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A Review on The Antimicrobial Properties of Bacterial Metabolites from *Serratia* spp. as Dye Material on Textile

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ABSTRACT. Synthetic dyes have long dominated industries for their cost-effectiveness, yet their environmental and health impacts are concerning. In response, natural dyes, particularly those from microbial sources are gaining attention for their eco-friendly and biodegradable properties, including unique bioactive features like antimicrobial activity. Therefore, microbial dyes such as prodigiosin from *Serratia* spp. is one of the alternatives to replace synthetic dyes. Despite its potential, the small extraction yield of prodigiosin limits its application in the textile industry. Moreover, *Serratia* spp. are found in diverse environments, yet the antimicrobial properties of prodigiosin for textile dyeing are less reported. Thus, the antimicrobial properties during human contact with various textiles are required to be reviewed. This review explores *Serratia* spp. as a promising microbial source for textile dyeing applications specifically focusing on producing prodigiosin pigment in mass production and its antimicrobial properties. Key questions revolve around *Serratia*'s ability to produce natural pigment, its benefits on textiles, and its antimicrobial properties. Recent studies indicate that optimizing bioprocess conditions and using effective substrates can significantly increase prodigiosin yields. High yields were achieved using improved bioprocess conditions in bioreactors, the one-factor-at-a-time (OFAT) approach, and the Box-Behnken design (BBD) for optimizing fermentation medium conditions. Prodigiosin exhibits strong antimicrobial activity, effectively inhibiting bacteria and fungi, making it a viable eco-friendly alternative to synthetic dyes in the textile industry. Notably, prodigiosin-dyed fabrics can inhibit harmful bacteria like *Staphylococcus aureus*, suggesting potential uses in hospital textiles and skin health applications. Further research on allergenicity and toxicity is needed to ensure safety.

Key words: Serratia spp., microbial dye, prodigiosin, antimicrobial activity, textile application

INTRODUCTION

Natural dyes or pigments from plants and animals have been used as colorants in the textile industry for a long time which is until the mid-18th century (Lellis et al., 2019). However, it has not been everlasting since synthetic dyes developed during the Industrial Revolution. Synthetic dyes such as lead, chromium, copper, sodium chloride or benzene have been gradually replacing natural ones due to their affordability, stability, ease of use in producing a wide range of color shades, resistance to light, pH changes as well as oxygen and have potential applications in many industries (Olas et al., 2021, Soni et al., 2021).

As a result, synthetic dyes overtook natural dyes by the 19th century and kept dominating the market despite their hazardous and negative effects on both living organisms and the environment. Furthermore, Ardila-Leal et al. (2021)

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stated that the discharge of untreated dye effluents during the dyeing process leads to water pollution since synthetic dyes contain toxic chemicals that can harm aquatic ecosystems and pose a threat to the health of marine life. Accumulation of synthetic dyes can form harmful aromatic complexes that result in mutations by reacting with several byproducts of effluent (Olas et al., 2021).

A study by Khan et al. (2019) shows when synthetic dyes are exposed to living organisms in higher concentrations, it has genotoxic, cytotoxic, and mutagenic properties. Moreover, when exposed to a variety of biotic and abiotic factors, synthetic dyes can result in DNA breakage, allergies, skin rashes, and organ malfunctions because they produce toxic breakdown products. Nowadays, a wide range of chemicals including synthetic, semi-synthetic, and natural ones are useful for textile antimicrobial finishing. Some synthetic antimicrobial agents commonly used in textile finishing are quaternary ammonium compounds, triclosan, and polyhexamethylene biguanide. Nonetheless, even if it enhances the defense against microorganisms, it can be harmful to the environment (Kamboj et al., 2021).

However, since the natural dyes are produced in small amounts, several methods are utilized to extract the dyes in larger amounts such as aqueous extraction, acid and alkali extraction, ultrasonic microwave extraction (sonication), fermentation, and solvent extraction. In the textile industry, sonication, fermentation, and solvent extraction are usually used (Gupta, 2019). A study by Padhan et al. (2021) shows the pink pigment of *Paenibacillus* sp. BPW19 which has been cultured in the bioreactor was successfully extracted by sonication after dissolved in 100% methanol (v/v). A study from Venil et al. (2021) also indicates red pigment by *S. marcescens* SB08 was successfully extracted by dissolving and filtering assisted with 95% methanol (v/v). Moreover, Ragab et al. (2022) stated that sonication and solvent extraction can extract a higher yield of pigment compared to the traditional way, aqueous extraction. Venil et al. (2021) extracted prodigiosin from *S. marcescens* and investigated the dyeing potential as well as the antimicrobial effect against the microbes on silk and yarns on the lab scale. Another study indicated that Metwally et al. (2021) extracted prodigiosin from *S. rubidaea* and evaluated the dyeing potential and antimicrobial activity of dyed fabrics on the lab scale too. Thus, the production of prodigiosin on an industrial scale needs to be explored.

Serratia spp. are allocated in many places such as soils, feces, water, and insects. It also can be easily found in any moist location such as bathrooms as it grows in places where phosphorous-containing fatty substances accumulate (Nazzaro, 2019; Friedrich et al., 2021). *Serratia* microbial dye is derived from pigment that is produced by the bacteria. However, the antimicrobial properties of *Serratia* spp. pigment, prodigiosin for dyeing textiles is less reported. Thus, the antimicrobial properties during human contact with various textiles are required to be reviewed. A study from Thomas et al. (2021) only indicates the pigments of *S. marcescens,* that were isolated from the soil have the potential to dye cotton clothes. This strain demonstrated their potential as pigment producers suitable for dyeing purposes but not as antimicrobial agents in textiles. Therefore, the suitability of *Serratia* microbial dye on the textile is unidentified. In addition, Ghosh et al. (2021) claim that *Serratia* spp. could produce dye with antimicrobial properties, but the antimicrobial benefit of *Serratia* microbial dye should be explored for future applications in the textile industry. Hence, this review will provide more information about *Serratia* spp. metabolite as dye material in textiles, therefore, it can be useful in the textile industry in the future. This review was carried out to review the process

for increasing the yield of prodigiosin as a substitution for synthetic dye and to discuss the effectiveness of prodigiosin from *Serratia* spp. on textiles in terms of antimicrobial activity.

SERRATIA OVERVIEW

Briefly, *Serratia* was previously in the Enterobacteriaceae family, then diverted to the Yersiniaceae family since Serratia interacted more with Yersinia species compared to Enterobacteriaceae family members. Table 2.1 indicates the classification of *Serratia* spp. *Serratia* is known as a gram-negative, rod-shaped, facultatively anaerobic, and non-spore-forming bacteria. Certain *Serratia* spp. can produce a pigment called prodigiosin as a secondary metabolite, which varies in color depending on how old the colonies are. Its color ranges from dark red to pale pink (Othman et al., 2019; Ghosh et al., 2021). Some factors such as temperature, culture time, and quorum sensing can impact prodigiosin production (Liu et al, 2021).

It also is a common inhabitant of our environments and can be found in many places like soils, feces, water, and insects (Friedrich et al., 2021). A recent study from Metwally et al. (2021) indicates that the RAM_Alex strain that can produce prodigiosin pigment was isolated from Temsah Lake in Egypt and was identified as *Serratia rubidaea* as well as its pigment able to dye in both cotton and synthetic fabrics. A study by Shete et al. (2021) also isolated *S. marcescens* from subsurface water of alcohol sterilization containers and its pigment was able to dye cotton cloth without the use of mordant. Another study by Venil et al. (2021) exhibits *S. marcescens* was successfully isolated from an insect enteric gut bacterium and its pigment has the potential to dye pure silk, China silk, and cotton efficiently.

Table 2.1 Classification of *Serratia* spp. (Friedrich et al., 2021)

Domain	**Bacteria**
Phylum	Pseudomonadota
Class	Gammaproteobacteria
Order	Enterobacterales
Family	Yersiniaceae
Genus	*Serratia*
Species	*S. marcescens*

Serratia spp. widely known as virulent pathogens as well as multi-drug resistant bacteria which will cause infections or diseases in humans, animals, and plants since it extracellular enzymes like nucleases, proteases as well as hemolysin are involved in the diseases of species-associated pathogenesis (Cooney et al., 2014 as cited in Radeva et al., 2023; Ghosh et al., 2021). A study by Schappe et al. (2020) has obtained the red bacterial ooze on the leaves, stems, and flower parts of Industrial Hemp (*Cannabis sativa*). The ooze was initially small and dark brown, then grew to create larger areas of necrosis that covered huge sections of leaves as the disease spread and eventually killed the entire plant. The researchers believe that *S. marcescens* cause the leaf spot disease after performing the identification tests and it became a concern among plants' yield as well as human health. Besides that, *S. marcescens*

is one of the most common bacterial pathogens found in patients with urinary tract infections (UTIs). The authors stated that hospitalized UTI patients' results of the analysis show that *S. marcescens* are commonly isolated from them (Radeva et al., 2023). Furthermore, Allen et al. (2022) declared that *Serratia* spp. resistance in antimicrobials fluoroquinolones, cephalosporins, aminoglycosides, and the disinfectant chlorhexidine which causes infection in animals such as dogs, horses, cats, birds, and rabbits. They also compared the *Serratia* sp. isolates nosocomial infection patients from hospitals and turns out it resists too (Allen et al., 2022). These studies indicate that *Serratia* spp. can cause serious opportunistic infections in plants, humans as well as animals.

However, there is a good side to *Serratia* spp., which is it can produce antimicrobial properties from its pigment. Therefore, the usefulness of bacterial pigments or bio-pigments has become acknowledged after researchers do some studies on various related fields. In this case, the benefits of prodigiosin pigment from *Serratia* spp. on the textile industry are emphasized.

Prodigiosin pigment

One of the prodiginines is Prodigiosin. It is a red pigment that is produced by both gram-negative and gram-positive bacteria. Several *Serratia* strains were discovered to have cell surface hydrophobicity caused by hydrophobic molecules, which has a Log partition coefficient n-water (POW) of 5.16. The prodigiosin group is a part of the tripyrrole family, which is composed of 2-2, 4-methoxy bipyrrole rings. Prodigiosin also is the product of a two-step biosynthesis process that starts with the synthesis of the mono and bipyrrole precursors as two separate units and ends with their combination.

Serratia spp. such as *S. marcescens, S. rubidaea* and *S. nematodiphila* can produce prodigiosin pigment. The pigment can be used in many industries such as food production, printing, cosmetics, pharmaceuticals, and textiles. Therefore, to utilize the prodigiosin pigment on textiles, several factors such as temperature, pH, mordant application, and types of fabrics need to be contemplated. Several studies indicate that *Serratia* spp. can produce red pigment on cotton cloth and without the application of a mordant, it demonstrated good dyeing capability after being treated with a mild detergent (Ghosh et al., 2021; Metwally et al., 2021). Although Shete et al. (2021), Syaifudin and Sutrisno (2022) and Mouro et al. (2023) claimed that the most efficient dyeing method was discovered to be simultaneous dyeing with the mordant Ferrous Sulfate ($FeSO_4$) and Cysteine (L-Cys) on cotton, wool and nylon fabrics. Amide groups in wool and nylon can interact with dyes to enhance dyeing potential (Shete et al., 2021; Syaifudin and Sutrisno, 2022; Mouro et al., 2023). Apart from that, the effect of temperature and pH was studied by Ren et al. (2021) to know how it affects dyeing on synthetic fabric. The study resulted in the higher temperature and the low pH, and the depth color penetrated and dyed on the synthetic fabric. It resulted in 100°C and 2.8 pH respectively (Ren et al., 2021).

Antimicrobial activity of prodigiosin

Textiles and clothing are known to be prone to microbial attack due to the vast surface area and absorb moisture, which both factors are essential for microbial growth (Venil et al., 2021). Nowadays, people are starting to be aware and choose a sustainable and eco-friendly lifestyle which includes their outfits, furnishing as well as bedding. According to Venil et al. (2021), the characteristics of the textile itself play an essential role in antimicrobial activity. Thus, the bio-pigment on the textile was studied by the researchers about its advantage which is antimicrobial

properties. For instance, a recent study from Sengupta and Bhowal (2022) indicates pyocyanin (blue green) pigment extracted from *Pseudomonas aeruginosa* can inhibit *E. coli, S. aureus, B. subtilis,* and *S. typhi* with 10 mm, 13 mm, 9 mm and 7 mm zone of inhibition respectively. *P. aeruginosa*'s dye also exhibits no allergic or hypersensitive reaction on human skin and has the potential as a dyeing agent on fabrics. Another study by Bisht et al. (2020) shows red pigment from *Rhonodellum psychrophilum* GL8 that was isolated from the lake has antimicrobial and antifungal activities on several pathogenic microbes such as *E. coli, S. aureus, Candida albicans,* and *Saccharomyces cerevisiae.* The red pigments extracted were also successfully developed as antimicrobial fabrics and showed no cytotoxicity. Therefore, the antimicrobial activity of prodigiosin pigment from *Serratia* spp. was discussed in this review by categories which are antibacterial activity, antifungal activity, antioxidant activity and anti-cancer activity.

Antibacterial activity of Serratia spp. dye

Previous studies indicate that pigment from *Serratia* spp. was effective against gram-positive bacteria and gram-negative bacteria such as *Staphylococcus aureus, Bacillus subtilis, Escherichia coli* and *Pseudomonas aeruginosa* on natural and synthetic fabrics by following Japanese Industrial Standard JIS L 1902:2002, Antibacterial Activity Assessment Textile Testing (AATCC) 100 and China national standard GB/T 20944.3-2008 (Shete et al., 2021; Ren et al., 2021; Metwally et al., 2021; Mouro et al., 2023; Kiruthika and Roja, 2021). According to Ren et al. (2021), the production of autolysis can be induced by prodigiosin inside *Bacillus subtilis* which causes cell lysis and death. In addition, biofilm formation of *Staphylococcus aureus* can be inhibited by butyl-meta-cycloheptyl-prodigiosin. Yip et al. (2019) have shown that prodigiosin's antibacterial properties emerge from its capacity to penetrate the outer membrane and inhibit specific enzymes like DNA gyrase and topoisomerase IV. This inhibits the growth of cells by producing reactive oxygen species (ROS) that cause damage to biological molecules (Yip et al., 2019 as cited in Mnif et al., 2022).

Moreover, a study by Metwally et al. (2021) demonstrated that prodigiosin extracted from *S. rubidaea* can inhibit *E. coli* and *S. aureus* effectively with a range of 19% to 95%, and 15% to 97% percentage of inhibition respectively on chiffon, satin, linen, dacron, and gabardine fabric by following AATCC 100. As *E. coli* is a gram-negative bacterium, prodigiosin can suppress bacteria's division and metabolic activity and lead to cell death (Metwally et al., 2021). Other than that, prodigiosin from *S. marcescens* BWL1001 can inhibit the growth of *Microcystis aeruginosa* by 91.1% algicidal activity since *Microcystis aeruginosa* can form harmful algal blooms (Liu et al., 2021). Besides, research from Jardak et al. (2022) resulted in prodigiosin's antibacterial effect against *S. aureus* and *E. coli* with minimum inhibitory concentration (MIC) of 78-156 μg/mL and 39-78 μg/mL respectively.

These studies show that the prodigiosin pigment extracted by *Serratia* spp. has the potential to inhibit the pathogenic bacteria. However, further studies should be performed on hospital textiles as pathogenic bacteria such as *E. coli* and *S. aureus* are well-known as infectious agents that occur in hospital infections (Metwally et al., 2022). This is to minimize the occurrence of infections such as respiratory infections, surgical wounds, and cross-infection. Ghosh et al. (2021) stated that the antibacterial activity performed after dyeing fabric has the potential to be used in bandages and wound dressing. Thus, *Serratia*'s dye has the potential to be studied on hospital textiles and can be used in hospital practices.

Antifungal activity of *Serratia* spp. dye

In textiles, the antifungal properties of prodigiosin can inhibit the growth of fungi, which prevents issues of mildew and decay. The mechanism behind antifungal activity involves prodigiosin disrupting the fungal cell membrane, interfering with essential cellular processes. When incorporated into textiles, prodigiosin can act as a protective barrier, inhibiting the colonization and growth of fungi that could lead to textile deterioration. Prodigiosin by *Serratia* sp. can increase permeability in fungal cell membranes that helps to occupy fungal hyphae which further inhibit fungal growth (Hazarika et al., 2021 as cited in Mnif et al., 2022). Table 2.2 below shows *Serratia* spp. that inhibits fungi growth.

A study by Kiruthika and Roja (2021) demonstrates that *Candida albicans* showed the highest zone of inhibition after being assayed with prodigiosin pigment from *S. marcescens*. Another study by Shete et al. (2021) indicates that prodigiosin pigment produced by *S. rubidaea* and *S. marcescens* able to inhibit *Aspergillus niger* growth with MIC of 4 μg/mL. Besides that, prodigiosin by *S. nematodiphila* can inhibit the growth of *Penicllium citrinum* with 11 mm of zone inhibition (Ghosh et al., 2021). Based on the reported study, the study on antifungal activity of prodigiosin pigment from *Serratia* spp. on textiles is an important factor in ensuring the effectiveness of *Serratia* microbial dye on textiles. This is due to the Malaysian weather with high humidity which is the perfect condition for fungal growth, unpleasant odor, and discoloration on the textile. To the author's knowledge, the data for prodigiosin pigment from *Serratia* spp. are still in low number, thus, more research is needed to encourage the usage of microbial dye in the textile industry.

Table 2.2. Fungi that inhibited by *Serratia* spp.

Fungi	*Serratia* species	References
Candida albicans	*S. marcescens*	Kiruthika and Roja, 2021
Aspergillus niger	*S. rubidaea, S. marcescens*	Shete *et al.*, 2021
Penicillium citrinum	*S. nematodiphila*	Ghosh *et al*., 2021

Sources: Kiruthika and Roja (2021), Shete et al. (2021), Ghosh et al. (2021)

Antioxidant activity of Serratia spp. dye

Prodigiosin produced by *Serratia* spp. has been studied for its properties. Antioxidants play a crucial role in inhibiting oxidative stress which can lead to the degradation of materials, including textiles. Changes in 2,2-Diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity (RSA) of prodigiosin extracted from *Serratia* spp. were observed at different concentrations. Results of a study by Othman *et al*. (2019) show that the antioxidant activity of prodigiosin increased gradually with increasing concentration and lower than a standard of ascorbic acid. Besides that, the DPPH and 2,2-azinobis-3-ethylbenzothiazoline-6-sulfonate (ABTS) assays were performed and completely scavenged by prodigiosin at the concentration of 10 mg/L (Arivizhivendhan et al., 2018).

Nevertheless, there is a lack of data on the antioxidant activity of prodigiosin in textiles. The antioxidant activity of prodigiosin pigment in textiles works by neutralizing free radicals and inhibiting oxidative processes. Prodigiosin acts as a potent scavenger for free radicals. Free radicals can initiate oxidative stress which causes damage to textile materials. Furthermore, oxidative reactions occur in chains, where one free radical trigger a chain of reactions leading

to damage. Prodigiosin interrupts these chain reactions by breaking the cycle. It prevents the propagation of oxidative damage within the textile material by neutralizing free radicals in the early process (Arivizhivendhan et al., 2018).

Anti-cancer activity of Serratia spp. dye

Prodigiosin pigment produced by *Serratia* spp. also exhibited anticancer properties in biological contexts, which can be applying these properties directly to textiles, however, it is not common. Cancer is a serious disease that attacks any organ in humans regardless of age. The World Health Organization stated that there were 10 million cancer-related that leading to deaths and 19 million newly diagnosed cancer cases globally in 2020 (Mnif et al., 2022).

The mechanism of anti-cancer activity of prodigiosin is attributed to its ability to induce apoptosis, the process of programmed cell death in cancer cells which acts in cell cycle inhibition, DNA cleavage as well as pH modulation (Lin et al., 2019; Jardak et al., 2022). According to Williamson et al. (2007), anti-cancer activity by prodigiosin was reported against more than 60 cancer cell lines. Probably, in recent years there are more than that. Recently, a study from Jardak et al. (2022) stated that human breast cancer cells, MCF-7 and MDA-MB231 were inhibited by prodigiosin from *Serratia* spp. with IC50 values of 16 μg/mL. Another study indicates that prodigiosin produced by *S. marcescens* QBN VTCC 910026 can inhibit human breast cell, MCF-7, oropharyngeal cancer KB, and lung cancer LU-1 strongly (Nguyen et al., 2022). The authors also demonstrated that it could inhibit tumor growth by decreasing 36.82% of tumor volume after 28 days. Furthermore, a study from Lazic et al. (2022) also shows that prodigiosin extracted from *S. marcescens* ACC 27117 able to inhibit cancer cell lines with IC50 values range 0.62 to 17.00 μg/mL and successfully induced apoptosis.

Previous studies exhibited that textiles that have anti-cancer properties could be produced by the researchers and, therefore, can prevent people from activating their cancer cells. However, further studies are required as prodigiosin's anti-cancer activity is intriguing in medical research, meanwhile, its application in textiles for anti-cancer purposes is not widely studied.

***Serratia* metabolite as a dye**

To bring sustainability to the textile industry and improve its environmental impact and safety, further studies from some researchers have been done to evaluate *Serratia*'s dye's stability and colorfastness properties. Prodigiosin is known for its vibrant red color. Nonetheless, its stability can be influenced by factors like exposure to light, atmospheric humidity, and temperature. In textiles, colorfastness refers to the ability of a fabric to retain its color over time despite exposure to environmental conditions.

Results from Metwally et al. (2021) indicate that fabrics like satin and chiffon have very good light-fastness properties after being dyed with prodigiosin extracted from *S. rubidaea* by following AATCC-16 standard methods. Meanwhile, fabrics like linen, baft, gabardine, dacron, and jersey have poor light-fast properties. These show that prodigiosin's susceptibility to fading upon exposure to light may affect its lightfastness in fabrics. Protection from exposure to sunlight or atmospheric humidity is essential to maintain the pigment's color stability (Metwally et al., 2021). Other than that, Mouro et al. (2023) demonstrated that nylon fabric that has been dyed with prodigiosin by *S. plymuthica* plus bio-mordant has very good light fastness after being exposed to black light and daylight. Moreover, results from Ren et al. (2021) also exhibit that synthetic fabric that has been dyed prodigiosin has the best color fastness and good

stability against perspiration by following GB/T 3921-2008 standard. Meanwhile, a study from Venil et al. (2021) indicates yarn that has been dyed from *S. marcescens* SB08 pigment has good color fastness to washing and rubbing but modest light fastness according to Indian Standards IS 6191-1971.

In short, colorfastness in textiles needs to be maintained by considering many factors such as light exposure, pH levels, and humidity since the prodigiosin has a naturally vibrant color. Appropriate textile treatments and careful handling could help maximize the color stability of prodigiosin in various applications, especially in textiles.

OPTIMIZATION OF FERMENTATION CONDITION OF PRODIGIOSIN BY *SERRATIA* SPP.

To let the pigment be utilized in the textile industry, a large production needs to be made. The primary focus is on the optimization processes to enhance the yield of prodigiosin produced by *Serratia* spp. which aimed at its application in the textile industry. Recent studies have identified several parameters such as temperature, substrates, revolutions per minute (rpm) that expected to lead to an increased yield of prodigiosin (Lin et al., 2019; dos Santos et al., 2021; Sun et al., 2021). However, there is no fixed temperature to get the high yield of prodigiosin, however there is a range of temperature which is 26°C-30°C. Therefore, optimizing specific fermentation parameter such as temperature will significantly increase the yield of prodigiosin from Serratia spp.

Thus, the researchers should utilize bioreactors in lab scale to test various fermentation conditions systematically by applying statistical design such as the one-factor-at-a-time (OFAT) approach and the Box-Behnken (BBD) to optimize fermentation medium conditions. The outcome will measure prodigiosin yield under different fermentation conditions and record as well as analyze variations in yield based on changes in the independent variables. Nonetheless, results may vary with different strains, and lab scale findings might need adjustments for industrial scale application.

Moreover, the researchers need to follow strict ethical guidelines, ensuring safe handling and disposal of Serratia cultures according to biosafety rules. A feasibility assessment will be checked if they have the necessary resources like bioreactors, instruments, and materials as well as will consider the costs of scaling up the process. Researchers are required to seek advice from experts in microbiology and the textile industry to improve the research plan. This approach aims to increase prodigiosin yield through better fermentation processes, supporting sustainable and eco-friendly dyeing in the textile industry.

Safety of pigmented textile by Serratia spp. on human contact

Although *Serratia* spp. is known as virulent, *Serratia*'s pigment have antimicrobial properties which have the possibility of safety on human skin. This analysis is focusing on evaluating the safety and efficacy of prodigiosin-dyes textiles. This involves testing the antimicrobial properties of the dyed textiles to ensure they effectively inhibit harmful bacteria without causing adverse reactions on human skin. Existing studies indicated that prodigiosin-dyed fabrics by *Serratia* spp. have antimicrobial properties (Venil et al., 2021; Shete et al., 2021; Ren et al., 2021; Mouro et al., 2023; Mewally et al., 2021; Kiruthika and Roja, 2021; Jardak et al., 2022). Hence, it was assumed consist of antimicrobial effects of prodigiosin and potential skin safety.

Therefore, laboratory experiments need to be conducted by the researchers to assess the antibacterial activity of the dyed textiles, ensuring they effectively inhibit harmful bacteria such as *S. aureus* and *E. coli*. Additionally, tests need to be performed to evaluate any possible skin irritation or allergenicity. Ensuring the dyed textiles are both

antimicrobial and safe for human contact will be crucial for their application in the textile industry, especially for items like hospital fabrics where infection control is essential. By confirming that prodigiosin-dyed textiles provide effective antimicrobial protection without adverse effects on the skin, we can support their use as a sustainable and eco-friendly alternative to synthetic dyes. This comprehensive approach will address any safety concerns and help establish guidelines for the commercial use of *Serratia*-derived pigments in various textile applications.

Durability and stability of prodigiosin pigment on the textile

Natural dyed textiles using pigments from *Serratia* spp. face issues like inconsistent dye quality, vulnerability to environmental conditions, poor abrasion resistance, and limited color fastness. Several studies demonstrated that prodigiosin-dyed textiles by *Serratia* spp. have color stability and color fastness after washed and rubbed (Metwally et al., 2021; Mouro et al., 2023; Ren et al., 2021). However, there is no evaluation of prodigiosin pigment's durability and stability under diverse conditions like exposure to sweat, oils, or everyday chemicals which can lead to discoloration of the textile.

Therefore, laboratory experiments of colorfastness and resilience of the pigment need to be evaluated by the researchers, ensuring it remains vibrant and effective after prolonged use. By understanding the longevity of prodigiosin-dyed textiles, their suitability for practical applications in different environments, from everyday clothing to specialized uses like outdoor fabrics can be determined. This research aims to provide insights into the durability of *Serratia*-derived pigments, supporting their potential as sustainable alternatives to synthetic dyes in the textile industry.

4.0 CONCLUSION

Despite growing interest in bio-based dyes as sustainable alternatives in the textile industry, research into antimicrobial properties of bacterial metabolites particularly those from *Serratia* spp. is still in its early stages. However, several method has succeed in increasing the yield of prodigiosin from *Serratia* spp. Technically, based on this review, the process condition are the main factor that contributed to higher yield of prodigiosin such as temperature. Moreover, Box-Behnken design (BBD) method are able to optimize the response surface of fermentation medium by reducing the loss during extraction.

Prodigiosin pigment from *Serratia* spp. is proven to have the antimicrobial and antibacterial properties. Prodigiosin are able to inhibit the formation of bacteria on the dyed textile as well as the skin that in contact to the textile. In addition, prodigiosin pigment are able to protect the dyed textile where prodigiosin improved tensile strength, elongation, abrasion resistance, crease recovery, stiffness, thickness, tear strength, and bursting properties. It is confirmed that the stability and durability of the prodigiosin-coated fabric.

To sum up, Serratia spp. can produce natural pigment, prodigiosin with significant antimicrobial activity. These properties make prodigiosin an attractive alternative to synthetic dyes which offer both aesthetic and functional benefits to the textile industry. To fully utilize these benefits, optimizing fermentation conditions for large-scale prodigiosin production is crucial for achieving consistently high yields and cost-effectiveness. Additionally, thorough studies are necessary to ensure prodigiosin-dyed textiles are safe for human skin, addressing any potential health risks. Evaluating the stability and durability of prodigiosin-dyed textiles is also essential to meet standards and

consumer expectations. This includes ensuring resistance to washing, sunlight, wear, and environmental conditions. Demonstrating that prodigiosin can provide long-lasting antimicrobial protection on textiles will further enhance its value proposition. Ultimately, resolving these research gaps is key to making *Serratia*-derived pigments commercially viable, promoting more sustainable and health-conscious practices in the textile industry.

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SUPPLEMENTARY MATERIAL

Supplementary material is available on the publisher's website along with the published article.

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