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A Review of Bacterial Pigments: Harnessing Nature's Colors for Functional Materials and Dyeing Processes

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ABSTRACT

The use of synthetic dyes has been found to have negative environmental impacts, leading to a growing demand for natural alternatives. This study explores the potential of bacterial pigments, derived from microorganisms, as a sustainable alternative for textile dyeing. The first chapter examines the ecological impact of synthetic dyes and the potential of natural dyes, including bacterial pigments, as a sustainable alternative. Biodegradability and life-cycle-assessment are discussed in this chapter since they are important factors to evaluate the environmental impact of any substance. The second chapter discusses the potential for bacterial pigments to functionalize textile materials with new therapeutic properties, including antifungal and anti-inflammatory effects. Additionally, some bacterial pigments can be used as semiconductors for electronics. The third chapter outlines the challenges of using natural pigments in textile production and suggests techniques to improve colourfastness. The chapter also highlights the successful uses of pigments such as anthraquinone, carotenoid, violacein, melanin, and prodiginine in textile colouring. Finally, the future perspectives section identifies potential areas for further research and development in the field of bacterial pigments, which could revolutionize the textile industry towards a more eco-friendly and innovative approach to textile production.

KEYWORDS

sustainability, bacterial pigments, textile functionalization, dyeing

INTRODUCTION

The production of synthetic dyes, which includes a vast array of different types such as basic dyes, acid dyes, disperse dyes, direct dyes, sulfur dyes, and metal dyes, amounts to approximately 70000 tons per year out of the 10,000 available dyes. It is estimated that between 5 and 50% of these dyes are lost in effluent discharge from the textile industry [1]. Furthermore, numerous studies have demonstrated that synthetic dyes have a high toxicity level and have been linked to mutagenic and carcinogenic effects [2,3].

Given the detrimental impact of the textile industry on the environment, it is imperative to thoroughly understand these processes and seek out more sustainable alternatives [4]. In light of this, there has been a growing interest in natural dyes, which are biodegradable and do not produce toxic waste [5].

In recent years, bacterial pigments have been extensively studied for their low environmental impact and diverse range of colours. After being successfully applied in the cosmetics and food industries, they are now being tested in the textile industry [6,7].

These pigments can be obtained from various sources, such as agricultural waste or bodies of water, and collecting different microbiological cultures allows the production of substances capable of colouring textile substracts in more sustainable processes [7,8]. These living beings also produce stable pigments composed of carotenoids and flavonoids with higher affinity than other natural dyes [9].

Additionally, they are not dependent on specific environmental conditions for their production, unlike some natural dyes derived from vegetal sources. They are also quick and easy to produce and, in some cases, they may also impart other beneficial properties such as antibacterial, antioxidant, and even anti-cancer activities [7].

From a scientific standpoint, these microorganisms are also highly interesting as they are easily genetically manipulated and can be extracted and produced with relative ease. Furthermore, a wide variety of species can be used to colour both natural and synthetic textile fibres [7].

In the realm of textile manufacturing, the application of bacterial pigments remains a relatively new area of investigation. However, several challenges impede the widespread use of these substances. A primary hurdle is the cost of such pigments, which can exceed five times that of synthetic dyes. This pricing disparity limits the accessibility of natural dyes to consumers with a particular concern for environmental issues in textile production. Additionally, bacterial pigments exhibit limited colour variations compared to synthetic dyes, making it difficult to achieve more vibrant hues. While natural colourants can produce distinct and unique shades, their intensity can be challenging to enhance. Furthermore, bacterial pigments tend to have shorter shelf lives than their synthetic counterparts, as they are particularly sensitive to light, pH, UV, and other environmental factors [10].

One of the primary challenges associated with natural dyes is the difficulty in obtaining large quantities of pigments, which can be influenced by various factors such as the growth medium, temperature, and pH. Furthermore, bacterial pigments may exhibit lower colourfastness and stability compared to synthetic dyes, and in some cases, may require additional chemical treatments to enhance these properties. A further limitation is the lack of standardization in the production of bacterial pigments, which can lead to variations in colour and quality across different batches. Additionally, the use of bacterial pigments in the textile industry is still in the experimental stage, and further research is necessary to fully comprehend their properties and potential applications [11].

On the other hand, incorporating bacterial pigments into the textile industry has the potential to provide a sustainable and locally sourced substitute for synthetic dyes. This sustainable alternative could be particularly attractive to environmentally conscious consumers willing to pay more for eco-friendly and ethically sourced products. A successful bacterial pigment industry could also provide positive economic impacts in regions where traditional textile manufacturing has decreased, as the pigments can be obtained from a variety of locally available waste products such as agricultural by-products or wastewater, potentially offering a new source of revenue for farmers and small businesses. Furthermore, the low-cost and easy-to-produce properties of bacterial pigments could reduce the overall cost of textile production and increase profit margins for manufacturers [11].

METHODS

Defining research aims

This research study aims to investigate the potential of bacterial pigments as an alternative to synthetic dyes in textile dyeing processes. The study will specifically focus on the environmental impact of bacterial dyes and the potential for functionalization of technical textiles using these dyes.

To achieve this aim, the following research objectives have been established:

1. To conduct a comprehensive review of the literature on bacterial dyes, their properties, and their potential applications in textile dyeing processes.
2. To investigate the environmental impact of bacterial dyes, including their biodegradability and toxicity.
3. To assess the potential for functionalization of technical textiles using bacterial dyes, including the development of medical and electronic materials.
4. To compare the properties of bacterial dyes to those of synthetic dyes commonly used in textile dyeing processes.

This research aims and objectives will guide the study's methodology, including the selection of research methods, data collection, and analysis techniques, and the interpretation of results. By clearly defining the research aims and objectives, the study can be conducted in a structured and systematic way, ensuring that the research questions are answered effectively and efficiently.

Bibliographic research

Bibliographic research was conducted to identify and select relevant literature for this review. A comprehensive search was performed using electronic databases such as PubMed, ScienceDirect, and Scopus, as well as manual searches of relevant journals and reference lists of identified articles. The search strategy included a combination of keywords related to bacterial dyes, environmental impact, textile dyeing, and technical textiles. The search was limited to articles published in English and from the last 10 years to ensure the most up-to-date information.

The selected articles were screened for their relevance to the review's research questions and objectives. Inclusion criteria included studies that reported on the environmental impact of bacterial dyes, their potential applications in textile dyeing, and their use in technical textiles. Exclusion criteria included studies that did not address these topics or were not relevant to the scope of the review.

The extracted data included information on the pigment groups found in microorganisms, their potential applications in technical textiles, and their environmental impact. The data were analyzed and synthesized to identify patterns, trends, and future directions for research on bacterial dyes.

Overall, this bibliographic research provided the basis for the review's analysis of the environmental impact of bacterial dyes and their potential for use in textile functionalization, contributing to the sustainable development of the textile industry.

Outline

The following section provides an overview of the organization and structure of this paper. It outlines the main sections or chapters that will be included, along with summaries of the content covered in each section. This will give the reader a clear understanding of the paper's organization and flow and enable them to navigate the content more easily. By providing a clear and structured outline, the reader can better understand how the research study has been conducted, what has been found, and what conclusions have been drawn. This will also help to demonstrate the logical progression of the research and how each section contributes to the overall study.

The first chapter of this paper focuses on the ecological impact of synthetic dyes and the potential of natural dyes, particularly those derived from microorganisms, as a sustainable alternative. Synthetic dyes are known to pollute water and soil with toxic chemicals and are not biodegradable, leading to detrimental effects on the environment. On the other hand, natural dyes have the advantage of being biodegradable and easily accessible, and pigments extracted from microorganisms have demonstrated technological and therapeutic potential. Moreover, sourcing microorganisms from agricultural waste can reduce the environmental impact of production. "Green dyes" have the potential to reduce the use of toxic materials, offer no concerns related to disposal, and have potential health benefits. The chapter concludes with the importance of further research on sustainable alternatives to synthetic dyes.

The second chapter discusses the potential of using bacterial pigments to functionalize textile materials with new therapeutic properties. The chapter highlights two main areas of interest: antifungal activity and anti-inflammatory effects. The antifungal properties of bacterial pigments have been extensively studied, with promising results. The chapter suggests that the use of bacterial pigments could constitute a new technique to grant a variety of new functions to textile materials and confer new therapeutic potential to materials. Furthermore, some bacterial pigments can also be used as semiconductors and applied to electronics.

The third chapter discusses the challenges of using natural pigments in textile production despite their potential benefits. The pigments can be obtained through fermentation or extraction from bacterial mycelia using solvents. However, scaling up extraction processes and ensuring colourfastness can be challenging. The use of auxiliaries such as mordants and enzymes can help improve colourfastness, and fermentation tanks can be installed to address the lack of necessary machinery. Despite these challenges, many investigators have successfully used pigments such as anthraquinone, carotenoid, violacein, melanin, pyocyanin, and prodiginine in textile colouring.

The fourth chapter discusses conclusions that could be gathered from the content of this paper.

The future perspectives section of the report aims to identify potential areas for further research and development in the field of bacterial pigments. As research continues, bacterial pigments may revolutionize the textile industry, paving the way for a more eco-friendly and innovative approach to textile production.

ECOLOGICAL IMPACT

Synthetic dyes are artificially manufactured chemicals that are widely utilized in a plethora of industrial and consumer products, including the textile, food, and cosmetic industries. However, their usage can have detrimental effects on the environment, as they have the potential to pollute water and soil with toxic chemicals, and many synthetic dyes are not biodegradable, thereby persisting in the environment for prolonged periods. Additionally, the production of synthetic dyes often entails the utilization of non-renewable resources, leading to the release of harmful chemicals and greenhouse gases into the atmosphere [12-14].

As a result, natural dyes have been the subject of extensive research as a potentially sustainable alternative to synthetic dyes [15]. It is crucial to conduct a thorough analysis of how these alternatives affect the environment in comparison to conventional products, to meet the high demand for sustainable options. Researchers have examined various factors to make that evaluation [7].

Despite the possible applications of bacterial pigments, it has been found that some pigmented bacteria might be responsible for pathogens such as infections in humans and animals [16]. Therefore, there is a growing need to identify pigmented bacteria that do not pose a risk to human health or other organisms. Numerous studies are currently underway to address this issue [17].

Biodegradation is a crucial factor to consider when speaking about the breakdown and recycling of natural products in the environment. This can be affected by several factors such as chemical structure, molecular weight, and solubility. Furthermore, the degradation process can be performed by different types of microorganisms, like bacteria, fungi, and algae that are present in the environment. When developing sustainable solutions for environmental protection, it is crucial to study the biodegradability aspect of the substances in question [18].

The biodegradability of bacterial pigments is an important factor to consider in their potential use as sustainable alternatives to synthetic dyes. Research has shown that many bacterial pigments are biodegradable, meaning that they can be broken down naturally by microorganisms in the environment [16]. However, the rate and extent of biodegradation can vary depending on factors such as the chemical structure of the pigment and the conditions of the environment [19]. Further research is needed to fully understand the biodegradability of bacterial pigments and their potential impact on the environment.

Bacterial pigments have attracted attention as sustainable alternatives to synthetic dyes, owing to their biodegradability and potential therapeutic and technological applications. However, the impact of wastewater generated from dyeing with bacterial pigments on the environment remains unclear. Further research is needed to determine the long-term effects of bacterial pigment wastewater on the environment and to optimize the treatment processes for their efficient removal.

While synthetic colourants can provide an affordable source of intense and durable colours, their most significant drawback is their toxicity. In contrast, natural dyes, particularly those derived from microorganisms, are biodegradable and easily accessible [13]. Furthermore, pigments extracted from microorganisms have demonstrated technological and therapeutic potential, conferring them a significant advantage over synthetic dyes [21-28].

Life cycle assessment (LCA) is also an essential tool for evaluating the environmental impact of products and processes throughout their entire life cycle, even though there is no available information yet.

The environmental impact of production can also be reduced by sourcing microorganisms from agricultural waste, as several studies have reported [17,20].

In a review, Venil and coworkers concluded that “green dyes” can positively impact the environment in multiple ways, including reducing the use of toxic materials as the products are naturally sourced, and there are no concerns related to their disposal. Additionally, there are potential health benefits associated with applying these pigments to textiles. Furthermore, biomass can be repurposed for energy generation, and the growth media can also be recycled, thereby avoiding waste [7].

MATERIAL FUNCTIONALIZATION FROM THE APPLICATION OF BACTERIAL PIGMENTS

These colourants might constitute a new technique to grant a variety of new functions to textile materials.

Some findings have revealed several intriguing characteristics in these microorganisms. Among many others, the ability to reduce the risk of cancer, exhibit antifungal activity, possess antibacterial properties, and the reduction of local inflammation, appear to be the most interesting from a textile engineering perspective. This means that the use of these pigments could confer new therapeutic potential to materials [13]. Furthermore, some bacterial pigments can also be used as semiconductors and applied to electronics [21].

Antifungal activity

Antifungal properties may represent a new way to prevent problems caused by fungi that put human health at risk. These properties have been studied for decades in bacterial pigments. A study from 1963 provided some of the first developments in this area. Ayers and Papavizas studied the isolation of a violet pigment from the genus *Pseudomonads,* which was then tested for its antifungal properties against eighteen species of fungi AT two distinct concentrations (320 units/mL and 32 units/mL). It was the most effective against the species *Endothia parasitica* and *Sclerotinia sclerotiorunt* when applied at the highest concentration [22].

A study by Dawoud et Al. focused on the application of a yellow pigment produced by the microorganism *Bacillus* sp. DBS4 as an antifungal agent. This characteristic was tested using the agar well-diffusion method and it was tested against different species, namely R. *solani*, F. *oxysporum*, and S. *rolfsi*. A commercial antifungal agent (Terbinafine hydrochloride) was used as a comparison. The results were determined by the inhibition of fungus growth. The study concluded that the pigment had different levels of activity against each species of fungi. When it comes to R. *solani* and S. *rolfsi,* the pigment was classified as effective against them [23].

The antifungal properties of various types of bacterial pigments have been extensively studied, with many revealing promising results. For instance, a fluorescent pigment found in the species *Pseudomonas* spp. EM85 was found to be effective against the fungal pathogen *Rhizoctonia solani* [24]. When present in nature, this fungal pathogen can be responsible for the severe destruction of flora [25]. Additionally, a pigment from the group violacein was isolated from the species *Collimonas* sp. DEC-B5 and analyzed for its antifungal properties. The colourant was tested against *Botrytis cinerea, Colletotrichum acutatum,* and *Fusarium oxysporum*, showing effective activity against the first and the third species. Furthermore, the pigment was found to inhibit the growth of *Botrytis cinerea* by 65% [26]. This fungus is known to cause severe damage to crops, manifesting as grey mould on fruits and vegetables [25]. Another violacein pigment was extracted from the strain of *Chromobacterium* sp. NIIST (MTCC 5522). The investigators were able to produce around 0.6g of crude violacein per gram of weight biomass, by using a modified Luria Bertani medium for the incubation process. This pigment was tested against several pathogenic fungi and yeast species, being found effective against species like *Cryptococcus gastricus, Trichophyton rubrum, Fusarium oxysporum, Rhizoctonia solani, Aspergillus flavus, Penicillium expansum, Candida albicans*. It was most effective against the species *Trichophyton rubrum,* namely 2 µg/ml. This innovative method for pigment production consists of a Luria Bertani broth without sodium chloride where a 24-hour culture was used as the inoculum, and the experiment was conducted in a 250 ml Erlenmeyer flask at room temperature and 150 rpm. Biomass and violacein were assessed by taking 1 ml of culture broth, centrifuging it, and extracting the pigment to the ethanol phase. The supernatant's optical density was taken at 575 nm to quantify violacein, and the pellet's optical density was taken at 600 nm to quantify biomass. The experiment was conducted under different pH, temperatures, and salinity, and all batch experiments were repeated with triplicates. The average values with standard deviation were accounted for [27].

Anti-inflammatory effect

Inflammation is a biological response that occurs in living tissues when they are subjected to injury. Anti-inflammatory drugs work by inhibiting the lysosomal enzyme that is released during inflammation [27,28].

A study by Wei Bai and their team aimed to extract two different azaphilone pigments from the species *Talaromyces albobiverticillius* and analyze their anti-inflammatory activity. The pigments were isolated and identified using various spectroscopic techniques. In vitro assays were used to assess the anti-inflammatory activity of the pigments, including the inhibition of nitric oxide (NO) production and the release of tumour necrosis factor-alpha (TNF-α) in lipopolysaccharide (LPS)-stimulated RAW264.7 macrophage cells. The results revealed that the pigments exhibited significant anti-inflammatory activity by inhibiting the production of NO and TNF-α in the macrophage cells. The study concludes that the newly discovered azaphilone pigments have the potential for development as anti-inflammatory drugs[29].

Another study, published in 2017, focused on collecting bacterial species from a marine environment. Through isolation, a diversity of pigments in shades of pink, yellow, orange, and brown were identified among the species. One such pigment, a bright yellow pigment, sourced from the species *Brevibacterium sp*, was chosen as the focal point for the study. The pigments' efficacy in reducing inflammation was evaluated using a model of induced paw oedema in male Wister Albino rats. The results demonstrated a 100% effectiveness of the pigment in ameliorating inflammation [30].

A separate group of researchers successfully documented the anti-inflammatory effect of a pigment-protein complex extracted from the species *Chlorella Pyrenoidosa*. The colour of this pigment is not specified as the focus of the study was on its anti-inflammatory properties. The effect was evaluated by stimulating RAW 264.7 cells with lipopolysaccharide and treating them with varying concentrations of the protein-pigment complex. All concentrations were deemed effective at reducing inflammation [31].

Antibacterial activity

Textile materials are prone to bacteria growth for their ability to retain humidity [32]. As such, one of the most sought-after functionalizations for the textile industry is antibacterial performance. In 2021, Ren et al. were able to achieve this by dyeing acrylic fibres with red bacterial pigments (extracted from *Serratia marcenscens* and *Staphylococcus aureus*). The prodigiosins (red bacterial pigments) were able to inhibit the growth of *Escherichia coli,* and the dyed fabric was also found to be effective against *Staphylococcus aureus,* a highly detrimental bacteria to human health [33]. In 2009, Selvameenal and their team discovered antibiotic activity in a yellow bacterial pigment, obtained from *Streptomyces hygroscopicus* and it was shown effective against cultures of *E.coli* and *Klebsiella sp.* [34].
Similar activity was also found on fabrics dyed with prodigiosin extracted from strain *Serratia rubidaea* RAM_Alex. The pigment was applied to several structures, resulting in different antimicrobial activity levels. *Escherichia coli* and *Staphylococcus aureus* were chosen as test pathogens since they are responsible for a multitude of skin infections. The colourant was found to be more effective against *E. coli* when applied to linen (97% of inhibition) and more effective against S. *aureus* when used on chiffon (97% of inhibition). This can be explained by the dye uptake, which was higher on those fabrics [35].

Anticancer activity

Another characteristic found in some bacterial pigments is anticancer activity. This could be revolutionary, not only for the textile industry but also for the field of medicine. A study from 2017 focused on the extraction of a pigment from a marine species (*Arthrobacter* sp. G20) with anticancer activity. The carotenoid pigment revealed antioxidant activity, as well as cytotoxic and antibacterial activity. The antioxidant activity means that these carotenoids can neutralize free radicals in the body, which are responsible for the formation of defective cells that cause diseases like cancer [36]. A melanin pigment produced by *Streptomyces glaucescens* NEAE-H was isolated and studied for its antioxidant and anticancer properties. The pigment was tested on cancerous and non-cancerous cells and then compared to a standard anticancer drug, 5-fluorouracil. The results showed that obtaining melanin from this culture was a viable and more simple way of developing anticancer treatments [45-37].

Shindo and Misawa have studied the extraction of carotenoid pigments from marine bacteria. They were found in the species *Rubritalea squalenifaciens* and *Planococcus maritimus* and they were tested for their antioxidant properties. From both species, they were able to find rare carotenoids (C_{40} carotenoids, (3R)-saproxanthin, and (3R,2'S)-myxol) and to extract yellow pigments. Based on these findings, the pigments were expected to show antioxidant activity, since these marine bacteria produce carotenoids as a defence mechanism against sunlight [38].

This could be very useful for the textile industry when applied to garments as a treatment for skin conditions, as the antioxidant properties of these pigments could potentially protect the skin from harmful UV rays and other environmental factors. Additionally, the potential anticancer properties of these pigments could also be beneficial in the textile industry, as they could potentially provide an added layer of protection against harmful chemicals and pollutants that may come into contact with the skin. Overall, the use of these natural and sustainable pigments in the textile industry could greatly benefit both the environment and human health [39].

Semiconductors

Despite being less researched, a recent study has shown the potential use of an indigoidine pigment as an organic semiconductor. Yumusak and their team published their investigation of a blue pigment synthesized from *Escherichia coli* as an organic semiconductor. The strain was cultivated under optimal growth conditions and the indigoidine synthetase was then induced. The pigment was finally collected and purified, and a film was formed to observe its properties. Optical structural and electrical properties were evaluated. The material was characterized via UV-vis and fluorescence spectroscopy and molar extinction was calculated through the Beer-Lambert law for absorbance. It was determined that the films did not present any emissions. In conclusion, the pigment exhibited an optical bandgap of ~1.3 eV, close to planar structure, and intra- and intermolecular hydrogen bonding yield in ambipolar charge carriers constitute favourable characteristics for this pigment to be used in semiconductor circuits. Based on these findings, the study suggests that the indigoidine pigment synthesized from *Escherichia coli* has potential as an organic semiconductor. Its optical bandgap and favourable structural characteristics make it a promising candidate for use in semiconductor circuits. The study also notes that further research is needed to fully understand the potential applications of this pigment in the field of electronics [21].

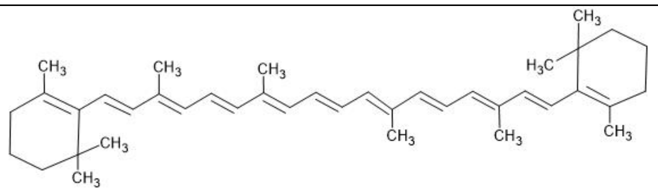
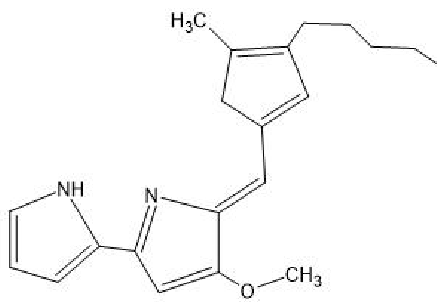
DYEING APPLICATION AND RESULTS

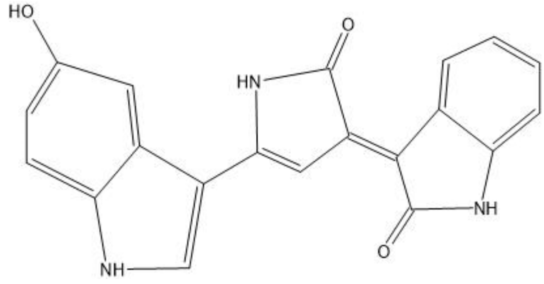
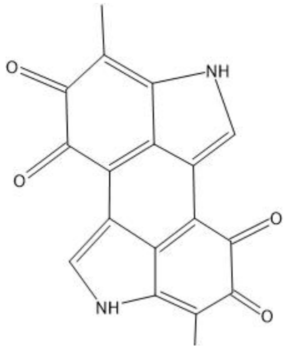
As previously mentioned by Venil et. Al, the pigments can be obtained in a variety of ways, including being naturally released during a fermentation process or by extracting them from the bacterial mycelia using a solvent, such as acetone, by filtering the mycelia [7].

However, utilizing these natural pigments in textile production can present certain challenges. One such challenge is the scale-up of extraction processes, as well as the resistance of the colour when exposed to daily factors such as washes and light. The necessary machinery may not be common in textile production lines, but this issue can be addressed by the installation of fermentation tanks, which are commonly found in other industries that rely on the use of bacteria. Additionally, researchers have found that the use of different auxiliaries such as mordants and enzymes can improve the colour fastness of the pigments [7,40,41].

Despite these challenges, many investigators have successfully applied these pigments in textile colouring processes. Microorganisms can produce a wide range of pigments, such as anthraquinone, carotenoid, violacein, melanin, pyocyanin, and prodiginine (Table 1). This chapter has highlighted some of the most commonly used pigments in textile colouring. Additionally, a group of investigators reviewed a specific type of bacterial pigment found in cold-adapted microorganisms, which consume pigmented substances to perform photosynthesis and release them as a protective mechanism against extremely low temperatures and other environmental factors. A variety of pigments were found in this study, including carotenoids, prodigiosins, melanin, violacin, indigoidine, and scytonemin [42].

Table 1. Pigment group structures and some microorganism species where they can be found

Pigment Group	Structure	Species
Carotenoid		*Metabacillus idriensis, Planococcus sp.TRC1* [34,35]
Prodigiosin		*Staphylococcus aureus, Serratia marcenscens, Serratia rubidaea* [35,43,44]

Pigment Group	Structure	Species
Violacein		*Janthinobacterium lividum, Chrmobacterium violaceum* [52,53]
Melanin		*Streptomyces glaucescens, Streptomyces* [56,57]

Prodigiosin

Prodigiosin is a group of red-coloured pigments that have been extensively studied due to their unique colours and special properties [43].

In 2021, a study by Ren et Al. aimed to develop an environmentally friendly method for extracting prodigiosins from liquid fermentation. Different surfactant fermentation systems were used to extract the pigments from the interior of the thalli to the exterior. Pigments extracted from *Serratia marcenscens* and *Staphylococcus aureus* were applied in high concentration to the fabric in an infrared dyeing machine, with a bath ratio of 1:20. The temperature was analyzed and it was concluded that under 80 °C the red dye couldn't penetrate the fibre. The most intense hue was obtained when dyeing at 100 °C. The pH of the dye bath was also carefully studied, as it can influence the intensity and the hue of the sample. An increase in dye bath pH was found to soften colour depth, with 2.8 being the ideal pH for maximum intensity. The results showed that nonionic surfactants were more effective than anionic surfactants, with a maximum transfer ratio of 94.3% when Tween 80 was used at a concentration of 18 g/L. This method allowed for the efficient extraction of prodigiosins without the use of organic solvents. The prepared prodigiosins suspension was used as a natural dye for acrylic fabric dyeing and a cationic dyeing technology based on a nano-suspension system was developed, resulting in deep colour and antibacterial functionality for the acrylic fabric [44].

In a study by Chauhan et al., a red biochrome was isolated from *Serratia* sp. and tested on cotton and wool as a natural dye. They found that it was possible to obtain a colour with a high K/S value on both fabrics. For optimal dye uptake, samples were dyed at 50 °C, for 50 minutes, with a 4.3 g/L dye concentration. The bath ratio was 1:20. Fastness results showed that acceptable washing and light fastness were obtained when mordent treatments were applied. Specifically, the colour change rate was evaluated at 18.1 K/S for cotton and 5.9 K/S for wool for washing fastness, 13.4 K/S for cotton, and 4.4 K/S for wool for light fastness [45].

A study published in 2021 focused on the extraction of prodigiosin from the marine species *Serratia rubidaea* RAM_Alex from bivalve molluscs, as well as its application of cotton samples with a variety of structures (linen, baft, gabardine, and jersey), as well as synthetic fabrics (chiffon, satin, Dacron, and polyester). 1 g of fabric was dyed with 40 mL of the extract at 80-90 °C for 1 h. It is important to mention that for this study, the fabric was post-mordanted with several different mordants. Those being $FeSO_4$, $CuSO_4$, $NaHCO_3$ and lemon. The use of baking soda and lemon juice as mordants can cause different colour shades, as the alkalinity of baking soda and the acidity of lemon juice affects the final colour. The selection of mordant type and concentration is crucial in textile dyeing as it can change the final colour of the dyed sample. The group found that Copper sulfate was the most effective mordant for this pigment, which was applied at 60 °C for 20 minutes. It states that synthetic fabrics (chiffon, satin, Dacron, and polyester) have a higher affinity to the dye prodigiosin compared to cotton fabrics (linen, baft, gabardine, and jersey) due to the dye molecule's inability to form a hydrogen bond with the cellulose molecule. Light fastness and wash fastness were tested. The results for the first test were considered “very good” for satin and chiffon samples, and “poor” for linen, baft, gabardine, Dacron, polyester, and jersey. When it comes to washing fastness, it was considered “excellent” for every sample. These observations support the idea that natural pigments like prodigiosin are less stable in light compared to synthetic pigments. When it comes o the results obtained in the washing fastness test, the tendency of the dye to wash out is decreased as the fibre has better interaction strength with the dye. The most intense hue was seen on the chiffon sample [35].

Figure 1. Samples dyed with *Serratia rubidaea* RAM_Alex [30]

These results support the idea that natural pigments like prodigiosin can be used in textile dyeing, but their application and stability must be carefully considered.

Carotenoid

Carotenoids are a group of pigments that are capable of producing a wide range of colours, including shades of red, orange, and yellow [46]. They are one of the most commonly found pigments in nature and have been used in a variety of industries for many years, including the textile industry.

A study by Majumdar et. al explored the production of a carotenoid pigment by a bacteria isolated from paper mill effluents. This study aims to use the "waste treats waste" strategy for the bioremediation of paper mill effluent in a fluidized bed reactor (FBR) using paper mill sludge (PMS) as an immobilizing matrix for *Planococcus sp*. TRC1, a wastewater bacterial isolate. The study also explores this isolate for the yellowish-orange pigment it produces and characterizes it as a member of the pharmacologically important carotenoid pigment family. The antioxidant potential of this pigment was studied. In FBR, the PMS immobilized bacteria showed high removal of phenol, lignin, colour, and COD from the effluent after 60hr of treatment. The study also showed that PMS can be used as an immobilization matrix in an eco-friendly and economical way for paper pulp mill effluent treatment along with the production of carotenoid pigment from this potential bacterial isolate as a value-added product [47].

Another study by Gurkok shows the extraction of an orange pigment from the species *Metabacillus idrensis* LipT27 and its application as a textile dye on cotton fabric. The fabric was immersed in the pigment solution at 50 °C, for 30 minutes. It was then mordanted with a thiourea solution for 30 minutes, at 45 °C. After being washed, the samples had a brownish-yellow colouration. Although the study did not evaluate the fastness or K/S of the samples, the obtained hue was visibly intense [48].

Violacein

This violet pigment has been used in several industries for its exceptional properties [49,50]. In recent years, researchers have attempted to introduce it to the dyeing industry. A study from 2000 explored the use of this pigment as a textile colourant, having it isolated from *Janthinobacterium lividum* and applied to a variety of fibres, including natural fibres such as silk, cotton, and wool, as well as synthetic fibres like polyester, acrylic, acetate, vinylon, and nylon. The microorganism responsible for the colour change was discovered when a piece of silk thread waste began to exhibit a blueish-purple tone after being wet for an extended period. The team meticulously studied the change in colour until the responsible microorganism was found and applied to other materials for the study. Different hues could be obtained by altering the culture medium and temperature. The ideal medium was found to be a semi-synthetic potato agar medium since it was able to produce the most pigment. The ideal growth temperature was found to be 25 °C, where the maximum amount of pigment was produced. The pigment was extracted at different temperatures and this was also the one responsible for the most intense color. The optimal strain, S-9601, was isolated as it produced the highest amount of pigment. For the dyeing process, the team experimented with two methods: involved dyeing the samples with the extract solution, where the dry pigment was dissolved in organic solvents such as methanol, acetone, ethyl acetate, and ethanol, and the fabric was immersed in the solution; the second method involved boiling the bacterial cells with water and dipping the samples in the solution for 20 minutes. After testing for fastness, the method didn’t seem to influence dye uptake. A comparison of the different fibres showed that polyester and acrylic samples were barely tinted and rayon also resulted in a very light shade. On the other hand, Nylon was described as “the easiest to dye”, followed by vinylon, acetate, raw silk, cotton, and wool. In what concerns colour fastness, only silk was analysed, reaching satisfactory levels. When it comes to staining, dry and wet rubbing fastness was evaluated as a 5, alkaline sweat fastness as a 3, acidic sweat and hot water fastness as 3-4, washing fastness as a 2, and light fastness as a 1. On fading, dry rubbing fastness was classified as a level 3, while wet rubbing fastness was viewed as a 2-3, alkaline and acidic sweat fastness reached level 3 and 3-4, respectively, hot water fastness was able to reach a level 4, and washing fastness was classified as 2-3 [50]. Results from this study constituted a great base for the investigation of violacein bacterial pigments, so it could later be picked up by other investigators and deeply explored.

A more recent study by Venil et al. focused on the application of a pigment extracted from *Chrmobacterium violaceum* on several fabrics, namely pure cotton, pure silk, pure rayon, rayon jacquard, silk satin, cotton, and polyester. Every sample was post-mordanted with alum, ferric sulfate, copper sulfate, sodium silicate, and slaked lime but alum produced the best results. This means that this mordant brought out samples with higher fastness levels than other mordants but it is still important to mention that the natural mordant (slake lime) was able to produce the most intense shades for cotton and silk satin. The dyeing process resulted in a unique palette of blue and violet hues. Cotton and silk satin seemed to be the samples with better fastness results, ranging from 1 (light fastness) to 5 (perspiration and water fastness) for cotton and ranging from 2 (light fastness) to 4/5 (rubbing fastness, perspiration fastness, and water fastness) for silk satin. These results were then compared to a reactive dye where fastness levels were very similar [51].

A more recent study focused on the application of this pigment on polyamide 6.6 fabric. The colourant was extracted from the species *Janthinobacterium lividum* and it was applied to the samples in different processes. The most effective process seemed to be based on simultaneous fermentation and dyeing, where the fabrics were incubated with the microorganism culture under ideal growth conditions. This method produced a very intense purple shade, with the highest colour change (ΔE) as well as the strongest colour (highest K/S). When it comes to colour fastness, it was considered excellent for acid perspiration, alkaline perspiration, and washing fastness tests, where it obtained a level 5. Light fastness was considered poor [52]. Several other authors have published about the successful use of violacein as a textile dye [53].

Melanin

Melanins are usually brown or black colored pigments but yellow and red melanins have also been mentioned in literature [62]. A team of investigators published, in 2021, their work about the production of a melanin pigment from the species *Streptomyces glaucescens* and *Escherichia coli* BL21 (DE3). To that culture solution, was added caffeic-acid to produce the desired pigment. The melanin was then used to dye cotton fibres in six methods. The first method consisted of simply dyeing the samples with melanin, the second one consisted of adding copper ions to the culture solution, the third one consisted of adding copper ions during the dyeing process, the fourth one consisted of treating the pigment with laccase enzyme, the fifth one consisted of double dyeing without any treatment, and the last one consisted of double dyeing cycles with a laccase treatment during the dyeing process. The sample that resulted from the fourth method, where laccase enzyme was used, had the highest resistance to washing, maintaining 90.6% of its colour. For comparison, the sample obtained from the first method kept less than 40% of its original colour after washing [55].

Another group of investigators collected this brown pigment from the species *Streptomyces* and applied it to wool dyeing and printing. The dye was applied to the wool fabrics without mordanting. The dye bath contained 1 g/L of an amphoteric levelling agent, which ensures a slow and even rate of absorption. The dyeing temperature started at 50 °C, for ten minutes, and it was then raised to 100

°C, for 45 minutes. In the end, it was lowered to 60 °C and the samples were rinsed and washed. By varying factors like pH, age, and incubation period, the team was able to obtain 10 different hues, ranging from light brown to yellow-brown, dark brown, and red-brown. K/S was the highest when the initial pH was 6, resulting in a dark brown sample. Wash fastness, alkaline perspiration, acid perspiration fastness, and light fastness were tested and the results of the samples were evaluated between levels 3 and 5 [56].

Indigoidine

Indigoidine is a natural product produced by bacteria that possesses antioxidant and antimicrobial properties. Its bright blue hue is similar to the industrial dye indigo, making it a potential natural alternative for use in the textile industry [57].

Additionally, Ghiffary et al. also studied the production of a natural blue pigment and its application to cotton dyeing. The colourant was produced by *Corynebacterium glutamicum* and improved by increasing glucose uptake, therefore minimizing the formation of by-products and increasing pigment production yield. The improved pigment was then used to dye cotton and compared to an indigo dye and a synthetic dye (Brilliant Blue FCF). K/S values suggested that the indigoidine pigment could be as stable and as intense as the indigo dye [58].

CONCLUSION

Synthetic dyes are known to have adverse effects on the environment due to their toxicity and non-biodegradability, which can lead to water and soil pollution. In contrast, natural dyes have the advantage of being biodegradable and easily accessible, and pigments extracted from microorganisms have demonstrated technological and therapeutic potential. Microorganisms can be sourced from agricultural waste, which can further reduce the environmental impact of production.

Additionally, bacterial pigments can be used to functionalize textile materials with new therapeutic properties. The antifungal and anti-inflammatory properties of bacterial pigments have been extensively studied, with promising results. Bacterial pigments can also be used as semiconductors and applied to electronics, which further increases their potential. However, there are still challenges to the use of natural pigments in textile production, such as scaling up extraction processes and ensuring colourfastness. The use of auxiliaries such as mordants and enzymes can help improve colourfastness, and fermentation tanks can be installed to address the lack of necessary machinery. Overall, bacterial pigments have great potential in the textile industry as a sustainable and innovative approach to textile production. Further research and development in this field can lead to the creation of "green dyes" that offer no concerns related to disposal, reduce the use of toxic materials, and have potential health benefits. This can contribute to the sustainable development of the textile industry and promote an eco-friendlier approach to textile production.

FUTURE PERSPECTIVES

Pigments obtained from bacteria might represent a big change in the future of the dyeing industry. These are easily available and very interesting from an economic and ecological point of view. The different achievable tones and the special characteristics of these colourants can make a difference in garment making and areas like medicine and biomedical research.

Future perspectives for bacterial pigments in the textile industry might include:

1. Development of more efficient and sustainable methods for extracting and purifying bacterial pigments for use as natural dyes.
2. Exploration of new bacterial species and strains for the production of pigments with unique colour properties.
3. Investigation of the potential for using bacterial pigments as functional dyes, with properties such as UV protection, antimicrobial activity, and others.
4. Research into the use of bacterial pigments in the production of bio-based and biodegradable textiles.
5. Development of new dyeing techniques that can be used to produce textiles with unique patterns, designs, and finishes.
6. Development of new methods for incorporating bacterial pigments into textile fibres during the spinning process, which could lead to the production of pigmented textiles that do not require dyeing.
7. Research on the environmental impact of bacterial pigments, to minimize any negative effects associated with their use in textile production.

Overall, there are many exciting opportunities for the future use of bacterial pigments in the textile industry, as research continues to develop new methods for extracting, purifying, and using these pigments to create sustainable, functional, and visually appealing textiles.

Author Contributions

Conceptualization – Gomes M and Soares G; methodology – Gomes M and Soares G; formal analysis – Gomes M and Soares G; investigation – Gomes M and Soares G; writing-original draft preparation – Gomes M and Soares G; writing-review and editing – Soares G; visualization – Soares G; supervision – Soares G. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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