Jurnal Tumbuhan Obat Indonesia
Vol. 17, No 2, Des 2024, hal 75-86

ISSN: 1979-892X (print)
ISSN: 2354-8797 (online)

A Review of Fungal-Derived Natural Dyes: Chemical Diversity and Multifaceted Health Benefits

Tinjauan Pewarna Alami dari Jamur: Keanekaragaman Kimia aan Beragam Manfaatnya Bagi Kesehatan

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ABSTRACT

Various industrial sectors, from food and drug production to textiles, have widely used pigments or dyes as coloring agents. Generally, we can distinguish between two types of coloring agents: synthetic and natural. Currently, the use of synthetic colorings is a topic of debate due to their potential health risks, toxicity, and environmental pollution. This prompts a deeper exploration of natural resources as a more secure substitute for coloring agents. Plants, animals, microbes, and fungi can all provide natural coloring agents. Besides animals and microbes, some challenges in developing plants as major sources of natural coloring agents include variations in production or harvest times, strongly influenced by season, weather, and the intensity of sunlight. These factors influence not only the stability of the produced color but also its physicochemical properties, such as solubility and pH. Moreover, overexploitation of plants has an impact on ecosystem imbalances and leads to extinction. Among natural resources, pigments or dyes from fungi have shown their potential to address these challenges. This review focuses on the potential of various microfungi that produce natural dyes, especially from Monascaceae, Trichocomaceae, and Nectriaceae, as well as the classification based on their chemical structure. Furthermore, we describe their diverse biological impacts as antioxidants, antibiotics, antidiabetics, anticancer agents, and anti-cholesterol agents, along with their health advantages.

Keywords: *Dyes, Fungi, Natural, Pigments, Potency*

ABSTRAK

Zat warna telah digunakan secara luas di berbagai sektor industri mulai dari produksi makanan, obat-obatan hingga tekstil. Secara umum zat warna dapat dibedakan menjadi dua yaitu sintetik dan alamiah yang berasal dari alam. Dalam perkembangannya, penggunaan zat warna sintetik memunculkan perdebatan terkait dengan keamanannya bagi kesehatan, potensi toksisitas, dan kasus pencemaran lingkungan. Hal tersebut mendorong kajian yang lebih dalam terhadap sumber daya alam sebagai alternatif yang lebih aman untuk digunakan sebagai zat warna. Zat warna alam dapat bersumber dari tanaman, hewan, mikroba dan jamur. Beberapa tantangan pada pengembangan zat warna alami adalah variasi waktu produksi atau waktu panen yang sangat dipengaruhi oleh musim, cuaca, dan intensitas cahaya matahari. Hal ini dapat mempengaruhi stabilitas warna yang dihasilkan serta sifat fisikokimia, diantaranya kelarutan dan pH. Lebih jauh lagi, eksploitasi berlebihan dari sumber alam dapat berdampak pada ketidakseimbangan ekosistem yang berakibat kepunahan. Diantara sumber pewarna alami, zat warna dari jamur mempunyai potensi yang menjawab berbagai tantangan tersebut. Ulasan ini menitikberatkan zat warna alami yang berasal dari jamur mikro terutama dari kelas Ascomisetes dan keluarga Monascaceae, Trichocomaceae, dan Nectriaceae serta klasifikasinya berdasarkan struktur kimia. Zat warna alami dari jamur mikro memiliki potensi sebagai antioksidan, antibiotika, antidiabet, antikanker, antikolesterol, dan manfaatnya bagi kesehatan.

Kata kunci: Alami, *Dyes*, Jamur, Pigmen, Potensi

Received 14-09-2023
Revised 25-04-2024
Accepted 18-12-2024
Publish 31-12-2024

DOI: 10.31002/jtoi.v16i2.885

INTRODUCTION

Synthetic dyes are a significant part of the global market but carry serious environmental and health issues. These dyes derived from petrochemicals can contribute to pollution during production. Some synthetic dyes may contain substances such as heavy metals and carcinogens, which raise legitimate health concerns. Natural dyes from plants, animals, fungi, and microbes are sustainable alternatives (Alegbe & Uthman, 2024). Dyes or pigments play a big role in our daily lives as coloring agents in food, cosmetics, textiles, and medicine. Plants have long been recognized as sources of dye, animals, microbes, and fungi and have also proven valuable contributors. The diverse range of these sources expands the possible uses of natural dyes while tackling environmental and health issues. The study divides coloring agents into two categories based on their solubility: pigments and dyes. Pigments are insoluble in organic solvents and water, while dyes are soluble in both (Elkhteeb & Daba, 2023). However, plants as coloring agent producers face several limitations, including season-dependent growth, the potential for rare or extinct species, color variability, and instability to light, heat, pH, and water solubility. These limitations could have a significant impact on the food industry. For instance, plants cannot produce red colors from the anthocyanin group across a wide pH range, necessitating the continued use of insects for red food coloring in some countries (Lebeau et al., 2017; Lagashetti et al., 2019).

Natural dye production is not limited to plants. Some animals producing colors, such as the carmin bug (*Dactylopius coccus*), produce carmine red while lobsters, shrimp, and salmon produce astaxanthin red (Pratiwi & Limantara, 2008; Lebeau *et al*., 2017). Sea urchin produces orange echinenone and phoenicoxanthin, while *Halocynthia roretzi* produces halocynthiaxanthin and fucoxanthinol pigments, which are also reddish orange (Adadi *et al*., 2018). *Hexaplex trunculus*, a species of purple snail, produced a purple-blue color and thrived in imperial Rome (Oliver, 2015). However, producing animal dyes often requires large quantities, leading to concerns about extinction and waste.

Microbes also have potential as pigment producers. *Staphylococcus aureus* produces golden pigment while *Pseudomonas* spp. produce blue-green to yellow and brownish-red pigment. However, due to their toxic and pathogenic nature, the production and commercialization of pigments from these microbes are prohibited. However, safer microbial sources, such as Paracoccus marcusii (bacteria), Hematococcus pluvialis (algae), and Xanthophyllomyces dendrorhous (fungi), are being explored for their vibrant and antioxidant-rich pigments, such as astaxanthin.(Harker et al., 1998; Tsubokura et al., 1999; Muzaki et al., 2008). The color substance astaxanthin has antioxidant activity 14 times stronger than vitamin E, 54 times stronger than β-carotene, and 65 times stronger than vitamin C (Igielska-Kalwat *et al*., 2015). According to Cordero (2017), fungi have the potential to produce colors that can serve as a protective coating against high electromagnetic radiation, particularly from sunlight, x-rays, and rays, in medicine and technology.

As color producers, fungi offer several advantages over plants, including season-independent cultivation, water-soluble and stable dyes, and an easy production process. Advantages make fungi a promising alternative for sustainable dye production.Fungi from the phylum Ascomycetes are famous for their stable red pigments and are more water-soluble than pigments produced by plants, so dyes or pigments from fungi are prospective for development

(Lebeau *et al*., 2017; Lagashetti *et al*., 2019). This review explores the potential of microfungi, particularly from Monascaceae, Trichocomaceae, and Nectriaceae, as sources of natural dyes. It also examines their chemical classification and highlights their biological activities.

METHOD

The literature review employed a systematic search strategy using several electronic databases, including PubMed, Springer, and Google Scholar, to gather relevant studies on pigments and dyes, particularly from edible mushrooms and microfungi. The search was performed using the following Boolean keywords and operators: ("natural colorants" OR "natural pigments" OR "fungal pigments" OR "microbial pigments" OR "pigments from fungi" OR "secondary metabolites" OR "flavonoids" OR "carotenoids" OR "melanin" OR "natural dyes") AND ("Monascus" OR "Penicillium" OR "Aspergillus" OR "Trichoderma" OR "fungi") AND ("antioxidant" OR "antimicrobial" OR "food colorants" OR "cosmetics" OR "industrial applications" OR "biotechnology"). The search strategy focused on natural pigment sources and their applications for a comprehensive literature review. There were 33 relevant articles in PubMed, 385 in Springer, and 4,360 in Google Scholar. The collected literature was further selected using inclusion criteria such as full-text journal access, and the accessed literature contained structural images, while the exclusion criteria included irrelevant topics such as sequencing, DNA, genomic, and biomolecular. In addition, co-occurrence bibliometrics were used to explore research trends and gaps. A total of 44 documents were analyzed using bibliometric data from the Scopus database. The data was analyzed with VOSviewer software to visually represent connections among common terms, helping to discover patterns and major trends in the research area.

RESULTS AND DISCUSSION

1. Classification of dyes or pigments based on their structure

Fungi produce secondary metabolites, known as exometabolites, which are small molecules that secrete, accumulate, or store inside or outside the cell wall. Contrary to this, endometabolites, also known as primary metabolites, exhibit fluctuating concentrations and can undergo transformations into various forms such as endometabolites, exometabolites, exopolysaccharides, and exoproteins. Almost all fungal species produce endometabolites, while only certain species can produce exometabolites (Caro et al., 2017). Exometabolites have remarkable roles, including creating the pigments responsible for the vibrant colors of fungi. The classification of these pigments, based on their chemical structures, is key to understanding their biological importance and applications as natural colorants (Afroz Toma et al., 2023).

The natural colors shown in Figure 1 were put into groups based on their structures: tetrapyrrole derivatives (1), benzopyran derivatives (2), N-heterocyclic (3), isoprenoid derivatives (4), quinones (5), and melanins (6) (Delgado-Vargas et al., 2010).

Figure 1. Classification of natural pigment structures

Chlorophyll is an example of the tetrapyrrole class with a pyrrole ring surrounding a magnesium ion in the center. Plants, algae, and cyanobacteria all contain chlorophyll as a pigment. The colors produced from fungi are differ from those produced by higher plants. Unlike plants, fungi lack chlorophyll and anthocyanins, which are present in many flowers. Age influences fungi color intensity. In the initial phase of growth, *Penicillium chrysogenum* is white in color, which, as age increases, becomes blue-green (Tiwari et al., 2011). In addition to changing color with age, different parts of the fungus, such as the conidia, can also produce various colors. *Aspergillus glaucus* produces green while the hyphae are colorful from bright yellow to red. One species of fungus has the ability to produce a variety of pigments, each of which has a unique biological activity that contributes to its life cycle. The pigments also serve to protect the fungus from UV radiation and the bacteria around which it grows (Mukherjee *et al*., 2017).

Flavonoids are secondary metabolites containing the benzo-γ-pyrone skeleton (Liga et al., 2023). Flavonoids have broad biological activities such as antiaging, antioxidant, antidiabetic, and anticancer (Choi et al., 2002; Forbes et al., 2014; Budipramana et al., 2019; Guo et al., 2019). Gil-Ramirez et al. (2016) reported that fungi cannot produce flavonoids because they do not have 3 flavonoid-producing enzymes like plants, such as chalcone flavanone isomerase (CHI), chalcone synthase (CHS), and phenylalanine ammonia-lyase (PAL). The presence of flavonoids in the bodies of fungi can be because they are able to absorb various kinds of nutrients from their host or the plant to which they are attached. They reported that HPLC-MS failed to identify flavonoids in 24 fungal species from 29 genera. However, Wang et al. (2022) found 81 flavonoids in the fungus *Sanghuangporus baumii* and studied it using metabolomics and transcriptomics methods. However, *S. baumii* did not contain most of the genes required to code for flavonoid formation. The discovery of only 4 genes related to flavonoid synthesis in *S. baumii* suggests that the flavonoid synthesis formation pathway in the fungus differs from that in plants. The flavonoid-forming genes that are lost in the fungal body are subtituted by genes that come from the same superfamilies but have a distant relationship.

British chemist Alexander Wynter first noticed a greenish-yellow fluorescent pigment in milk in 1872, but it was not until the early 1930s that scientists identified the pigment as riboflavin (vitamin B2). Riboflavin compounds belong to the class of N-heterocyclic compounds. Plants and many microorganisms can synthesize riboflavin themselves, but animals must obtain it from their diets (Northrop-Clewes and Thunrham, 2012). The fungus *Ashbya gossypii* can also produce riboflavin, as shown in Figure 2. Nowadays, scientists produce riboflavin synthetically or through biotechnological methods (Averianova et al., 2020; Silva et al., 2022). Marcus (2013) suggests using riboflavin as a food coloring, in cheese, cereal, pasta, and as an additive in some baby food products and beverages.

Vitamin B2 is not only water-soluble but also heat-resistant, so the human body uses it to metabolize proteins, fats, and carbohydrates into energy. The body cannot digest proteins, fats, and carbohydrates without vitamin B2. The yellow color of urine is a sign that one's body is absorbing riboflavin. Vitamin B2 also activates the conversion of tryptophan into vitamin B3, which activates vitamin B6. Vitamin B2 deficiency can lead to cataracts, anemia, migraines, and thyroid dysfunction. Vitamin B2 is also a vitamin required during growth, lactation, maintaining healthy skin and hair, and reproduction. (Mahabadi *et al*., 2021).

Carotenoids are compound structures that are lipophilic and have eight isoprenoids. All carotenoids, also known as lycopene derivatives ($C_{40}H_{56}$), undergo color changes based on their age, the presence of isomeric carotenoids, and their processing method. The study divides the 600 types of carotenoids into two major groups: xanthophylls, which contain oxygen, and carotenes, which do not (Amat & Rendon, 2016). The fungus *Blakeslea trispora* produced the first carotenoid dye that Europe approved as a food ingredient (Dufosse, 2009). Apart from being a colorant, carotenoids also have antioxidant and anticancer activities (Michaud et al., 2000; Voorrips et al., 2000). Besides *Blakeslea* sp., the fungus *Neurospora crassa* also produces carotenoid pigment (Zheng *et al*., 2023). In invertebrate marine animals, especially from the Crustaceae family, the complex between astaxanthin-type carotenoids and protein (crustacyanin) causes the lobster shell to be dark purplish blue. If this protein is heated, there will be a wavelength shift in the bathochromic direction to a reddish-orange color (Cianci et al., 2002).

The quinone group is a class of secondary metabolites with the greatest structural variation compared to other groups. The main structure consists of desaturated ketone rings ranging from mono aromatic to poly aromatic ring derivatives (Sanchez-Munoz et al., 2020). Menakuinon is found in bacteria while anthraquinone is found in fungi and lichens. Examples of fungi that produce anthraquinone-class pigment are *Aspergillus*, *Trichoderma*, and *Fusarium* fungi (Mukherjee *et al*., 2017).

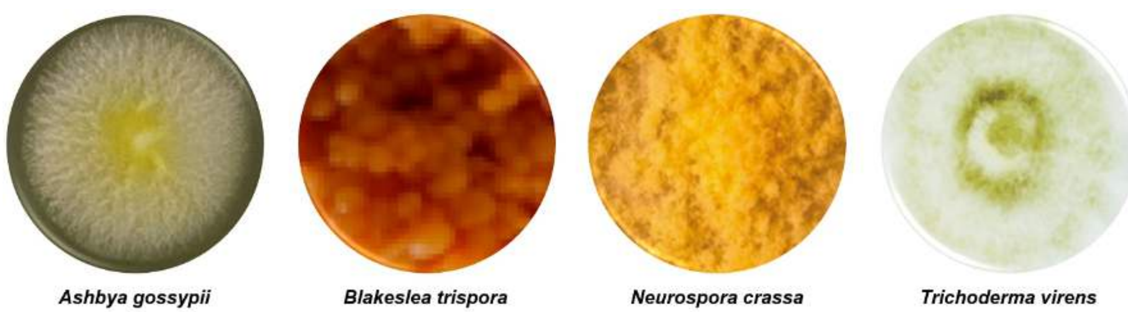

Figure 2. Some microfungi produce coloring agents

Apart from the quinone group, fungi also contain melanin, another colored substance. Melanin, a color substance from fungi, has a blackish brown color and is insoluble in water and regularly used organic solvents such as chloroform, acetone, methanol, ethanol, and ethyl acetate. Melanin is also resistant to heat, cold, acid, and bleaching degradation but soluble in alkaline (Nosanchuk et al., 2015; Łopusiewicz, 2018; Sanchez-Munoz et al., 2020). Plants, animals, and microorganisms naturally contain melanin as a pigment. Melanin finds numerous applications in the manufacturing of glasses, cosmetics, sunblock creams, pharmaceutical products, and food ingredients (Sen et al., 2019).

Fungi produce melanin to block UV radiation, gamma rays, X-rays, and particle radiation from the environment, so this is the principle for melanin to be used as a radioprotection coating material for space travel. Electronic devices, film coatings, varnishes, glass lenses, food industries, cosmetics, medicinal materials, and nanotechnology widely use melanin because of its ability to absorb these rays (Cordero, 2017; El-Naggar & El-Ewasy, 2017). Another report on a potential melanin pigment comes from *Gliocephalotrichum simplex.* The modulation of radiation-induced lower extracellular signal-regulated kinase (ERK) signaling by melanin is a compelling argument for its use as a radioprotective agent. Melanin also increases the expression of cyclin D1 and reduces the BAX/Bcl-XL ratio (Kunwar *et al*., 2012). When normal human liver L-02 cells were exposed to alcohol and then treated with melanin from *Auricularia auricula*, cell viability and GSH/GSSG levels increased. After treating alcohol-induced rats with melanin from ear fungus, tests revealed decreases in triglycerides, malondialdehyde (MDA), aspartate transaminase (AST), and alanine transaminase (ALT), and increases in superoxide dismutase (SOD), alcohol dehydrogenase (ADH), and catalase (CAT). Melanin can help with healing by stopping the activity of cytochrome P450 2E1 (CYP2E1) and nuclear factor E2-related factor (Nrf2) (Hou et al., 2019).

2. Fungi family producing pigments

The pigments of specific fungal families have important ecological roles and industrial applications across food, cosmetics, and pharmaceuticals. The families of fungi most recognized for their pigment production are Monascaceae, Trichocomaceae, and Nectriaceae (Afroz Toma et al., 2023).

2.1 Family of Monascaceae

Monascus, which gives *angkak* or red-brown rice its red color, is the source of one of the oldest pigments that humans have used extensively for a long time. *Angkak* not only produces red, but also yellow pigments from citrinin, monascin, ankaflavin, monasphilone A, and monophilol A compounds, while rubropunctatin compounds produce orange color and monascorubrin produces red color. The color substances from *Monascus* sp. are sensitive to pH, heat, and light, and they do not dissolve well in water. However, reacting with amino-containing compounds can make them more stable (Dufosse, 2009; Lagashetti et al., 2019).

In *Monascus*, there are yellow pigments called monascin and ankaflavin that can lower the levels of reactive oxygen species (ROS) and tumor necrosis factor-α (TNF-α) in human aortic endothelial cells. It was found that giving monascin and ankaflavin to 3T3-L1 cells lowered triglycerides and raised PPAR-γ activity (Pan & Hsu, 2014). It was found that the orange pigments rubropunctatin and monascorubrin were very good at killing bacteria, with an MIC of 2.5 ppm for *E. coli.* Under electron microscopy, it was seen that the phospholipids in the cytoplasmic membrane interacted with the pigment, killing the bacteria cells (Zhao et al., 2016).

Endo first isolated Monacolin K, also known as mevinolin or mevacor, from *Monascus ruber* in 1979. Monacolin K can reduce cholesterol levels by inhibiting the HMG-CoA reductase enzyme like statin drugs. Monakolin J, L, and M are structural analogs of monakolin K that also have cholesterol-lowering activity (Pan & Hsu, 2014; Pravst, 2015). The fungus *Aspergillus terreus* produces Simvastatin, a semi-synthetic cholesterol-lowering drug and a lovastatin derivative (Lebeau et al., 2017). There are chemicals in *Monascus* that can lower cholesterol and also a chemical called monascidin that can kill *Bacillus, Streococcus, and Pseudomonas* bacteria (Dufosse, 2009).

2.2 Family of Trichocomaceae

a. *Genus Penicillium and Talaromyces*

The genera of *Penicillium* and *Talaromyces* belong to the family Trichocomaceae. Soil, decaying organic material, grains, livestock, and other environments commonly harbor fungal species of the genera *Penicillium* and *Talaromyces*. The Trichocomaceae family includes fungi like *Aspergillus*, which makes 1984 exometabolites; *Penicillium*, which makes 1338 exometabolites; *Fusarium*, which makes 507 exometabolites; and *Talaromyces*, which makes 316 exometabolites. The two genera commonly produce pigments that range from yellow, red, orange, and brownish red. Both *P. atrovenetum* and *P. herquei* produce atrovenetin, the yellow pigment, while *P. brevicompactum* also generates the yellow pigment called xanthoepocin. In addition to producing atrovenetin, *P. atrovenetum* also produces *norherquinone*, a red pigment, while *P. atrosanguineum* produces the red pigment of phoenicin. *P. oxalicum* produces the red pigment of anthraquinone, Arpink redTM (now called natural red™), while *P. atramentosum* produces a dark brown color whose structure is still unknown. Apart from being a useful dye in clothing, food, and cosmetics, dyes from fungi also have important activities as antimicrobials against various fungi and bacteria. The fungus *P. notatum* produces penicillin, the first discovered antibiotic (Elsebai *et al.*, 2014; Kildgaard *et al*., 2014; Caro *et al*., 2017; Gaynes, 2017; Fan *et al*., 2019; American Chemical Society, 2023).

Some species of *Talaromyces* produce red pigments, while others, like *T. funiculosus*, produce yellow pigments such as emodin and luteoskyrin. *T. islandicus*, formerly known as *P. islandicum*, produces erythroskyrin, an orange-red pigment, and skyrin, an orange pigment. PP-R [(10Z)-7-(2-hydroxyethyl)-monascorubramine], which was once known as *P. purpureogenum*, is a reddish-purple pigment made by *T. purpureogenus*. Biotechnologists widely use *T. ruber* to produce enzymes, but *T. purpureogenus* produces 4 mycotoxins; *T. stollii* and *T. amestolkiae* are pathogenic to immunodeficient individuals (Yilmaz et al., 2012). Researchers discovered that the atrovenetin pigment in *P. atrovenetum* had antibacterial properties against *S. aureus* and *B*. *subtilis*. Atrovenetin, a kind of herquinone molecule, has high antioxidant activity and works well with vitamin E. This has motivated researchers to investigate the use of herquinone compounds and derivatives as antioxidants (Ishikawa et al., 1991).

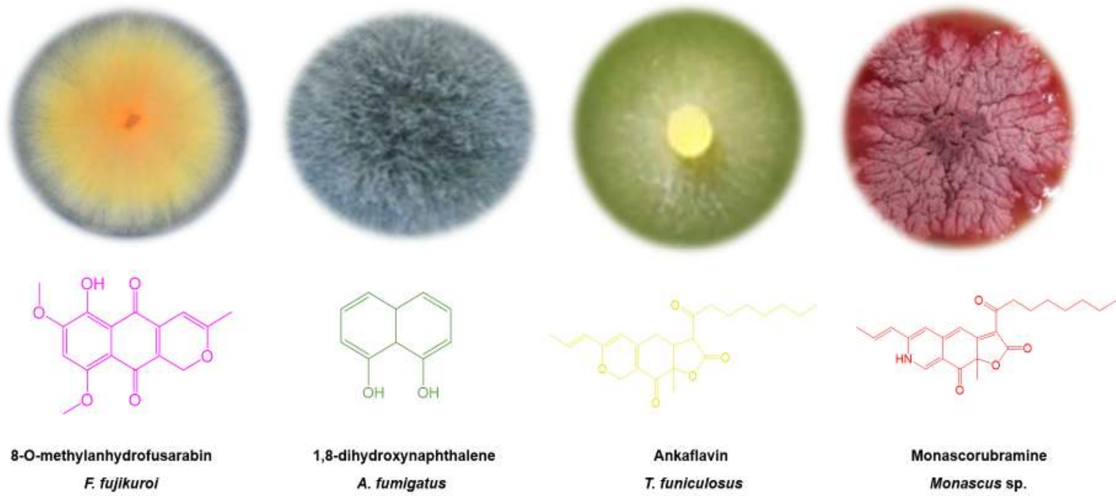

Figure 3. Pigments produced by *Fusarium fujikuroi*, *Aspergillus fumigatus*, *Talaromyces funiculosus*, and *Monascus* sp.

Arpink Red™ is an anthraquinone derivative pigment isolated from *Penicillium oxalicum* and first commercialized in the Czech Republic. People widely use Arpink Red for red coloring in meat products and wine, including ice cream making (Venil et al., 2020).

b. *Genus Emericella and Aspegillus*

Fungi from the Trichocomaceae family, like *Emericella* and *Aspergillus*, make pigments from hydroxyanthraquinone and azaphilone derivatives. The genus *Aspergillus* produces some major hydroxyanthraquinone-derived pigments, such as catenarin (red), erythroglaucin (red), and rubrocristin, a dimer of emodin, which also gives a red color. *Aspergillus* also produces minor hydroxyanthraquinone derivative pigments, which include cynodontin (bronze), chrysophanol (orange), ascoquinone A, averantin, averufin, norsolorinic acid, tritisporin (brownish red), variecolorquinone, and versicolorin. *A. melleus, ochraceus, sulphureus,* and *westerdijkiae* make pigments that are called viopurpurine (purple), viomellein (brownish red), rubrosulfin (red), and xanthomegnin (orange). *A. nidulans* is also known to generate blackish-brown melanin, which protects the fungus from environmental stress (Caro *et al*., 2017). *A. fumigatus* has a blue-green chemical called 1,8-dihydroxynaphthalene (DHN) that is like melanin and can fight free radicals (Upadhyay et al., 2013; Caro et al., 2017).

The genus *Emericella* comprises 34 species, and the name *Emericella* refers to the sexual stage of these fungi. Some fungal species of this genus are commonly known to produce yellow pigments with azaphilone structural skeletons, such as falconensins A-H. The compounds falconensones A1 and B2 and epurpurins A-C also produce yellow pigments despite not having azaphilone structural skeletons. Researchers report the presence of sterigmatocystin, a yellow-colored but carcinogenic substance, in the genus *Emericella*, including *Em. nidulans*, *Em*. *parvathecia*, and *Em. rugulosa*. The fungus *Aspergillus versicolor* is also known to contain sterigmatocystin. Differences in light exposure during the day and night, as well as wavelengths of 492–780 nm in the growth, intracellular, and extracellular phases of the fungus *Em. nidulans* will produce different pigments (Velmurugan et al., 2010).

2.3. Family of Netricaceae

Fusarium belongs to the Nectriaceae family, which is known to produce many pigments. The major pigments from the genus *Fusarium* are 5-*O*-methyljavanicin and 9-*O*-methylfusarubin, all of which are red whilst 8-*O*-methylanhydrofusarabin is purple. *F. fujikuroi* produces an orange color due to the presence of neurosporaxanthin. Baker & Tatum (1998) successfully isolated two yellow-orange pigments of hydroxyanthraquinone from *F. oxysporum*. Another compound from *Fusarium* fungi that gives a yellow pigment is aurofusarin from *F. culmorum*. The pH of the solvents strongly affects the stability of the yellow pigment aurofusarin. When the pH of the solvent is alkaline, then the color is red-purple, but if the solvent is acidic, then the pH is yellow. There are several secondary metabolites of *Fusarium* that are toxic such as beauvericins, fusarins, fusaric acid, zearalenones, and fumonisins (Caro *et al*., 2017).

3. Bibliometric analysis

A bibliometric analysis of fungal pigment and dye research is presented in Figure 4. Three main clusters, each in a different color, are highlighted on this map. Fungi and pigment analysis in chemical studies are the primary subjects of the initial, green-highlighted cluster. Isolation and fermentation processes, essential for researching fungal pigments, are strongly linked to this cluster. The blue cluster highlights fermentation, isolation, and purification as crucial for producing high-quality pigments. Meanwhile, the red-marked third cluster focuses on metabolism and antioxidant activity. This research cluster explores the potential health benefits of fungal pigments as bioactive compounds. The three clusters in this map all connect to a central "Chemistry" node. The study of fungi, pigments, and their applications is fundamentally linked by chemistry. However, this analysis uncovers a research gap—the absence of direct connections between the fungi pigment cluster and its human health applications, mainly antioxidant properties.

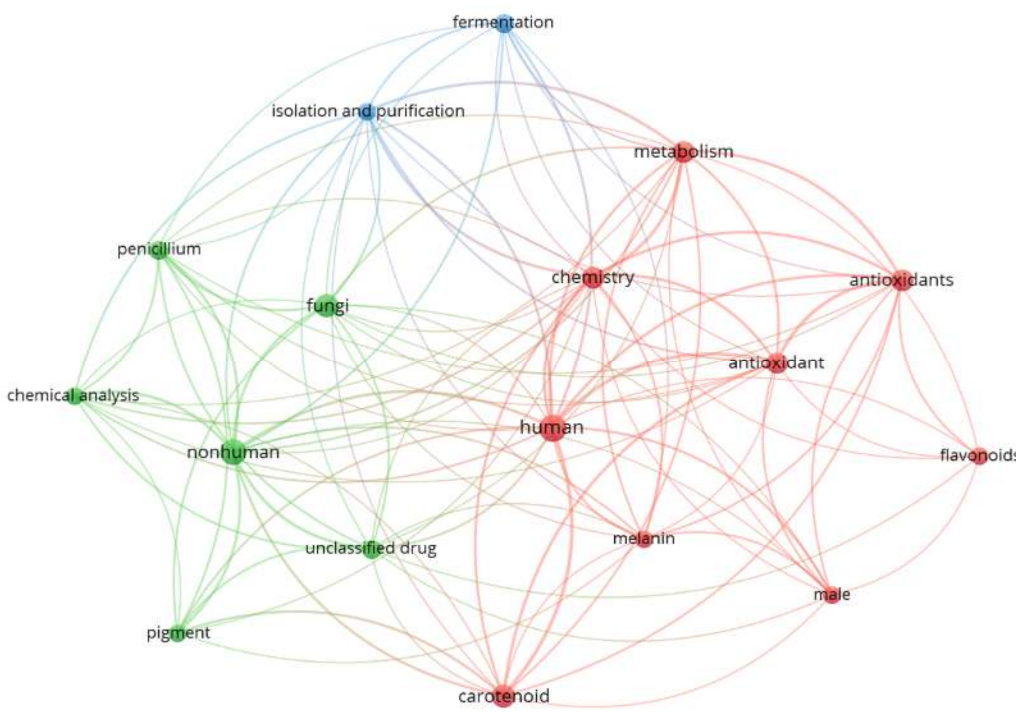

Figure 4. Co-occurrence map of research on fungal pigments or dyes: a bibliometric analysis

CONCLUSION

Compared to plants, fungi hold significant potential as natural coloring agents. Researchers have extensively researched natural pigments or dyes produced by microfungi, including carotenoids, anthraquinones, melanin, and ankaflavins from the Trichocomaceae, Monascaceae, and Nectriaceae family, but their commercial use has been less widespread. Utilizing natural coloring agents from microfungi can potentially alleviate the waste that synthetic dyes cause. Moreover, bibliometric analysis shows chemistry's key role in bridging fungal pigment research and its applications. It highlights a critical lack of research on the direct relationship between fungal pigments and their potential health benefits, mainly antioxidant effects. This gap highlights a valuable opportunity for further research into the link between fungal pigments and potential health benefits.

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