



Recent Advances In Fermentation-Based Production Of Microbial Natural Pigments And Their Applications In Sustainable Textile Dyeing: A Review

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Abstract :Environmental pollution and health risks caused by synthetic dyes have created a strong need for safer and more sustainable alternatives, especially in textile and other industrial sectors. Natural pigments obtained from microorganisms have recently gained attention as potential substitutes for synthetic dyes because they are biodegradable, less toxic, and can be produced under controlled conditions using fermentation techniques. Many microorganisms such as bacteria, fungi, and actinomycetes are capable of producing a variety of pigments including carotenoids, prodigiosin, violacein, and melanin, which have applications in textile dyeing as well as in food, cosmetic, and pharmaceutical industries. Compared to plant-based dyes, microbial pigments offer several benefits such as continuous production throughout the year, easier control of production parameters, and reduced dependency on natural resources. This review mainly discusses the production of microbial pigments through fermentation processes, methods used for pigment extraction and characterization, and their potential application in textile dyeing. Analytical techniques such as UV–Visible spectroscopy, FTIR, and Scanning Electron Microscopy (SEM) are also discussed for pigment analysis and for studying the surface morphology of dyed fabrics. Even though microbial pigments offer many environmental and industrial advantages, some challenges such as low production yield, scale-up difficulties, and production cost still exist. However, ongoing research in fermentation technology and biotechnology is expected to overcome these limitations, making microbial pigments a promising alternative to synthetic dyes for sustainable industrial applications.

Keywords: Microbial pigments, fermentation, natural dyes, textile dyeing, SEM analysis, eco-friendly dyes, microbial colorants

Introduction

Synthetic dyes are extensively used in textile, food, pharmaceutical, and cosmetic industries because of their bright color, low production cost, and easy availability. Despite these advantages, synthetic dyes pose serious environmental and health concerns. Many synthetic dyes contain toxic chemicals, heavy metals, and non-biodegradable compounds, which contribute to water pollution and environmental contamination when discharged into water bodies without proper treatment [1]. The presence of dyes in wastewater also reduces light penetration in aquatic environments, which affects photosynthesis in aquatic plants and disrupts the ecological balance [2].

In recent years, increasing environmental awareness and strict environmental regulations have created a growing interest in eco-friendly and sustainable alternatives to synthetic dyes. Natural dyes obtained from plants, animals, and microorganisms are receiving significant attention because they are biodegradable, less toxic, and environmentally safe [3]. Among these sources, microorganisms are considered highly promising for pigment production due to their rapid growth rate, ease of cultivation, and ability to produce pigments under controlled fermentation conditions throughout the year [4].

Microbial pigments are secondary metabolites produced by various microorganisms such as bacteria, fungi, algae, and actinomycetes. These pigments include carotenoids, melanin, prodigiosin, violacein, flavins, and quinones, which have applications in textile dyeing, food coloring, cosmetics, pharmaceuticals, and biomedical industries [5]. The production of microbial pigments through fermentation offers several advantages, including continuous production, independence from seasonal variations, and the possibility of large-scale production using relatively simple fermentation techniques. Because of these advantages, microbial pigments are increasingly being explored as potential alternatives to synthetic dyes in textile dyeing and other industrial applications.

Microbial Sources Of Natural Pigments

Microorganisms have gained considerable attention as alternative sources of natural pigments due to their ability to produce a wide range of colors with diverse chemical structures. These pigments are typically produced as secondary metabolites and often play protective roles in microorganisms, such as shielding against ultraviolet radiation and oxidative stress [9]. Compared to plant-based pigments, microbial pigments offer advantages such as faster production rates and easier scalability under controlled laboratory conditions [10].

Among microorganisms, bacteria are widely studied for pigment production because of their rapid growth and simple nutritional requirements. Several bacterial species are known to produce pigments with distinct colors. For instance, species of *Kocuria* and *Micrococcus* produce yellow carotenoid pigments, while *Serratia marcescens* produces the red pigment prodigiosin. Similarly, *Chromobacterium violaceum* produces a violet pigment known as violacein [11]. These pigments are not only useful for coloration but also possess biological properties such as antimicrobial and antioxidant activities, which enhance their industrial value [12].

Fungi are another important group of pigment-producing microorganisms. Filamentous fungi such as *Monascus*, *Aspergillus*, and *Penicillium* are well known for their ability to produce stable and intense pigments. In particular, *Monascus* species have been extensively used for producing red pigments that are widely applied in food and textile industries [13]. Fungal pigments are often produced using cost-effective substrates, including agricultural waste materials, making the process more sustainable.

Algae also contribute to natural pigment production by synthesizing pigments such as chlorophyll, carotenoids, phycocyanin, and phycoerythrin. These pigments are mainly utilized in food, cosmetic, and pharmaceutical industries due to their antioxidant properties [14]. In addition, actinomycetes, particularly *Streptomyces* species, are known to produce a variety of pigments with potential applications in textiles and medicine. Overall, microbial sources provide a versatile and sustainable platform for natural pigment production.

Fermentation Production Of Microbial Pigments

Fermentation is one of the most widely used methods for the production of microbial pigments, as it allows controlled growth of microorganisms under optimized environmental conditions. In general, microorganisms are cultivated in suitable nutrient media, where factors such as temperature, pH, aeration, and incubation time are carefully regulated to enhance pigment production [15]. This controlled approach makes fermentation a reliable and efficient method for large-scale pigment production.

Two major types of fermentation processes are commonly employed: submerged fermentation and solid-state fermentation. In submerged fermentation, microorganisms are grown in liquid media, which allows better control over environmental parameters and facilitates easier extraction of pigments from the culture broth [16]. This method is widely used in industrial applications due to its simplicity and scalability.

On the other hand, solid-state fermentation involves the growth of microorganisms on solid substrates such as rice bran, wheat bran, and other agricultural residues. This method is considered more economical and environmentally friendly, as it utilizes low-cost raw materials and generates less wastewater [17]. However, controlling parameters such as moisture content and aeration can be more challenging in solid-state systems.

Several factors influence the production of microbial pigments during fermentation. These include the type of carbon and nitrogen sources, pH of the medium, incubation temperature, and duration of fermentation. It has been observed that optimization of these parameters can significantly improve pigment yield and quality [18]. Therefore, fermentation remains a key technique in the development of microbial pigments for industrial applications, particularly in eco-friendly textile dyeing.

Pigment Extraction And Characterization

Microbial pigments produced during fermentation need to be extracted and analyzed in order to understand their chemical properties and suitability for dyeing applications. The extraction of pigments is generally carried out after fermentation by first separating the microbial biomass from the culture broth using centrifugation. After centrifugation, the pigment present in the supernatant or biomass is extracted using organic solvents such as methanol, ethanol, acetone, or ethyl acetate, depending on the solubility of the pigment [19]. The extraction process usually involves separation of cells, mixing with solvent, filtration, and evaporation of the solvent to obtain the concentrated pigment extract.

Once the pigment is extracted, it is important to characterize it using analytical techniques to determine its absorption properties and chemical nature. UV-Visible spectroscopy is one of the most commonly used methods for pigment analysis, as it helps in determining the maximum absorbance wavelength of the pigment and provides information about the pigment type [20]. This technique is simple, fast, and widely used for microbial pigment analysis.

Another important technique used for pigment characterization is Fourier Transform Infrared Spectroscopy (FTIR), which helps in identifying the functional groups present in the pigment molecules and gives information about the chemical structure of the pigment [21]. These characterization methods are useful for understanding pigment stability, composition, and possible industrial applications.

In addition to UV-Visible spectroscopy and FTIR, other techniques such as High Performance Liquid Chromatography (HPLC) and Thin Layer Chromatography (TLC) are also used for pigment separation and identification [22]. These techniques help in determining pigment purity and separating different pigment components if present. Overall, pigment extraction and characterization are essential steps before using microbial pigments for textile dyeing and other industrial applications.

Application Of Microbial Pigments In Textile Dyeing

In recent years, microbial pigments have attracted significant attention as natural dyes for textile applications because they are biodegradable, non-toxic, and environmentally friendly. Various textile materials such as cotton, silk, wool, and blended fabrics can be dyed using microbial pigments [23]. The use of microbial pigments in textile dyeing can reduce the environmental pollution caused by synthetic dyes.

The textile dyeing process using microbial pigments generally involves several steps, including fabric pre-treatment, mordant treatment, dyeing, washing, and drying. Pre-treatment is carried out to remove impurities such as wax, oil, and dust from the fabric surface to ensure proper dye absorption. Mordants such as alum, copper sulfate, or iron salts are sometimes used to improve dye fixation and color strength on the fabric.

After mordant treatment, the fabric is immersed in the pigment solution and heated for a specific period to allow proper dye uptake. The dyed fabric is then washed to remove excess dye and dried at room temperature. The dyed fabrics are usually evaluated for color fastness properties such as washing fastness, light fastness, and heat stability to determine the durability of the dye on the fabric. Microbial pigments have shown good dyeing ability on cotton fabrics and have the potential to be used as eco-friendly alternatives to synthetic textile dyes.

Sem Analysis Of Dyed Fabric

Scanning Electron Microscopy (SEM) is widely used to study the surface morphology of textile fibers before and after dyeing. It provides detailed images that help in understanding how the pigment interacts with the fabric surface. By comparing SEM images of undyed and dyed fabrics, it becomes possible to observe changes in surface structure and confirm the presence of pigment on the fiber surface [26].

In undyed fabrics, the fiber surface usually appears smooth and uniform. However, after dyeing with microbial pigments, the SEM images often show the presence of small particles or layers deposited on the fiber surface. This indicates that the pigment has successfully adhered to the fabric. In some cases, slight changes in surface roughness can also be observed, suggesting interaction between the pigment molecules and the fiber.

SEM analysis is therefore useful in evaluating the effectiveness of the dyeing process and understanding pigment distribution on textile materials. It also helps in comparing different dyeing conditions and determining how well the pigment binds to the fabric. Overall, SEM provides supportive evidence for successful dyeing using microbial pigments.

Advantages Of Microbial Pigments Over Synthetic Dyes

Microbial pigments offer several advantages when compared to synthetic dyes, especially in terms of environmental safety and sustainability. One of the major advantages is that microbial pigments are biodegradable and do not accumulate in the environment, unlike synthetic dyes which often persist for long periods and cause pollution [27].

Another important benefit is that microbial pigments are generally non-toxic and safer for both humans and the environment. Since they are produced from natural sources through fermentation, they do not involve harmful chemicals commonly used in synthetic dye production. This makes them more suitable for applications in textiles, cosmetics, and even food industries.

In addition, microbial pigment production is not dependent on seasonal variations, unlike plant-based dyes. Microorganisms can be grown throughout the year under controlled laboratory conditions, allowing continuous pigment production [28]. Some microbial pigments also exhibit additional properties such as antimicrobial and antioxidant activity, which can add functional value to dyed fabrics.

Challenges And Future Prospects

Despite the advantages of microbial pigments, there are still several challenges that need to be addressed before they can be widely used in industrial applications. One of the major limitations is the relatively low yield of pigments during fermentation, which makes large-scale production less economical [29]. In addition, the cost of production, including media components and downstream processing, can be higher compared to synthetic dyes.

Another challenge is the stability of microbial pigments under different environmental conditions such as light, temperature, and pH. Some pigments may fade or degrade over time, which affects their performance in textile applications. Furthermore, scaling up fermentation processes from laboratory level to industrial level can be technically challenging.

However, future research in this field is focusing on improving pigment yield through optimization of fermentation conditions and the use of genetic engineering techniques. Advances in biotechnology and process engineering may help in reducing production costs and improving pigment stability. There is also increasing interest in developing sustainable and eco-friendly dyeing processes using microbial pigments, which may lead to their wider acceptance in the textile industry [30].

Conclusion

Microbial pigments are emerging as promising alternatives to synthetic dyes due to their eco-friendly nature, biodegradability, and potential for sustainable production. A wide variety of microorganisms, including bacteria, fungi, algae, and actinomycetes, are capable of producing pigments with diverse colors and applications. Fermentation-based production allows controlled and continuous generation of these pigments, making them suitable for industrial use. Different extraction and characterization techniques such as UV-Visible spectroscopy, FTIR, and SEM play an important role in understanding the properties of microbial pigments and their interaction with textile materials. The application of these pigments in textile dyeing has shown encouraging results, particularly in terms of color development and basic fastness properties. Although there are some limitations related to production cost, yield, and stability, ongoing research and technological advancements are expected to overcome these challenges. With increasing environmental concerns and the need for sustainable solutions, microbial pigments have strong potential to replace synthetic dyes in the future. Overall, they represent an important step towards environmentally friendly and sustainable textile dyeing practices.

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