotenoids function as potent antioxidants, providing protection against photo-oxidation and scavenging reactive oxygen species (Maria Afroz Toma, Md. Hasibur Rahman, et al., 2023). Notable examples include carotenes like β-carotene, lycopene, and torulene, as well as xanthophylls such as astaxanthin, canthaxanthin, and torularhodin. These pigments are produced by a diverse array of fungal species, including Blakeslea trispora, Phycomyces blakesleeanus, Mucor circinelloides (Papaioannou & Liakopoulou-Kyriakides, 2012), Fusarium sporotrichioides, Neurospora crassa, Neurospora intermedia (Gmoser et al., 2017). and various species within the Rhodotorula, Sporidiobolus (Kot et al., 2018), Aspergillus, Penicillium (Caro Y., 2017; Mapari et al., 2009), Cercospora, Sclerotium (Georgiou et al., 2001), and Sclerotinia genera (Zervoudakis et al., 2003).

Melanin constitute another broadly distributed class of fungal pigments, typically presenting as dark brown to black compounds with high molecular mass and a negative charge. These pigments are polyphenolic and/or polyindolic in nature (Lin & Xu, 2020) and play a crucial role in the survival of fungi within challenging environments. Melanins provide protection against a range of stressors, including UV light, heat, ionizing radiation, oxidative damage, and antimicrobial agents (Elkhateeb & Daba, 2023).They also exhibit antioxidant activity, radioprotective properties, the ability to chelate heavy metals, and the capacity to absorb organic compounds (Lin & Xu, 2022).Melanins are produced by a wide variety of fungi, such as Aspergillus niger, *Aspergillus nidulans Aspergillus fumigatus (Caro Y., 2017; Youngchim et al., 2004)* Xylaria polymorpha , Trametes versicolor, Inonotus hispidus (Tudor et al., 2013), Oxyporus populinus, Cryptococcus neoformans, Exophiala pisciphila , Langella dermatitidis, Schizophyllum commune (Pombeiro-Sponchiado et al., 2017)

Azaphilones are another prominent class of fungal pigments, typically displaying yellow, orange, and red hues . These polyketide pigments are characterized by a highly oxygenated pyranoquinone bicyclic core and are produced by numerous species of ascomycetous fungi, notably within the *Monascus*, *Penicillium*, *Talaromyces*, and *Aspergillus* genera (Lagashetti & Dufossé, 2019). Azaphilones have garnered significant interest for their potential applications in the dyeing, cosmetic, and printing industries (Pavesi *et al.*, 2023), and some exhibit valuable biological activities, including anti-inflammatory, cytotoxic, and antitumor effects (Antipova *et al.*, 2023). Well-known examples include Monascin and Ankaflavin from *Monascus*, and Arpink Red from *Penicillium oxalicum (Caro Y., 2017; Mapari et al., 2010)*.

Anthraquinones form a large group of quinoid compounds, with approximately 700 molecules identified to date, widely distributed in fungi. These pigments exhibit a broad spectrum of colors, ranging from pale yellow to dark red or brown, and violet. Anthraquinones have attracted considerable attention in various industries, including pharmaceuticals, textile dyeing, and food colorants. They possess good light-fastness properties and can form complexes with metal salts, enhancing their brightness and solubility in certain solvents.In the textile industry, hydroxyanthraquinones are considered "reactive dyes" due to their ability to form covalent bonds with fibers like cotton (Fouillaud et al., 2016).Furthermore, many anthraquinones exhibit significant biological activities, such as antibacterial, antiparasitic, insecticidal, fungicidal, antiviral, and anticancer properties (Maria Afroz Toma, Md. Hasibur Rahman, et al., 2023). These pigments are produced by a variety of fungal genera, including Aspergillus, Trichoderma, Fusarium, Penicillium, Curvularia, Sclerotinia, Thermomyces, Alternaria, and Cordyceps (Caro Y., 2017; Mapari et al., 2010).

Quinones represent another class of fungal pigments, producing a diverse array of colors, including yellow, orange, red, green, purple, brown, and blue. This class includes subclasses such as benzoquinones, terphenylquinones, and terpenoid quinines (Lagashetti & Dufossé, 2019).Quinonoid pigments often exhibit a broad spectrum of pharmacological activities, including immunomodulatory, anticancer, antioxidant, antibacterial, and antiproliferative effects (Maria Afroz Toma, Md. Hasibur Rahman, et al., 2023).These pigments are produced by various fungal genera, including Aspergillus, Penicillium, Fusarium, Trichoderma, Chlorociboria, and Scytalidium (Fouillaud et al., 2016; Huang et al., 2011; Trisuwan et al., 2010).

Other notable classes of fungal pigments include **Flavins**, often yellow in color, with riboflavin (Vitamin B2) produced by Ashbya gossypii being a prime example used in food and beverages (Caro Y., 2017). **Phenazines** produce a range of colors , while **Monascins**, a group of yellow, orange, and red pigments produced by Monascus spp., have a long history of use in Asian foods and exhibit various bioactivities.**Violacein**, a purple pigment, has found applications in cosmetics (Lagashetti & Dufossé, 2019).**Indigo** provides a blue hue , and **Betalains** contribute to the overall color diversity (Maria Afroz Toma, Md. Hasibur Rahman, et al., 2023). Finally, **Polyketides** represent a major biosynthetic pathway, encompassing several of the aforementioned pigment classes (Padhi, 2012).

Specific Examples of Fungal Pigments and Their Applications

The vast array of pigments produced by fungi translates into a multitude of potential and existing applications across various industries. Several fungal species have been identified as particularly promising sources of commercially viable pigments(Table 1).

- *Monascus* **spp.:** This genus of fungi is renowned for its production of a diverse range of azaphilone pigments, which impart yellow, orange, and red colors. These pigments, including Monascin, Ankaflavin, Monascorubrin, Rubropunctatin, Monascorubramine, and Rubropunctamine, have a long history of safe use in East Asia as food colorants and preservatives, most notably in the production of red mold rice (ang-kak) and red bean curd. Beyond traditional applications, *Monascus* pigments are finding use in various food products to enhance their color, such as candies, bread, yogurt, cheese, beer, and meat products (Egea *et al.*, 2023). Furthermore, these pigments exhibit significant potential as food additives with antioxidant and anti-cholesterol activities (Elkhateeb & Daba, 2023). Research has also demonstrated their antimicrobial, anticancer, anti-mutagenic, and anti-obesity properties (Narsing Rao *et al.*, 2017).

- *Cordyceps* **spp.:** Fungi belonging to the genus *Cordyceps* are known to produce stromata with orange to bright orange hues (Shrestha *et al.*, 2005). In vitro cultures of *Cordyceps* species exhibit diverse pigmentation, ranging from yellowish white to orange, influenced by the culture medium and age (Trisuwan *et al.*, 2010).Notably, the red pigment found in Cordyceps pruinosa has been shown to protect fungal spores from damaging reactive oxygen species. Cordyceps militaris, in particular, produces orange

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue VII July 2025

to bright orange pigments and is being investigated for its potential as a natural food colorant and for its potential anticancer and antibacterial activities (M. Afroz Toma et al., 2023).

- Aspergillus **spp.:** This genus is a prolific source of a wide array of pigments exhibiting diverse colors. Examples include aspergillin (black), asperenone, azaphilones (azanigerones A-F), melanin (brown/black), ascoquinone A, norsolorinic acid, and various anthraquinones ranging from yellow to red. Aspergillus niger produces black melanin, which has shown potential in applications such as cosmetics, eye glasses, sunscreens, and even water filters (Nagpal et al., 2011). Aspergillus carbonarius produces a yellow pigment that could potentially be used as a food colorant(Poorniammal et al., 2021) , while Aspergillus versicolor exhibits a pink pigment (Fouillaud et al., 2016). Azaphilones derived from Aspergillus species are under investigation for their potential as industrial pigments (Pimenta *et al.*, 2021), and anthraquinones from this genus have demonstrated applications in both the textile and pharmaceutical industries (Maria Afroz Toma, Md. Hasibur Rahman*, et al.*, 2023).

- *Penicillium* **spp.:** Species within the *Penicillium* genus are well-recognized for their ability to produce a variety of pigments, including Arpink Red (an anthraquinone with a red hue), talaroconvolutins, sclerotiorin, xanthoepocin, atrovenetin, dihydrotrichodimerol (yellow), and Monascus-like pigments. Notably, Arpink Red, produced by *Penicillium oxalicum*, holds the distinction of being the first commercially successful fungal pigment used as a food colorant(Arora, 2014). *Penicillium purpurogenum* produces a red pigment with significant potential for application in the food industry (Elkhateeb et al., 2023) , while Penicillium morceaux yields a yellow dye that exhibits an affinity for wool (Venil et al., 2020). Azaphilones from Penicillium hirayamae are currently under investigation as potential dyes for various industrial applications (Pavesi et al., 2023). Furthermore, certain pigments produced by Penicillium species have demonstrated antibacterial and antioxidant properties (Elkhateeb et al., 2023).

Beyond these prominent genera, other fungal species also contribute valuable pigments with diverse applications. Fusarium species produce pigments like aurofusarin and bikaverin (red), neurosporaxanthin (orange), and β-carotene (yellow-orange), with potential in food and as antimicrobial agents. Trichoderma species produce yellow and orange-red anthraquinones, such as pachybasin and chrysophanol, which have been used for dyeing silk and wool.Blakeslea trispora stands out as a major industrial fungus for the production of β-carotene, a food colorant authorized in the EU, and also produces lycopene.Rhodotorula glutinis produces carotenoid colors and has been used as a biological control agent.Epicoccum nigrum produces epicocconone, a polyketide pigment with antioxidant properties used in cell staining. Beauveria bassiana and B. brongniartii produce yellow pigments , while Chlorociboria aeruginosa yields the green pigment xylindein used for textile staining , and Scytalidium cuboideum produces the red pigment draconin red, also used in textile dyeing. Even Lactarius species produce blue pigments known as azulenes (Lagashetti & Dufossé, 2019).

Table 1: Specific Fungal Species, Pigments, and Key Applications

Fungal Species	Pigment(s)	Color(s)	Key Applications	References
Monascus purpureus	Monascin, Ankaflavin, Monascorubrin, Rubropunctatin, Monascorubramine, Rubropunctamine	Yellow, Orange, Red	Food coloring, antioxidants, anti-cholesterol, cosmetics, pharmaceuticals	(Egea et al., 2023; Elkhateeb & Daba, 2023)
Cordyceps militaris	Various carotenoids	Orange to Bright Orange	Food coloring, potential anticancer and antibacterial	(M. Afroz Toma et al., 2023)
Aspergillus niger	Melanin	Black	Cosmetics, sunscreens, water filters	(Nagpal et al., 2011)

Penicillium oxalicum	Anthraquinones (Arpink Red)	Red	Food coloring, textiles, potential anticancer and antifungal	(Arora, 2014)
Blakeslea trispora	β-carotene, Lycopene	Yellow-Orange, Red	Food coloring, vitamin A precursor	(Lagashetti & Dufossé, 2019)
Rhodotorula glutinis	Carotenoids (Torulene, β-carotene)	Yellow to Red	Food coloring, biological control of fruit degradation	(Lagashetti & Dufossé, 2019)
Trichoderma virens	Anthraquinones (Virone)	Yellow	Textile dyeing	(Lagashetti & Dufossé, 2019)
Chlorociboria aeruginosa	Xylindein	Green	Textile dyeing	(Lagashetti & Dufossé, 2019)
Scytalidium cuboideum	Draconin Red (Quinones)	Red	Textile dyeing	(Lagashetti & Dufossé, 2019)

Commercialization and Industrial Use of Fungal Pigments

Fungal pigments are currently employed as colorants, color intensifiers, and additives across a diverse range of industries, including textiles, pharmaceuticals, cosmetics, painting, food, and beverages.The earliest documented use of fungal pigments dates back centuries to the use of *Monascus* for the production of red mold rice (ang-kak).Today, *Monascus* pigments continue to find commercial applications in food, cosmetics, and pharmaceuticals, valued for their safety and natural origin (Intellect, 2025; Sharam, 2025).

Several specific fungal pigments have achieved commercial success. Arpink Red, an anthraquinone pigment from *Penicillium oxalicum*, riboflavin produced by *Ashbya gossypii*, and β-carotene derived from *Blakeslea trispora* are all established players in the global food colorant market (Maria Afroz Toma, Md Hasibur Rahman, *et al.*, 2023). While the market share of biotechnologically produced carotenoids from companies like Cyanotech (USA), Algatech (Israel), and Parry Nutraceuticals (India) is still smaller compared to synthetic producers, it is steadily growing(Igreja *et al.*, 2021).

The *Monascus* pigment market involves several key players, including Kiriya Chemical, SDBNI, Jiangmen Kelong, Tianyi Biotech, and Shandong Zhonghui, who are actively involved in production and innovation. Furthermore, major corporations like Nestlé™, Quaker Oats Company™, Shell®, YAEGAKI Bioindustry Inc., RIKEN VITAMINE Co., Ltd.™, and Shandong Luzhou Chemical Technology Co., Ltd.™ hold patents and have developed processes for the production of *Monascus* pigments(Intellect, 2025; Sharam, 2025).

The potential of fungal pigments is also being explored in emerging applications. Jesse Adler, leveraging her expertise in design and biomolecular science, has developed a novel method for extracting pigments from various fungi for use in make-up products, collaborating with cosmetic formulation chemists to bring these natural colors to life (Ferrer, 2023). Researchers at Empa have successfully developed a method for extracting large quantities of melanin from a specific fungus, opening up possibilities for its use in innovative materials and as a wood preservative (Ribera *et al.*, 2019).Even the U.S. Naval Research Laboratory is investigating the potential of microbes in space to produce novel melanin variants for advanced applications such as radiation-resistant coatings (Laboratory, 2023). Additionally, Birch Boys, a company specializing in chaga tea, has filed a patent for their method of extracting melanin from chaga fungi, targeting applications in the biotechnology sector(Cerbone, 2020).

Potential and Challenges in Fungal Pigment Production

The scientific literature extensively highlights the significant potential of filamentous fungi as a sustainable source for producing natural pigments with a wide range of industrial applications (Lagashetti & Dufossé, 2019)However, several challenges need to be addressed to fully realize this potential. The stability of microbial pigments can be susceptible to external physical and chemical factors (Zhou *et al.*, 2023). Furthermore, the lack of highly efficient pigment-producing strains and the potential for the co-production of toxins, such as mycotoxins, during pigment fermentation can limit their practical applications, particularly in food and pharmaceuticals. The purification of certain fungal pigments, such as melanin, can be challenging, and the yield of some pigments, like fungal melanin, can be low, posing obstacles to large-scale production (Zhou *et al.*, 2023).

The production of fungal pigments is influenced by a variety of factors, including temperature, the degree of medium agitation and oxygenation, the specific carbon and nitrogen sources used in the culture medium, and the pH (Lin & Xu, 2023).Additionally, environmental stresses, such as nutrient deprivation or unfavorable growth conditions, can trigger or enhance pigment production in certain fungi. Light exposure has also been shown to play a significant role in the pigmentation of some fungal species (M. Afroz Toma *et al.*, 2023).

To overcome these challenges, researchers are actively exploring advanced biotechnological approaches. Metabolic engineering and nanotechnology are being employed to optimize pigment yield, eliminate or minimize mycotoxin production, and enhance pigment stability(M. Afroz Toma *et al.*, 2023). Strategies such as utilizing low-cost substrates and implementing strain improvement programs are being pursued to reduce overall production costs and make fungal pigments more economically competitive (Narsing Rao *et al.*, 2017). Furthermore, advancements in greener extraction techniques are facilitating more sustainable and efficient recovery of both intracellular and extracellular fungal pigments(Antipova *et al.*, 2023).

Market Size and Growth Trends of Fungal-Derived Pigments

The global market for all food colorants was estimated at USD 3.88 billion in 2018 and is projected to reach USD 5.12 billion by 2023, exhibiting a compound annual growth rate (CAGR) of 5.7%(M. Afroz Toma *et al.*, 2023).Within this broader market, the natural food color segment is experiencing even more robust growth. It was estimated at USD 1.33 billion in 2022 and is expected to grow at a CAGR of 8.3% from 2023 to 2030, reaching a market size of USD 2.52 billion by 2030 (GVR-1-68038-740-7, 2023).Projections indicate further expansion, with the market potentially reaching USD 3,679.4 million by 2034 (Choudhury, 2024) .

The global bio-based pigments and dyes market is also demonstrating strong growth, with projections reaching USD 48.58 billion by 2034 at a CAGR of 4.5% (S.N., 2024) , and another estimate placing it at USD 43.9 Bn by 2031 with a CAGR of 4.23% (Ltd., 2025).The overall pigments market, encompassing both natural and synthetic sources, was valued at USD 24.28 Bn in 2023 and is expected to reach USD 36.58 Bn by 2030, growing at a CAGR of 6.03% (Research, 2024).Another report estimates the pigments market at USD 28,857.5 million in 2023, with a projected CAGR of 5.35% to USD 38.76 billion by 2030 (Insights, 2024). The organic pigments market specifically is expected to grow from USD 4.4 billion in 2024 to USD 6.0 billion by 2029, at a CAGR of 6.5% (Markets, 2024).The *Monascus* red pigment market alone reached approximately USD 200 million in 2023 and is projected to grow to around USD 350 million by 2032, with a CAGR of 6.8%(Dataintelo, 2024).

This significant market growth in the natural and bio-based pigment sectors is primarily driven by increasing consumer demand for natural and clean-label products. Advancements in fermentation technology are further enhancing the yield and quality of fungal pigments, thereby bolstering their market potential. The growing trend of utilizing natural ingredients in nutraceuticals and the cosmetic industry is also contributing to the expansion of the fungal pigment market.

CONCLUSION

Fungi stand out as a highly promising and versatile source of natural pigments, offering substantial advantages over traditional synthetic and plant-based methods. The remarkable diversity of fungal pigments, encompassing a wide array of chemical classes and colors, enables their application across numerous industries. Specific examples, such as the well-established use of *Monascus* in food and the emerging applications of *Aspergillus*-derived melanin in cosmetics and filtration, underscore the commercial viability and broad potential of fungal pigments. While challenges related to production efficiency and safety remain, ongoing research and technological innovations are continuously addressing these limitations, paving the way for increased utilization of fungal pigments. The robust growth observed in the market for natural colorants and bio-based pigments strongly suggests a bright future for fungal-derived pigments as sustainable and functional alternatives to conventional colorants. Continued research and development efforts are essential to fully harness the vast potential of fungi as a sustainable and efficient source of high-value pigments for a wide spectrum of applications.

REFERENCE

1. Afroz Toma, M., 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(4), 454. https://www.mdpi.com/2309-608X/9/4/454
2. Afroz Toma, M., Rahman, M. H., Rahman, M. S., Arif, M., Nazir, K. N. H., & Dufossé, L. (2023). Fungal pigments: Carotenoids, riboflavin, and polyketides with diverse applications. Journal of Fungi, 9(4), 454.
3. Afroz Toma, M., Rahman, M. H., Rahman, M. S., & Arif, M. D., L.Nazir, Khmnh. (2023). Fungal Pigments: Carotenoids, Riboflavin, and Polyketides with Diverse Applications. 9(4). https://doi.org/10.3390/jof9040454
4. Akilandeswari, P., & Pradeep, B. V. (2016). Exploration of industrially important pigments from soil fungi. Applied Microbiology and Biotechnology, 100(4), 1631-1643. https://doi.org/10.1007/s00253-015-7231-8
5. Antipova, T. V., Zhelifonova, V. P., Zaitsev, K. V., & Vainshtein, M. B. (2023). Fungal Azaphilone Pigments as Promising Natural Colorants. Microbiology, 92(1), 1-10. https://doi.org/10.1134/S0026261722601737
6. Arora, S. (2014). Textile dyes: it's impact on environment and its treatment. J. Bioremed. Biodeg, 5(3), 1.
7. Caro Y., V. M., Lebeau J., Fouillaud M., Dufossé L. (2017). Pigments and colorants from filamentous fungi. . Merillon J.-M., Ramawat K.G., editors. Fungal Metabolites. (Springer International Publishing; Cham, Switzerland), 499–568.
8. Cerbone, A. (2020). Mushroom chemistry Adirondack Daily Enterprise. https://www.adirondackdailyenterprise.com/news/local-news/2020/09/mushroom-chemistry/
9. Choudhury, N. R. (2024). Natural Food Colors Replace Synthetics amid Growing Concerns Over Health and Safety. FMI Provides Detailed Trends Overview. F. M. I. G. a. C. P. Ltd. https://www.globenewswire.com/news-release/2024/12/09/2993766/0/en/Natural-Food-Colors-Replace-Synthetics-amid-Growing-Concerns-Over-Health-and-Safety-FMI-Provides-Detailed-Trends-Overview.html
10. Dataintelo. (2024). Monascus Red Pigment Market Research Report 2032 Dataintelo. https://dataintelo.com/report/global-monascus-red-pigment-market
11. Downham, A., & Collins, P. (2000). Colouring our foods in the last and next millennium. International Journal of Food Science and Technology, 35(1), 5-22. https://doi.org/10.1046/j.1365-2621.2000.00373.x
12. Egea, M. B., Dantas, L. A., Sousa, T. L. d., Lima, A. G., & Lemes, A. C. (2023). The potential, strategies, and challenges of Monascus pigment for food application. Frontiers in Sustainable Food Systems, 7, 1141644.
13. Elkhateeb, W., & Daba, G. (2023). Fungal Pigments: Their Diversity, Chemistry, Food and Non-Food Applications. Applied Microbiology, 3(3), 735-751. https://www.mdpi.com/2673-8007/3/3/51
14. Elkhateeb, W., Elnahas, M. O., & Daba, G. (2023). Wide Range Applications of Fungal Pigments in Textile Dyeing. In T. Satyanarayana & S. K. Deshmukh (Eds.), Fungi and Fungal Products in Human Welfare and Biotechnology (pp. 289-304). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-8853-0_10
15. Ferrer, B. (2023). Mycocosmetic era: Shroom boom in skincare and cosmetics introduces new fungi

applications. Personal care insighths. Retrieved 04/04/2025 from https://www.personalcareinsights.com/ news/mycocosmetic-era-shroom-boom-in-skincare-and-cosmetics-introduces-new-fungi applications.html

16. Fouillaud, M., Venkatachalam, M., Girard-Valenciennes, E., Caro, Y., & Dufossé, L. (2016). Anthraquinones and Derivatives from Marine-Derived Fungi: Structural Diversity and Selected Biological Activities. Marine Drugs, 14(4), 64. https://www.mdpi.com/1660-3397/14/4/64
17. Georgiou, C. D., Zervoudakis, G., Tairis, N., & Kornaros, M. (2001). β-Carotene production and its role in sclerotial differentiation of Sclerotium rolfsii. Fungal genetics and biology, 34(1), 11-20.
18. Gmoser, R., Ferreira, J. A., Lennartsson, P. R., & Taherzadeh, M. J. (2017). Filamentous ascomycetes fungi as a source of natural pigments. Fungal Biology and Biotechnology, 4(1), 4. https://doi.org/10.1186/s40694-017-0033-2
19. GVR-1-68038-740-7. (2023). Natural Food Color Market Summary. G. V. Research. https://www.grandviewresearch.com/industry-analysis/natural-food-colors-market
20. Huang, C.-H., Pan, J.-H., Chen, B., Yu, M., Huang, H.-B., Zhu, X., . . . Lin, Y.-C. (2011). Three Bianthraquinone Derivatives from the Mangrove Endophytic Fungus Alternaria sp. ZJ9-6B from the South China Sea. Marine Drugs, 9(5), 832-843. https://www.mdpi.com/1660-3397/9/5/832
21. Igreja, W. S., Maia, F. A., & Lopes, A. S. C., R. C. (2021). Biotechnological Production of Carotenoids Using Low Cost-Substrates Is Influenced by Cultivation Parameters: A Review. 22(16). https://doi.org/10.3390/ijms22168819
22. Insights, P. B. (2024). Pigments Market Size, Share, Trends, Outlook, Growth Report P. B. Insights. https://www.precisionbusinessinsights.com/market-reports/pigments-market
23. Intellect, M. R. (2025). Monascus Red Pigment Market Size, Share & Trends By Product, Application & Geography - Forecast to 2033. Market Research Intellect. https://www.marketresearchintellect.com/ product/global-monascus-red-pigment-market/#reviews
24. Joshi, V. K., & Attri, D. (2014). Characterization and conversion of microbial pigments into water soluble pigments for application in food products. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 84, 1053-1058.
25. Kot, A. M., Błażejak, S., Gientka, I., Kieliszek, M., & Bryś, J. (2018). Torulene and torularhodin: "new" fungal carotenoids for industry? Microbial Cell Factories, 17(1), 49. https://doi.org/10.1186/s12934-018-0893-z
26. Laboratory, U. S. N. R. (2023). Unleashing the Power of Melanin in Space for Next-Gen Biomaterials https://issnationallab.org/press-releases/release-spxcrs29-nrl-melanin/
27. Lagashetti, A. C., & Dufossé, L. (2019). Fungal Pigments and Their Prospects in Different Industries. 7(12). https://doi.org/10.3390/microorganisms7120604
28. Lin, L., & Xu, J. (2020). Fungal Pigments and Their Roles Associated with Human Health. 6(4). https://doi.org/10.3390/jof6040280
29. Lin, L., & Xu, J. (2022). Production of fungal pigments: molecular processes and their applications. Journal of Fungi, 9(1), 44.
30. Lin, L., & Xu, J. (2023). Production of Fungal Pigments: Molecular Processes and Their Applications. Journal of Fungi, 9(1), 44. https://www.mdpi.com/2309-608X/9/1/44
31. Ltd., I. A. P. (2025). Bio-based Pigments and Dyes Market 2024 Latest Report with Forecast to 2031. I. A. P. Ltd. https://www.insightaceanalytic.com/report/bio-based-pigments-and-dyes-market/2342
32. Mapari, S. A. S., Meyer, A. S., Thrane, U., & Frisvad, J. C. (2009). Identification of potentially safe promising fungal cell factories for the production of polyketide natural food colorants using chemotaxonomic rationale. Microbial Cell Factories, 8(1), 24. https://doi.org/10.1186/1475-2859-8-24
33. Mapari, S. A. S., Thrane, U., & Meyer, A. S. (2010). Fungal polyketide azaphilone pigments as future natural food colorants? Trends in Biotechnology, 28(6), 300-307. https://doi.org/10.1016/j.tibtech.2010.03.004
34. Markets, M. a. (2024).The Organic Pigments Market, Industry Size Growth Forecast Trends Report. M. a. Markets. https://www.marketsandmarkets.com/Market-Reports/organic-pigments-market-1076.html
35. Nagpal, N., Munjal, N., & Chatterjee, S. (2011). Microbial pigments with health benefits-a mini review. Trends in Biosciences, 4(2), 157-160.
36. Narsing Rao, M. P., Xiao, M., & Li, W.-J. (2017). Fungal and Bacterial Pigments: Secondary Metabolites with Wide Applications [Review]. Frontiers in Microbiology, 8.

https://doi.org/10.3389/fmicb.2017.01113

37. Osman, M. Y., A., S. I., Y., O. H. M., A., E.-K. Z., & and Ahmed, E. I. (2004). Synthetic organic food colouring agents and their degraded products: effects on human and rat cholinesterases. British Journal of Biomedical Science, 61(3), 128-132. https://doi.org/10.1080/09674845.2004.11732657
38. Padhi, B. (2012). Pollution due to synthetic dyes toxicity & carcinogenicity studies and remediation. International journal of environmental sciences, 3(3), 940.
39. Papaioannou, E. H., & Liakopoulou-Kyriakides, M. (2012). Agro-food wastes utilization by Blakeslea trispora for carotenoids production. Acta Biochimica Polonica, 59(1).
40. Pavesi, C., Flon, V., Genta-Jouve, G., Pramil, E., Escargueil, A., Nasir, A., . . . Prado, S. (2023). Azaphilones Pigments from the Fungus Penicillium hirayamae. Colorants, 2(1), 31-41. https://www.mdpi.com/2079-6447/2/1/3
41. Pimenta, L. P. S., Gomes, D. C., & Cardoso, P. G. T., Jacqueline A. (2021). Recent Findings in Azaphilone Pigments. 7(7). https://doi.org/10.3390/jof7070541
42. Pombeiro-Sponchiado, S. R., Sousa, G. S., Gonçalves, R. C. R., Andrade, J. C. R., & Lisboa, H. C. F. (2017). Production of Melanin Pigment by Fungi and Its Biotechnological Applications. In M. Blumenberg (Ed.), Melanin. IntechOpen. https://doi.org/10.5772/67375
43. Poorniammal, R., Prabhu, S., & Dufossé, L. (2021). Safety Evaluation of Fungal Pigments for Food Applications. 7(9). https://doi.org/10.3390/jof7090692
44. 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(7). https://doi.org/10.3390/microorganisms7070186
45. Research, M. M. (2024). Pigments Market: Global Industry Analysis and Forecast (2024-2030) (15119). M. M. Research. https://www.maximizemarketresearch.com/market-report/global-pigments-market/15119/
46. Ribera, J., Panzarasa, G., Stobbe, A., Osypova, A., Rupper, P., Klose, D., & Schwarze, F. W. M. R. (2019). Scalable Biosynthesis of Melanin by the Basidiomycete Armillaria cepistipes. Journal of Agricultural and Food Chemistry, 67(1), 132-139. https://doi.org/10.1021/acs.jafc.8b05071
47. S.N., J. (2024). Bio-based Pigments and Dyes Market Size & Statistics 2034 Fact.MR. https://www.factmr.com/report/1050/bio-based-pigments-and-dyes-market
48. Sen, T., Barrow, C. J., & Deshmukh, S. K. (2019). Microbial Pigments in the Food Industry—Challenges and the Way Forward [Review]. Frontiers in Nutrition, 6. https://doi.org/10.3389/fnut.2019.00007
49. Sharam, R. (2025). Monascus Red Pigment Market Outlook. Dataintelo. https://dataintelo.com/report/global-monascus-red-pigment-market
50. Shrestha, B., Choi, S.-K., Kim, H.-K., Kim, T.-W., & Sung, J.-M. (2005). Genetic analysis of pigmentation in Cordyceps militaris. Mycobiology, 33(3), 125-130.
51. Trisuwan, K., Khamthong, N., Rukachaisirikul, V., Phongpaichit, S., Preedanon, S., & Sakayaroj, J. (2010). Anthraquinone, Cyclopentanone, and Naphthoquinone Derivatives from the Sea Fan-Derived Fungi Fusarium spp. PSU-F14 and PSU-F135. Journal of Natural Products, 73(9), 1507-1511. https://doi.org/10.1021/np100282k
52. Tudor, D., Robinson, S. C., & Cooper, P. A. (2013). The influence of pH on pigment formation by lignicolous fungi. International Biodeterioration & Biodegradation, 80, 22-28. https://doi.org/https://doi.org/10.1016/j.ibiod.2012.09.013
53. Venil, C. K., Velmurugan, P., Dufossé, L., Renuka Devi, P., & Veera Ravi, A. (2020). Fungal Pigments: Potential Coloring Compounds for Wide Ranging Applications in Textile Dyeing. Journal of Fungi, 6(2), 68. https://www.mdpi.com/2309-608X/6/2/68
54. Youngchim, S., Morris-Jones, R., Hay, R. J., & Hamilton, A. J. (2004). Production of melanin by Aspergillus fumigatus. J Med Microbiol, 53(Pt 3), 175-181. https://doi.org/10.1099/jmm.0.05421-0
55. Zervoudakis, G., Tairis, N., Salahas, G., & Georgiou, C. D. (2003). β-carotene production and sclerotial differentiation in Sclerotinia minor. Mycological Research, 107(5), 624-631. https://doi.org/https://doi.org/10.1017/S0953756203007822
56. Zhou, M., Yajun, C., Xue, F., Li, W., & and Zhang, Y. (2023). Isolation and identification of pigment-producing filamentous fungus DBFL05 and its pigment characteristics and chemical structure. CyTA - Journal of Food, 21(1), 374-385. https://doi.org/10.1080/19476337.2023.2207613