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DYEING AND TEXTILE FUNCTIONALIZATION WITH MICROBIAL PIGMENTS

TINGIMENTO E FUNCIONALIZAÇÃO DE TECIDOS COM PIGMENTOS MICROBIANOS

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Abstract

Over the decades, the interest of textile functionalization using microbial bioactives molecules has increased due to the demand for innovative and sustainable materials. Bioactive microbial pigments (biopigments) may attribute several functional properties to textile fibers. These properties include antimicrobial activity, UV protection and anti-odor. This systematic review enumerates the objective, evidence, and perspectives regarding the use of biopigments in documents published between 2015 and 2025. Three large scientific databases were used, and 137 documents were recovered, of which 6 matched the inclusion criteria. There was little material found, but an emerging literature exists, possibly encouraged by the demands of the in and post-covid-19 pandemic years. The studies showed how biopigments may have a positive impact on the functionalization of textiles, particularly natural fibers, through advanced dyeing and active ingredient incorporation technologies. The most assessed biopigment was prodigiosin, given its stability, several bioactive properties, and the vibrant and solid colors obtained. Few microorganisms have been studied, and many challenges need to be overcome for biopigments to be commercially competitive.

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keywords: natural textile fibers; synthetic textile; prodigiosin; sustainability.

Resumo

Ao longo das décadas, o interesse pela funcionalização de tecidos utilizando moléculas bioativas microbianas aumentou como demanda por materiais inovadores e sustentáveis. Pigmentos microbianos bioativos (biopigmentos) podem atribuir diversas propriedades funcionais às fibras têxteis. Essas propriedades incluem atividade antimicrobiana, proteção UV e antiodor. Esta revisão sistemática enumera o objetivo, as evidências e as perspectivas sobre o uso de biopigmentos em documentos publicados entre 2015 e 2025. Três grandes bases de dados científicos foram utilizadas e 137 documentos foram recuperados, dos quais 6 atenderam aos critérios de inclusão. Pouco material foi encontrado, mas existe uma literatura emergente, possivelmente incentivada pelas demandas dos anos pré e pós-pandemia de covid-19. Os estudos mostraram como os biopigmentos podem ter um impacto positivo na funcionalização de fibras, particularmente naturais, por meio de tecnologias avançadas de tingimento e incorporação dos ingredientes ativos. O biopigmento mais avaliado foi prodigiosina, dada sua estabilidade, diversas propriedades bioativas e as cores vibrantes e sólidas obtidas. Poucos microrganismos foram estudados e muitos desafios precisam ser superados para que os biopigmentos sejam comercialmente competitivos.
Palavras-chave: fibras têxteis naturais; fibras têxteis sintéticas, prodigiosina, sustentabilidade.

1. Introduction

The textile industry is valued at trillions of dollars and grew fivefold between 1975 and 2020 (Quintana et al., 2024). Even though it has extraordinary numbers, the textile industry also has negative records. It is the third largest environmental polluter in the world, behind agriculture (2nd) and the oil industry (1st) (Umesh et al., 2023). Textile fiber dyeing and treatment processes are responsible for around 20% of water contamination (Rafiq et al., 2021) and 10% of all CO_2 emissions (Garg and Bhardwaj, 2023). Several factors contribute to this: the nature of raw materials used, the supply chain, the diverse range of products, short fashion lifecycles (fast fashion) and the generation of fashion waste.

On the other hand, modern society demands sustainable and eco-friendly fibers that are comfortable and add value through their multifunctionality (Cortese et al., 2013). Textile fibers are a broad term for different types of materials used to produce textile structures, particularly fabrics (Chang et al., 2020). Fibers are

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classified as natural (plant, animal or mineral, for example cotton, linen, jute, silk, wool, satin and asbestos); and man-made fibers (regenerated fibers, synthetic polymers and inorganic fibers, such as viscose, polyester, polyamide, elastane and glass) (Gonzalez et al., 2023).

Modifications of fiber surface enable adaptation of the cloth to specific functions. These changes include the incorporation of bio-based molecules in the functionalization of fabrics (Mahltig et al., 2017). Products with great sustainable appeal like natural dyes are essential for the customers. For example, microbe-based pigments exhibit bioactive properties, are easy to obtain and exhibit a wide range of colors (Usman et al., 2017). In addition to dyeing, biopigments can also serve as antimicrobial (Kramar and Kostic, 2022), anti-odor (Huong and Thinh, 2019) or UV protection (Wu et al., 2023).

Vivid and luminous colors can be obtained by optimizing the dyeing processes with biopigments under acid or basic conditions, for example, pyocyanin (DeBritto et al., 2020) and prodigiosin (Venil et al., 2021), respectively. In addition, prodigiosins comprise one of the most investigated groups of biopigments, given their thermal stability, vivid red color, and antimicrobial properties (Zhang et al., 2024). This systematic review provides a summary of the interest in biopigments over the last 10 years and identifies trends and perspectives regarding their use in the functionalization of textile fibers.

2. Research Methodology

The study was designed according to the guidelines for the preparation of systematic reviews and meta-analysis of the Brazilian Ministry of Health (2012). Three online libraries of scientific literature were consulted: MEDLINE® (Medical Literature Analysis and Retrieval System Online, NLM, USA), ScienceDirect (Elsevier, Netherlands) and Portal de Periódicos CAPES (Brazilian Federal Agency for Support and Evaluation of Graduate Education).

The search took place in December 2024, aiming to select studies on the use of microbial pigments that enable new functionalities for textile fibers in addition to dyeing them. The keywords used were “dye”, “textile”, “microbial pigment”, and “fiber”. Only original articles, published in English, free full access, and published between January 2015 and January 2025, available at the time of the search, were

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considered. The documents were analyzed by excluding original articles that were repeated, as well as reviews, overviews, mini-reviews, technical notes, books, chapters, theses and original articles with only the abstracts available.

The country of study of these works was considered as the address of the corresponding author's institution. In addition, the documents were separated by the producing microbe and the type of fiber and biopigment.

3. Results and Discussion

As illustrated in Figure 1, the search retrieved 137 documents in the database consulted: 8 in MEDLINE®; 98 in ScienceDirect; and 31 in the Portal de Periódicos CAPES. After scanning and applying the exclusion criteria, the number of documents was reduced to 6. All documents were published between 2020 and 2024, carried out in institutions in China (3), followed by India (2); Chile (1) and Egypt (1).

The studies investigated only four type-strains of four microbial species (3 bacteria and 1 yeast). Three classes of biopigments (prodigiosins, pyocyanin and astaxanthin) were researched. Prodigiosins produced by *Serratia marcescens* ATCC 8100 were the most studied biopigment. However, there was only one study that evaluated the production of prodigiosin by a second species of *Serratia*. Apart from producing solid colors, most in shades of red, four *in vitro* promising functionalities were tested, namely: antimicrobial and antioxidant activities; increased hydrophobicity of the fiber surface; and UVA and UVB protection. Additionally, twelve textile fibers were evaluated (natural and man-made), with a predominance of cotton.

Figure 1. Diagram of selection of documents on the use of biopigments in the functionalization of textile fibers.

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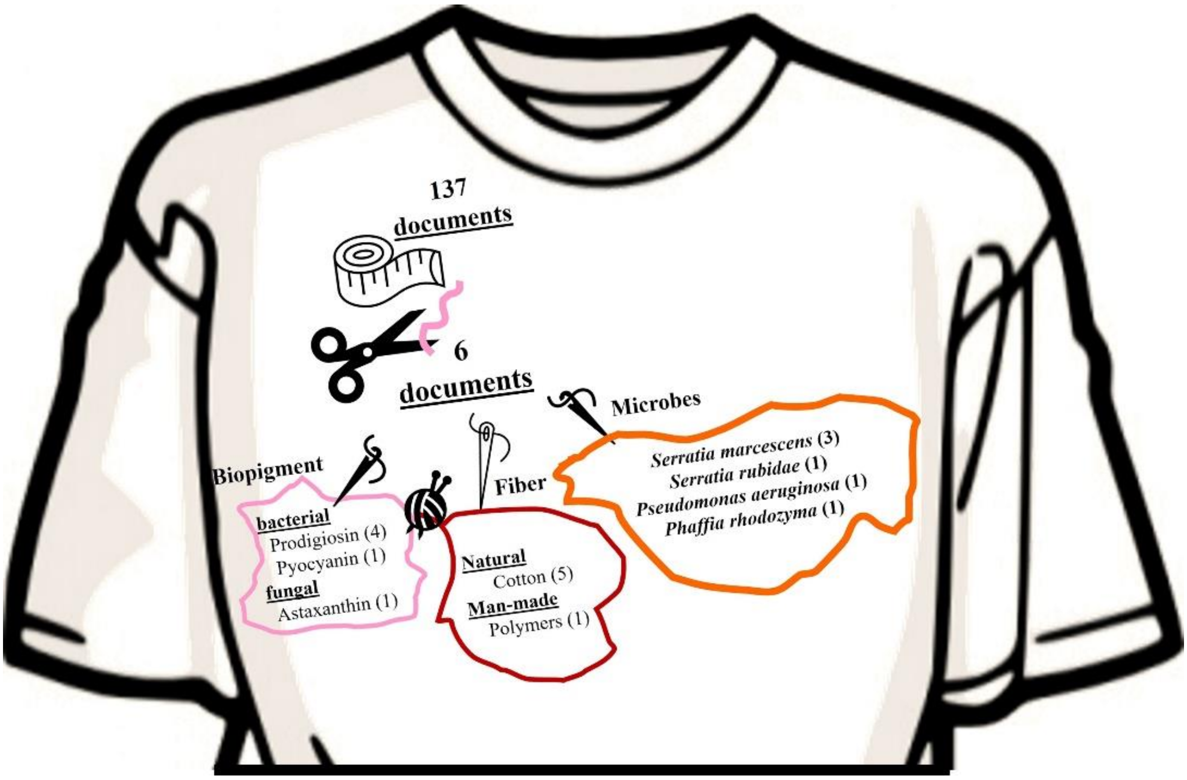

Source: Prepared by the authors.

Textile production is one of the oldest and most important practices of mankind. In the 19th century, it underwent significant advances that allowed true revolutions in the 20th and 21st centuries (Nadi et al., 2018). Given this, the concern for a sustainable world has produced market opportunities and the reintroduction of natural pigments, particularly microbe-based as potential substitutes for the dangerous and environmental polluter synthetic dyes (Mouro et al., 2023).

In addition, the bioactive properties of many microbial pigments can be incorporated into textile materials, transforming them into technical fabrics, and imposing the marketing concept of sustainability in all its four aspects: business, product, user and society (Kulsum, 2020). The functionality of textile materials has been achieved through different technologies such as nanotechnology and sol gel that produce changes on the surface of the fibers. Table 1 summarizes the main findings of the literature.

Table 1. Studies on the functionalization of textile fibers with biopigments.

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Biopigment	Fiber	Method	Results
 (DeBritto et al., 2020)	Cotton	Exhaustion dyeing Mordant: not informed	*Pseudomonas aeruginosa* KU_BIO2 produced 1,702 µg.mL^{-1} of pyocyanin in nutrient broth amended with sweet potato. Dyeing produced vivid shades of pink resistant to water and heat.
 Ren et al. (2021)	Acrilic fabric	Cationic nano-suspension system Mordant: not informed	226 mg.L^{-1} of prodigiosin was produced by *Serratia marcescens* ATCC 8100. The dyed fabric showed deep color (K/S 13.59) and antibacterial functionality against *S. aureus* ATCC 6538 (81.8%).
 Metwally et al. (2021)	Cotton, linen, baft, gabardine, jersey, chiffon, satin, dacron and polyester	Immersion dyeing Mordants: lemon juice, baking soda, $FeSO_4$, $CuSO_4$ and $NaHCO_3$	For hospital applications and compared to natural fibers, the synthetic samples, particularly chiffon, had higher affinity for prodiogiosin produced by *Serratia rubidaea* RAM_Alex. Several mordants produced different shades; $CuSO_4$ was the most effective. The dyed fabrics exhibited resistance to light and water. Antibacterial functionalities were observed against *E. coli* ATCC 8739 and *S. aureus* ATCC 25923.
 Mussagy et al. (2022)	Cotton	Immersion dyeing Mordant: $CuSO_4$	There was maximum production of 503.66 µg.g^{-1} of astaxanthin by the yeast *Phaffia rhodozyma* NRRL Y-17268. It produced solid colors in three types of cotton fibers with different thicknesses. *In vitro* studies demonstrated antioxidant functionality.
  Zhang et al. (2024)	Cotton	nano-suspension system Mordants: $Al_2(SO_4)_3$, $Fe_2(SO_4)_3$, and $CuSO_4$	For use in baby clothes, prodigiosins produced by *S. marcescens* ATCC 8100, resulting in soft colors (red-purple to yellow with a single pigment), with uniformity and resistance to fading. Compared to the immersion method, continuous dyeing with prodigiosin nano-suspension had significant advantages: 160% increase in pigment utilization, 80% reduction in dyeing time and 97.8% saving of dye liquid. The functionalities demonstrated with promising results were UV protection, antibacterial effect against *S. aureus* ATCC 6538 and increase of surface hydrophobicity

 Zheng et al (2024)	Cotton/ polyamide 70:30 and cotton/ polyester 61:39	Infrared dyeing Mordant: not informed	A highly stable suspension of prodigiosin synthesized by *S. marcescens* ATCC 8100 was used to dye two mixed fabrics. The synthetic fibers (polyester and polyamide) obtained bright and uniform color. Natural fibers (cotton) provided lighter color. There was high activity against *S. aureus* ATCC 6538 (97.31%: cotton/polyamide and 89.70%: cotton/polyester); ultraviolet protection factor reached 52.3 (UVA) and 93.5 (UVB).

Source: Prepared by the authors

The impregnation of biopigments occurs through different types of chemical bonds, and the best results can be obtained through covalent bonds between the pigment and the reactive groups of the fiber (Nadi et al., 2018). The result is a broad spectrum of functionalities (smart clothing), such as fabrics with odor control, water repellency, heat stability, antimicrobial, UV protection, polychromy, luminosity, low-temperature clothing and anti-stain properties (Zhang et al., 2024). Functionalized textiles, however, may have multiple applications beyond fashion, such as in agriculture, construction, sports, packaging, decoration, drug delivery, wound dressing, pollution adsorbents, oil-in-water absorbents, chemical protection and extreme wetting fibers (Ghosh et al., 2025).

Prodigiosins represent the class of biopigments that play a crucial role in the textile industry (Sundararajan and Ramasamy, 2024). Prodigiosins belong to a family of vibrant red alkaloids, synthesized by *Serratia* spp. and Actinobacteria, whose molecules have a characteristic linear tripyrrole chemical structure (Islan et al., 2022). In addition to exhibiting bioactive properties, the obtention of prodigiosin is simple, and it produces attractive colors and adds high durability to a fabric (Mussagy et al., 2022).

The findings of this study support viable and sustainable solutions for the use of biopigments in the textile sector. There are, however, important gaps, such as the lack of studies that evaluate the economic viability and scalability of industrial processes. Ironically, although the authors of all the selected documents highlighted the need for natural products to protect the environment, half of them

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did not mention the type of mordant used in the dyeing process. The other half of the authors used common inorganic mordants in the textile industry, such as copper sulfate. This molecule is known as one of the best mordants, responsible for producing deep tones (Zubairu and Mshelia, 2015); copper, however, is associated with health and environmental risks (Fagnano et al., 2020).

Interestingly, within the ten-year period investigated, the eligibility profile of the documents included works published both during and after the covid-19 pandemic. The pandemic caused by SARS-CoV-2 was the first major challenge to society in the first quarter of the 21st century and caused significant social changes (Khurana, 2022). The increasing number of studies on functionality of textile fibers with biopigments may reflect this moment. It is known that the lockdown increased society's concern with outdoor activities. The concern for safe environmental exposure became a characteristic of the generation that lived through the pandemic (Min et al., 2024).

Extending life span, adding value and giving a second or multiple functions to textile materials appears to be the future of biopigments. The production of smart clothing is gaining market acceptance, driven by global demand for more sustainable processes, stricter environmental regulations and consumer interest in environmentally responsible products. However, the consolidation of the sector faces many challenges, such as low production scalability, high costs compared to conventional dyes and the instability of some colors. Aggressive investment in research would help the textile industry face the limited technical and economic challenges present today.

4. Conclusion

Microbial biopigments are the subject of increasing research, in which advanced technologies are applied to offer an innovative and environmentally sustainable alternative for the textile industry. The number of studies is still limited; however, they have been on the increase since the covid-19 pandemic. In addition, there has been little exploration of microbial genetic heritage suggesting that studies with new biopigment-producing species should be encouraged. In addition, the adaptation of existing tools as well as the development of new technologies may soon overcome the current obstacles for biopigments to become commercially competitive.

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