Research Article

Functional Sustainable dyeing of Traditional Tembe Nggoli Textile using Bacterial Pigments with Dual Antibacterial and Antioxidant Properties

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Abstract | Sustainable multifunctional natural dye solutions are needed due to the ecological impact of the textile industry. Therefore, this study aimed to assess the potential of pigments obtained from the anoxygenic photosynthetic bacterial *Chromatium* sp. (red-orange pigment) and *Chlorobium* sp. (dark green pigment) as functional dyes for traditional Tembe Nggoli fabrics from Bima, Indonesia. The pigments were extracted using 80% acetone, followed by testing their biological activity before and after application to fabric. The results of 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay showed that red pigment from *Chromatium* sp. had an IC_{50} of 32.544 µg/ml, while the green pigment from *Chlorobium* sp. had an IC_{50} of 41.408 µg/ml, indicating strong antioxidant activity. One-way ANOVA analysis of the two initial pigment-producing bacteria confirmed a significant difference in antioxidant activity ($p < 0.05$). *In vitro* antibacterial assays showed that both pigments were able to inhibit *Escherichia coli*, *Staphylococcus aureus*, and *Streptococcus mutans* with varying degrees of effectiveness. Specifically, *Chromatium* sp. produced inhibition zone diameter (IZD) ranging from 10.27 to 28.53 mm, *Chlorobium* sp. IZD varied between 12.4 and 17.07 mm, while the positive control had the largest value (26-41 mm). Fourier Transform Infrared Spectroscopy (FTIR) analysis revealed differences in the composition of functional groups between the pigments of *Chlorobium* sp. and *Chromatium* sp. *Chlorobium* sp. pigments were characterized by the predominance of conjugated double bonds (C=C), indicating the possible presence of carotenoid compounds, whereas *Chromatium* sp. pigments exhibited more characteristics of carbonyl groups (C=O) and porphyrin structures associated with bacteriochlorophyll (BChl). After applying to Tembe Nggoli fabric, the green pigment displayed an IZD of 16.25 mm against *Escherichia coli*, higher than that of the red pigment (9.5 mm). Against *Staphylococcus aureus*, the red pigment produced a greater IZD of 21.5 mm, compared to the green pigment (18.125 mm). However, two-factor ANOVA showed no significant differences between both pigments or the tested bacterial species after application to the fabric ($p > 0.05$). These results showed that both pigments provided color on fabric and maintained a functionally relevant antibacterial activity, indicating their potential as sustainable textile dye with additional bioactive benefits.

Links Researchers

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Introduction

Textile industry is essential for the production and expression of culture globally, but it faces some environmental challenges. This is because traditional processes, such as dyeing, which require large amounts of water and generate high-pollutant wastes, including synthetic dyes, salts, heavy metals, and toxic substances with carcinogenic properties (Benkhaya *et al*., 2020). A previous study has also identified the dangers of the synthetic dyes wastes to the marine ecosystems and human health (Yusuf *et al*., 2017). To address these challenges, natural dye is considered more ecofriendly, although derivatives from the botanical sources are limited due to low colorfastness, scarce supply, narrow color gamut, and dependence on mordants, which may cause further damage. Therefore, finding new sustainable sources of dye with added functional properties is essential.

In response to these challenges, scientists are exploring new biological resources using the abundant potential of microorganisms as biological factories. The membranes of purple sulfur bacteria (*Chromatium* spp.) contain carotenoids and bacteriochlorophyll (BChl), while green sulfur bacteria (*Chlorobium* spp.) have chlorosomes with chlorophyll c, d, or e, and other primary pigments (Frigaard and Dahl, 2008). A previous study reported that pigments from bacteria have had complex chemical constituents that can be combined with other components to act as toxins with antifungal, antimicrobial, and antioxidant activities (Venil *et al*., 2020). The combination of biological activity and aesthetic function shows a promise for the development of a functional textile.

As antimicrobial technology continues to increase in textile, there is a corresponding rise in hygienic functions of clothing. Recently, antimicrobial coatings such as silver, quaternary ammonium, and chitosan have been applied to healthcare textiles, which have shown effectiveness in reducing the microbial load on textiles and/or the rate of Healthcare Associated Infections (HAIs), compared to the conventional textiles (Schneider *et al*., 2023). Fabrics that are able to ward off free radicals, antioxidants, and reduce odors have also been proven to display antimicrobial properties (Ghosh *et al*., 2025). For the development of functional textiles, the simplest method is *via* the application of silver nanoparticles (AgNPs) and fabric surface modification. However, dyeing with natural pigments that have similar properties will be a revolutionary alternative due to the ability to eliminate the need for potentially hazardous finishing chemicals. This single process enables sustainable, economical, and functional dye and finishing, which can integrate a function with a design.

In Indonesia, Tembe Nggoli is a traditional woven textile that functions as a cultural artifact, embodying the history, identity, and artistic expression of the people from Bima. The cultural significance extends beyond the confines of materiality. Throughout the years, Tembe Nggoli has played a major role in both economic and cultural contexts. However, the use of indigenous plants in a dyeing process limits the available color palette, preserving the cultural integrity of the practice. A recent study has shown the need to protect and modernize dyeing methods, ensuring cultural preservation and economic revitalization of the craft (Nasir *et al*., 2025).

Several modern dyeing methods have been explored, including the potential applications of bacterial pigments. However, the use of pigments derived from anoxygenic photosynthetic bacteria, specifically *Chromatium* and *Chlorobium* spp. on various materials, particularly cultural textile, remains underutilized. Preliminary studies reported that the pigment's extracts hade remarkable antibacterial properties

on the common pathogens, such as *Staphylococcus aureus* and *Escherichia coli*, alongside the considerable antioxidant activity, as shown by the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay.

Based on the description above, this study aimed to assess the potential of pigments obtained from the anoxygenic photosynthetic bacteria such as *Chromatium* sp. (red-orange pigment) and *Chlorobium* sp. (dark green pigment) as functional dyes for traditional Tembe Nggoli fabrics from Bima, Indonesia. It is hypothesized that pigments from both bacterial spp. can be used to color the "Tembe Nggoli" fabric, showing measurable antibacterial and antioxidant properties. This method is a new step in textile biotechnology, combining the application of rarely used biopigments with local textile traditions. The expected outcomes are anticipated to provide an ecofriendly alternative to the synthetic dyes and support the conservation as well as the innovation of a traditional textile craftsmanship based on local biological resources.

Materials and Methods

Bacterial isolates and pigments

Bacterial isolates producing pigments were obtained from the Microbial Technology Laboratory collection, Faculty of Mathematics and Natural Sciences, Mataram University, Indonesia stored in 20% glycerol at –20°C. A total of four isolates were used in this study, namely *Sagittula marina* (M1= The first isolate from the macroalgae Gracilaria), *Cytobacillus kochii* (U5 = The fifth isolate from the Ulva seaweed), *Chromatium* sp. and *Chlorobium* sp. Before application, all isolates were revived on solid media according to their physiological requirements. Heterotrophic isolates (*S. marina* and *C. kochii*) were revived on nutrient agar (NA) medium, while red (*Chromatium* sp.) and green (*Chlorobium* sp.) photosynthetic isolates were revived on Pfennig agar medium, prepared with the composition reported by Pfennig and Trüper (1981). Pure pigments were obtained through repeated streaking until single colonies with characteristic colors were produced, followed by storing on Pfennig slant agar medium at 4°C. The four isolates were initially used to evaluate their pigments formation potential. However, only *Chromatium* sp. and *Chlorobium* sp. were selected, as they produced photosynthetic pigments with high color intensity and were adequate visually for further application in textile dyeing.

Pigments production and extraction

Pigments production was carried out using a shaker incubator (160 rpm, at room temperature) for 2 × 24 h, according to Wang *et al.* (2025).

- *Sagittula marina* and *Cytobacillus kochii* were cultivated in nutrient broth (peptone 5 g/L, beef extract 3 g/L, NaCl 5 g/L) and incubated at 30°C for 48 h under aerobic conditions (pH 7.0).
- In contrast, *Chromatium* sp. and *Chlorobium* sp. were cultured in a broth medium adapted from a Pfennig medium, modified using a local egg-based nutrient source (egg-based medium). This medium comprised chicken eggs (50 g/l), monosodium glutamate (15 g/l), and biotin (10 mg/l) in sterile freshwater (pH 7.0), following the approach reported by Hirose *et al.* (2016). These anaerobic phototrophic isolates were incubated at 30°C under continuous incandescent illumination (approx. 2000 lux) for 7–10 d.

After incubation, observation of the harvested biomass confirmed that the pigments produced by all experimental isolates were intracellular, as the pigments remained within the cell structure and required extraction from the bacterial pellets. Pigments were extracted at a ratio of 1:10 (w/v) from the biomass with absolute methanol and 80% acetone for heterotrophic and photosynthetic isolates, respectively. The mixture was sonicated for 15 min., centrifuged at 2800 × g for 10 min., filtered, and the supernatant was dried using a rotary evaporator (IKA-Werke GmbH and Co. KG, Germany). The dry extract was redissolved in the same solvent to obtain a pigment concentration of 10 mg/ml (w/v) (Padhan *et al.*, 2021).

Antioxidant activity

The antioxidant activity of each pigment was tested individually using the DPPH method (Ekawati *et al.*, 2024). Each treatment was performed in five replicate (n= 5). The pigments stock solution (500 µg/ml) was serially diluted to 20, 40, 60, 80, and 100 µg/ml. Specifically, a 100 µg/ml DPPH solution was prepared in methanol and stored at 4°C in a dark container. The maximum wavelength was determined using a UV–Vis spectrophotometer (Shimadzu UV-1800, Japan) in the range of 200–800 nm. The mixture of sample and DPPH (1:1 v/v) were incubated for 30 min. at room temperature, and the absorbance was

measured at the maximum wavelength (~517 nm). Subsequently, the antioxidant activity was calculated as the percentage of radical scavenging. The IC_{50} value was determined from the linear regression analysis observed between sample concentration and antioxidant activity (% inhibition), representing the concentration required to inhibit 50% of free radicals.

Antibacterial pigments

The pigments antibacterial potential assay was conducted using the well diffusion method against three bacterial strains *Staphylococcus aureus*, *Escherichia coli*, and *Streptococcus mutans* (Høiby *et al.*, 2024). These bacterial strains were obtained from the culture collection of the Laboratory of Food Technology, University of Mataram. The bacterial suspension was adjusted to a McFarland 0.5 turbidity standard, corresponding to approximately 1.5×10^8 CFU/ml. A total of 100 µl of the bacterial suspension were spread aseptically onto the surface of Mueller-Hinton Agar (MHA) plates using a sterile glass spreader. A 6 mm diameter wells were made using a sterile cork borer and filled individually with 50 µl of pigments extract (10 mg/ml), amoxicillin (10 µg/ml) as a positive control, and sterile distilled water as a negative control. Each treatment was conducted in two replicate (n= 2). Subsequently, the plates were incubated at 37˚C for 24 h, and IZD was measured (mm) using digital calipers.

Application of pigments to textile fabric

Tembe Nggoli textile fabric was cut into 5 x 5 cm pieces and then individually soaked in a solution of a red pigment from *Chromatium* and a green pigment from *Chlorobium* at a concentration of approximately 30% (w/v). Each treatment was conducted in two replicate (n= 2). The soaking process was carried out for 12 h at room temperature. After soaking, the fabric was air-dried until dryness.

Analysis of bacterial pigments

Characterization of the pigment's functional groups was performed using Fourier Transform Infrared (FTIR) spectroscopy with the potassium bromide (KBr) pellet method in transmission mode using an FTIR spectrometer (Nicolet 6700, Thermo Fisher Scientific, USA). A total of 1 mg of dry pigment was mixed with 200 mg of KBr (Sigma-Aldrich, Germany) and compressed into a transparent pellet. The spectrum was recorded at the wavenumber range of 4000–400 cm^{-1} and analyzed to identify the major functional groups based on their characteristic absorption bands (Sundararajan and Ramasamy, 2024).

Antibacterial activity test of woven fabric

Antibacterial testing of the pigments coated Tembe Nggoli woven fabric was conducted using the disk diffusion method. Fabrics individually coated with a red pigment from *Chromatium* sp. and a green pigment from *Chlorobium* sp. were tested against two bacterial strains; mainly *Escherichia coli* and *Staphylococcus aureus*. These two bacterial strains were selected because they represent the Gram-negative and the Gram-positive groups commonly used in evaluating the antibacterial performance of textiles. Each treatment was conducted in two replicate (n= 2). Bacterial cultures were suspended and adjusted to a turbidity standard of 0.5 McFarland and spread evenly on the surface of MHA medium using a sterile glass spreader. Pieces of fabric (5 × 5 cm) were individually placed on the surface of the seeded media and incubated at 37 ˚C for 72 h. After incubation, the IZD formed around the fabric was measured (mm) using a calibrated ruler (Nasir *et al.*, 2025).

Statistical analysis

All data were processed using the Microsoft Excel 2021 (Microsoft Corporation, USA). Analysis was performed using one-way ANOVA to test for significant differences among the treatments, including the obtained antibacterial and antioxidant assay results.

Results and Discussion

Pigments production and extraction

This study successfully generated and isolated pigments from four bacterial isolates, showing unique color traits. These included yellow, cream, red, and green pigments from *Sagittula marina*, *Cytobacillus kochii*, *Chromatium* sp. and *Chlorobium* sp. (Figure 1). The production method used shaking incubation at an ambient temperature for 7 d, alongside the application of absolute methanol and 80% acetone for the heterotrophic and photosynthetic bacteria. The obtained results showed that the ideal conditions for producing pigments were substantially influenced by the bacterial metabolic type. Similarly, Venil *et al.* (2020) reported that the type of solvent used and the environmental conditions for microbial cultivation considerably influenced the yield and stability of the microbial pigments.

Table 1: *Antioxidant activity of crude extracts of the bacterial pigments.*

No.	Crude pigments extract	Types and origins of the bacterial pigments	DPPH antioxidant activity IC_{50} (µg/ml)	Antioxidant activity level
1	Vitamin C	Standart	4,716	Very strong
2	YELLOW	*Sagittula marina* (M1)	15,924	Very strong
3	CREAM	*Cytobacillus kochii* (U5)	138,139	Medium
4	Red orange	*Chromatium* sp.	32,544	Strong
5	Dark green	*Chlorobium* sp.	41,408	STRONG

Where; DPPH: 2,2-diphenyl-1-picrylhydrazyl. IC_{50} values are classified as: 151-200 µg/ml (weak), 100-150 µg/ml (moderate), 50–100 µg/ml (strong), < 50 µg/ml (very strong), according to Seneviratnhe et al. (2006).

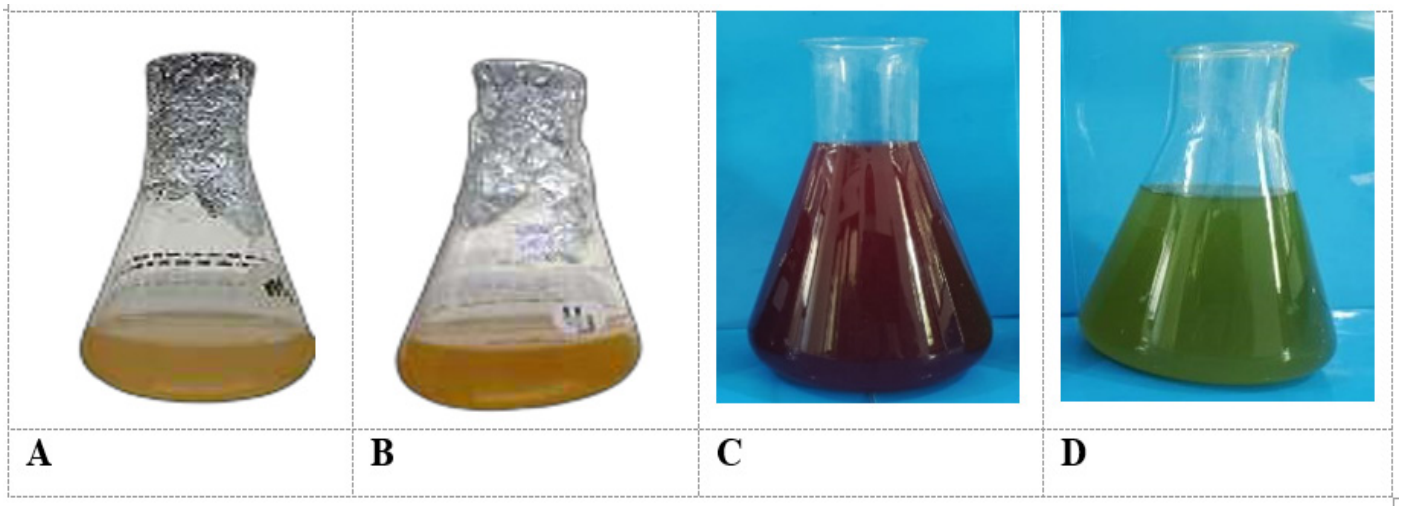

Figure 1: *Pigments production of by four bacterial spp., Sagittula marina (A), Cytobacillus kochii (B), Chromatium sp. (C), and Chlorobium sp. (D).*

Antioxidant activity

An antioxidant activity is defined as the concentration of a compound required to inhibit or neutralize 50% of the free radical activity (Nurdyansyah and Widyastuti, 2020). In this study, an antioxidant assay was conducted on crude pigments extracts and were grouped based on the obtained IC_{50} value. The obtained results are shown in Table 1.

The DPPH test showed that the four pigment's extracts had different levels of antioxidant activity. The yellow pigment from *Sagittula marina* displayed "very strong" activity (IC_{50}: 15.924 µg/ml), which was similar to vitamin C. Meanwhile, the red (*Chromatium* sp.) and green (*Chlorobium* sp.) pigments demonstrated "strong" activity. A one-way ANOVA analysis was performed to evaluate the differences in DPPH assay results of *Sagitulla marina*, *Cytobacillus kochii*, *Chromatium* sp. *and Chlorobium* sp. The obtained results expressed that there were significant differences between the tested groups, with a p-value of 1.06×10^{-11}, below the significance threshold value of 0.05. These results demonstrated that each pigment sample had remarkably different antioxidant capabilities. Microbial pigments serve as natural dyes and were documented in a previous study to possess antioxidant properties attributed to the presence of biocompounds like carotenoids and tetrapyrroles (Tuli *et al.*, 2015). Similarly, Galasso *et al.* (2017) reported that carotenoids derived from marine bacteria possessed potential antioxidant properties for use in the food and cosmetics sectors.

The occurrence of different IC_{50} values is an indication of a difference in the activity mechanisms and efficacy. Low IC_{50} value pigments, particularly from *Sagittula marina* had a fast and efficient scavenging activity for DPPH radicals. Scavenging activity for DPPH radicals includes a hydrogen atom transfer (HAT) or a single electron transfer (SET). Furthermore, microbial pigments have a myriad of biological activities, such as an antioxidant activity, displaying suitability for addition as active ingredients in the cosmeceutical formulations. This dual role supports their application in functional cosmeceutics, representing cosmetically active compounds for a coloring and biological activity (Kiki, 2023).

Antibacterial pigments

Based on the obtained results, IZs were obtained from extracts of crude pigments. The diameter of the inhibition zone against *Escherichia coli*, *Staphylococcus aureus*, and *Streptococcus mutans* was visualized as a clear zone around the well (Figure 2). The antibacterial assay conducted in three replicate was evaluated based on the size of the clear zone formed, expressing the ability to inhibit the bacterial isolates (Figure 3).

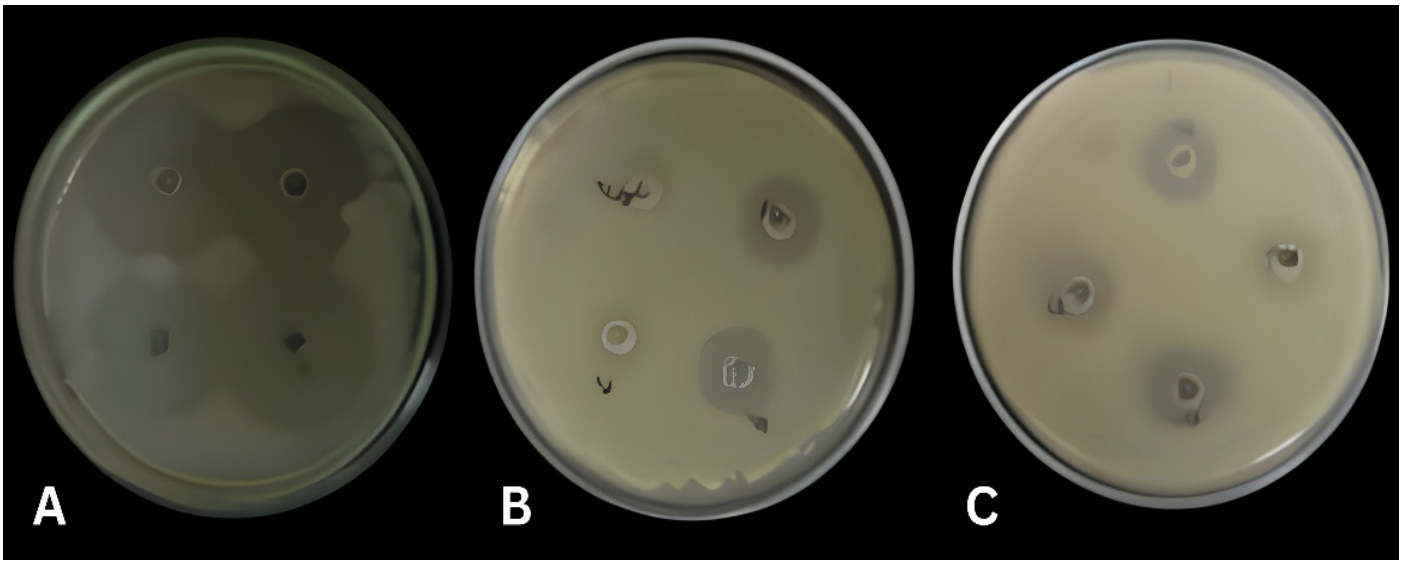

Figure 2: *Antibacterial activity of pigment against (A) Escherichia coli, (B) Staphylococcus aureus, and (C) Streptococcus mutans evaluated in vitro using the agar well diffusion method. The clear zones surrounding the wells indicate inhibition of bacterial growth. All experiments were performed in duplicate (n = 2), and the figure shows the obtained representative results.*

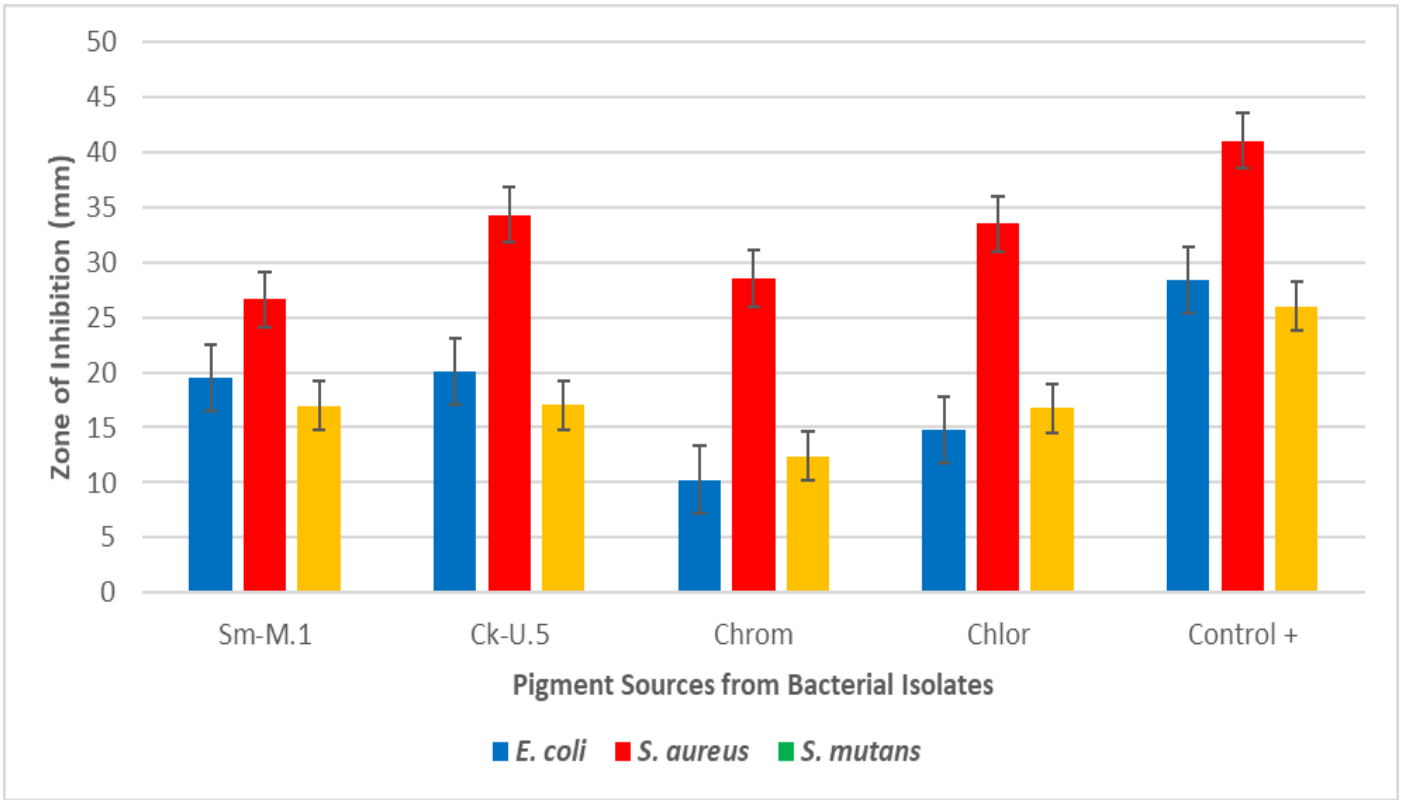

Figure 3: *Inhibition zone diameters of crude pigment extracts from Sagittula marina (Sm-M.1), Cytobacillus kochii (Ck-U.5), Chromatium sp. (Chrom), and Chlorobium sp. (Chlor) against Escherichia coli, Staphylococcus aureus, and Streptococcus mutans, measured using the agar diffusion assay. Amoxicillin (25 µg/10 ml) was used as a positive control. Error bars represent the standard deviation (±SD) of two independent replicate (n= 2).*

Antibacterial assay results showed that the inhibitory activity against *Escherichia coli*, *Staphylococcus aureus,* and *Streptococcus mutans* varied considerably among treatments. The highest IZD value against *Escherichia coli* was obtained by the *Cytobacillus kochii* (Ck-U.5) treatment (20.1 mm), while the lowest value was displayed by *Chromatium* sp. (10.27 mm). For *Staphylococcus aureus*, the highest IZD was also observed in Ck-U.5 (34.3 mm), while the lowest value was in Chrom (28.53 mm). Regarding *Streptococcus mutans*, the variation between treatments was relatively large, with IZD ranging from 12.4 mm (Chrom) to 17.07 mm (Ck-U.5). The positive control produced the highest IZD, mainly 28.4 mm, 41 mm, and 26 mm for *Escherichia coli*, *Staphylococcus aureus*, and *Streptococcus mutans*, respectively, while the negative control demonstrated no activity. Based on the results of the two-factor ANOVA analysis, the bacterial type factor obtained a p-value of 2.11×10^{-5}, while the treatments had p-value of 0.001149, showing significance effect ($\alpha < 0.05$). This suggested that the variation observed between bacterial species and effectiveness of the administered pigment treatment differed considerably. The very small p-values for both factors showed significant differences in response between the groups tested.

An existing study has provided results for bacterial pigments, particularly the carotenoid or chromogenic variants, showing greater antibacterial activity towards Gram-positive than Gram-negative bacteria (Chaturwedi *et al*., 2024). This difference is attributed to structural variation in the cell membrane, where a Gram-positive bacterium like *Staphylococcus aureus* has shown larger IZD than a Gram-negative one. Generally, Gram-negative bacterium such as *Escherichia coli* has a type-outer membrane, consisting of a lipopolysaccharide (LPS), acting as a barrier for penetration of the antibacterial entities (Epand *et al*., 2016). The active agents within pigments, mainly carotenoid or BChl). derivatives can interact more effectively with the accessible cytoplasmic membrane located in the Gram-positive bacteria.

Studies carried out on marine red pigments (prodigiosin) isolated from *Zooshikella* sp. and *Streptomyces* sp. bacteria have shown antibacterial potential against several human pathogens (Ramesh *et al*., 2020). Although the observed antibacterial activity was non-comparable to a standard antibiotic (*i.e*., amoxicillin), but there is still an appreciable use of these pigments as a natural source and have the potential to mitigate the antibiotic resistance. In this study, antibacterial testing confirmed that the crude pigments from *Chromatium* sp. and *Chlorobium* sp. displayed considerable IZDs, with the strongest performance observed against *Staphylococcus aureus.* The observed activity suggested that several novel bioactive compounds were produced due to the unique photosynthetic metabolism of the bacterium. Based on pigment analysis using FTIR, the pigments displayed several functional groups such as conjugated double bonds (C=C), which are characteristic of carotenoid compounds. Therefore, carotenoids are believed to have contributed to the observed antibacterial activity.

The carotenoids synthesized by sulfur bacteria, such as spirilloxanthin in *Chromatium* sp. and chlorobactene in *Chlorobium* sp. are lipophilic compounds that can readily penetrate the target cell membrane. After integration into the membrane, the carotenoids can impair the fluidity and integrity of cell, leading to high membrane permeability, ion leakage, and death (lysis). This mechanism is particularly effective against *Staphylococcus aureus* possessing a thick peptidoglycan layer but does not possess an outer membrane, allowing for lipophilic compounds to reach the cytoplasmic membrane more easily (Chen *et al*., 2023). Furthermore, carotenoids display biological activities that provide protective effects against several microorganisms, including Gram-negative bacteria such as *Escherichia coli* (Saini *et al*., 2022).

Application of pigments into textile fabrics

Biopigments are dyes produced by bacteria, but in the textile context, they behave more like dyes. Although insoluble in water, these metabolites can chemically bond with fabric fibers through functional groups, thus acting as dyes. However, the term "pigment" is retained in this study due to their generally insoluble nature, powder form after isolation, and often applied as a suspension (Kramar and Kostić, 2022). Based on the obtained results of this study, the use of photosynthetic pigments in the heterotrophic bacteria (*Cytobacillus kochii* and *Sagittula marina*) produced less vivid colors compared to those produced by the anoxygenic photosynthetic bacteria (*Chromatium* sp. and *Chlorobium* sp.).

The present successful application of pigments derived from anoxygenic photosynthetic bacteria for the fabrication of 'Tembe Nggoli' woven textile

Table 2: *Fourier transform infrared spectroscopy comparison between green vs. red pigment's extract.*

Wave number (cm^{-1})	Green extract	Red extract (PSB)	BChl literature	Carotenoid literature	Interpretation
3435	O–H / N–H (0,81%T)	O–H / N–H (3,73%T)	3400–3450: porphyrin H, N–H bonds	Sometimes there are (phenolic OH)	Polar groups / Solvent residues
2075–2078	Present (56,8%T)	Present (62,6%T)	Rarely reported; porphyrin overtone	Not typical	Combination of conjugate vibrations
1696–1634	1634 (C=O/C=C, 9,7%T)	1696 (C=O ester, 34,2%T) + 1638 (C=C, 18,9%T)	1700–1730: C=O porphyrin esters	1600–1650: C=C conjugation	Green: weak; Red: strong (more pronounced BChl + carotenoids)
1424–1370	Doesn't appear clearly	1424 (C–H bending, 65,1%T), 1370 (CH_3 bending, 59,0%T)	Minor in porphyrin	1420–1460 and 1360–1380: typical carotenoids	Specific carotenoids → dominant in red extract
1238–1094	Doesn't appear clearly	1238 (C–O ester), 1094 (C–O/C–N)	1220–1250 and 1080–1100: esters/ porphyrins	Not dominant	Typical BChl, appeared in red extract
703–700	703 (aromatic porphyrin, 40.6%T)	700 (aromatic porphyrin, 50.5%T)	700–710: porphyrin ring	Not typical	Both samples showed porphyrins
406–411	406 (fingerprint, 75.5%T)	411 (fingerprint, 78,9%T)	400–450: Mg–N porphyrin bonds	Not relevant	Suspected Mg–N signal from BChl

showed technological feasibility and contained profound cultural relevance. 'Tembe Nggoli' is a form of traditional textile from Bima, West Nusa Tenggara, established on philosophical principles of belief and social norms (Sholehah *et al*., 2024). Using bacterial pigments derived from local native West Nusa Tenggara (such as marine bacteria) creates a new notion of a "biological dyeing" practice, where local materials are applied for preservation of the cultural patrimony. Due to its development, Tembe Nggoli fabric has the potential to use natural dyes, supporting its local cultural security and has been identified through the application of scientific knowledge. Therefore, a functional textile with antibacterial properties has been created, providing an active protection for the user. For example, the textile fabric acts as clothing to provide a barrier to skin infections or packaging to extend the shelf life of food products due to its antioxidant properties (Choksi *et al* 2020). This study also addressed the creation of a conventional textile that is sustainable, aesthetically appealing, and deeply connected to a historical and cultural meaning. Despite this remarkable contribution, color stability and pigments fastness on textile fabric after washing or exposure to light were not analyzed, showing the need for further evaluations to ensure long-term performance of the functional textile using bacterial pigments.

Analysis of bacterial pigments

The various classes of compounds comprising the pigments of anoxygenic photosynthetic bacteria were determined through FTIR analysis. This analytical method was used to measure the absorption of infrared radiation by a sample. When radiation interacts with molecules, chemical bonds vibrate at characteristic frequencies and absorb energy at specific wavenumbers. This absorption pattern is recorded as a characteristic infrared spectrum, which can be used to identify the functional groups and chemical structure of the sample (Pasieczna *et al*., 2025). FTIR analysis results (chromatograms) of the two tested pigments are presented in Figure 4 and interpreted in Table 2 to understand which compounds existed in the bacterial pigments.

FTIR analysis provided information about the differences in functional groups present in the pigment extracts from *Chlorobium* sp. (green extract) and *Chromatium* sp. (red extract). *Chlorobium* sp. exhibited higher antibacterial activity compared to *Chromatium* sp., which is likely related to variations in the composition of the functional groups and chemical structures detected in the FTIR spectra. However, this relationship is indicative and does not directly prove the antibacterial mechanism; therefore, further analysis is required to confirm this association.

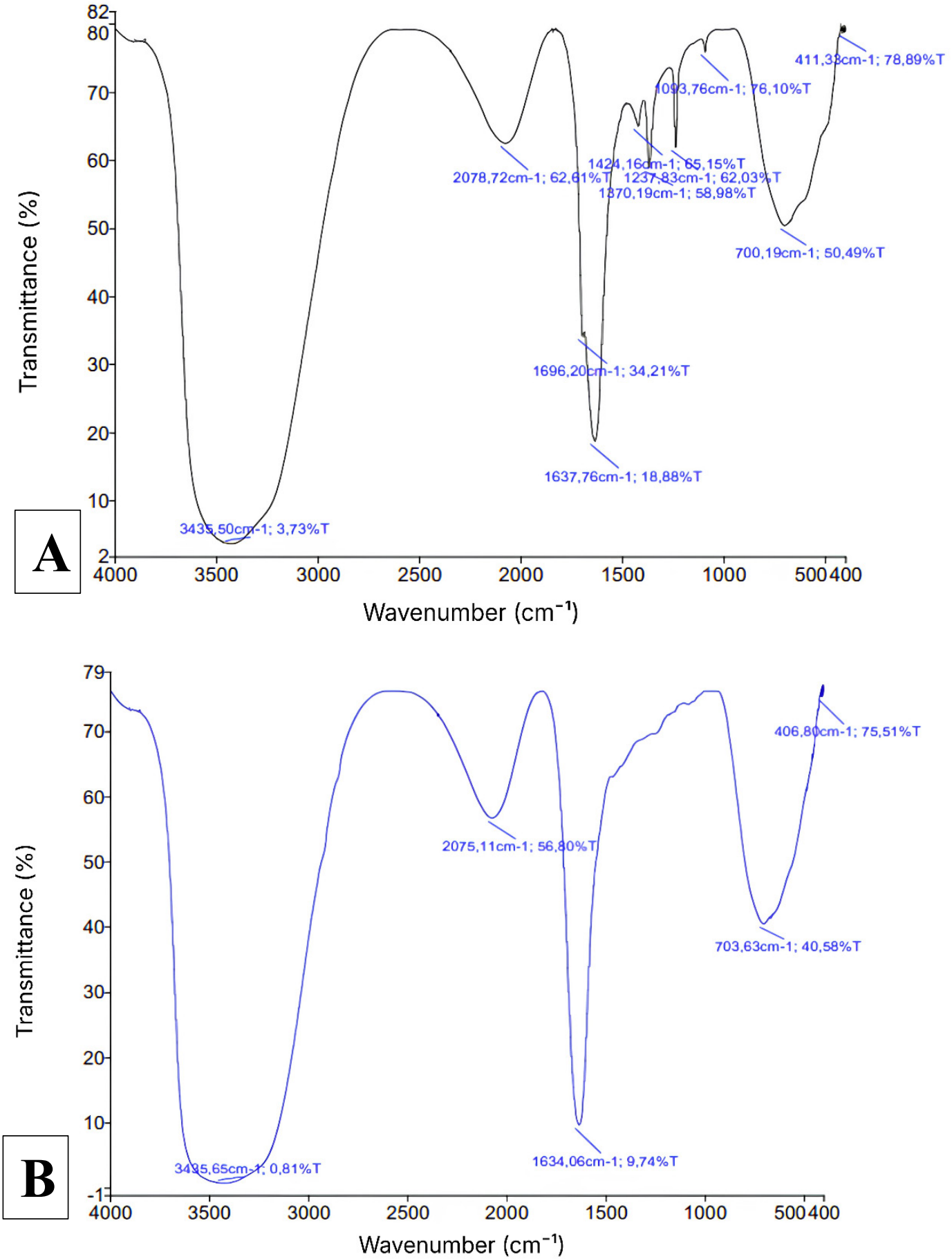

Figure 4: *Chromatograms of FTIR analysis demonstrating functional biochemical groups detected in: (A) An anoxygenic photosynthetic bacterium, Chromatium sp. and (B) A green sulfur bacterium, Chlorobium sp.*

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Based on the obtained results, the broad absorption peak at 3435 cm^{-1} expressed the presence of hydroxyl (O–H) and amine (N–H) groups, characteristic of porphyrin pigments such as BChl. The intensity of this peak was slightly higher in *Chromatium* sp., but didn't directly correlate with antibacterial activity, probably generated from residual solvent or polar groups that were inactive against the tested bacteria. A substantial difference was also observed in the 1696–1634 cm^{-1} range. In *Chlorobium* sp., the dominant peak at 1634 cm^{-1} demonstrated conjugated carbon-carbon double bond (C=C) stretching, characteristic of carotenoid conjugation systems. This conjugated structure played a role in electron transfer and the formation of reactive oxygen species (ROS), having antibacterial properties. In comparison, *Chromatium* sp. showed a strong peak at 1696 cm^{-1}, indicating carbonyl (C=O) stretching of the carboxylate ester group, typical of BChl, but with a weaker C=C peak intensity (1638 cm^{-1}). This displayed a greater dominance of the BChl structure but with a lower carotenoid contribution, potentially explaining the lower antibacterial activity compared to *Chlorobium* sp. (Gomes *et al.*, 2025).

The more pronounced peak observed at 1424–1370 cm^{-1} in *Chromatium* sp. indicated the presence of methyl (C–H) bends and minor porphyrin groups. Meanwhile, the absence of similar peaks in the green pigment expressed that *Chlorobium* sp. had a more dominant carotenoid structure than methyl porphyrin. The peak detected at 1238–1094 cm^{-1}, which appeared only in the red pigment demonstrated the presence of an ester and C–O–C=N bonds common to BChl. This confirmed that *Chromatium* sp. pigments were richer in BChl components but ddidn't elicit a stronger biological activity. Both extracts exhibited a typical aromatic porphyrin peak at approximately 700–703 cm^{-1}, indicating that the basic pigments structure remained intact. The greater peak intensity in *Chlorobium* sp. (40.6%) indicated higher stability of the aromatic structure. Additionally, the peak observed at 406–411 cm^{-1} displayed Mg–N vibrations in the porphyrin ring, which were stronger in *Chromatium* sp. (78.9%), but were insufficient to explain the weaker antibacterial activity.

FTIR analysis showed that *Chlorobium sp.* had a higher C=C conjugation ratio, contributing to ROS formation and high interaction with the bacterial cell membranes. However, *Chromatium* sp. had a higher BChl content but with weaker conjugation, causing a relatively lower antibacterial effect. These results suggested that the stability of the carotenoid-conjugative structure in *Chlorobium* sp. played a greater role in its antibacterial activity than the presence of BChl (Sundberg *et al.*, 2021). The obtained data confirmed that the bacterial photosynthetic pigments, particularly that from *Chlorobium* sp., functioned as natural coloring agents and possessed substantial antibacterial potential. Therefore, maintaining the stability of the conjugative and polar groups during extraction is a key factor in maintaining the pigment's bioactivity. These results support the development of an ecofriendly functional dye that contributes to a sustainable textile industry (Fried *et al.*, 2022).

Antibacterial activity test of woven fabric

The test results demonstrated that Tembe Nggoli fabric treated with red and green bacterial pigments was capable of producing an inhibition zone against *Escherichia coli* and *Staphylococcus aureus* (Figure 5), but with varying degrees of effectiveness. In tests against *Escherichia coli*, the green pigment showed a larger IZD (16.25 mm) than the red pigment (9.5 mm). This indicated that the green pigment had relatively stronger antibacterial properties against Gram-negative bacteria. However, a different pattern was observed in *Staphylococcus aureus*, where the red pigment expressed more effectiveness by producing a larger IZD (21.5 mm) than the green one (18.125 mm).

A two-factor ANOVA analysis without replication was conducted to determine the effect of the tested bacterial pigments on the antibacterial activity of Tembe Nggoli fabric. The obtained results showed that the *p*-values for the tests conducted against *Escherichia coli* and *Staphylococcus aureus* in the red and green pigment treatments were 0.401326 and 0.795167, respectively. As both *p*-values were greater than the significance level of $\alpha = 0.05$; accordingly, there was no statistically significant difference. This showed that the variation in antibacterial response was insufficient to be considered statistically significant. Therefore, the antibacterial effectiveness of the two pigments can be considered to be relatively equivalent after their application to the fabric. This equivalence is attributed to several factors, including fiber type, pigments affinity, selected fabric structure, pH, solution ratio, and pre-dyeing treatments that may have been applied to the fabric. In dyeing processes, treatment application is often through two different methods,

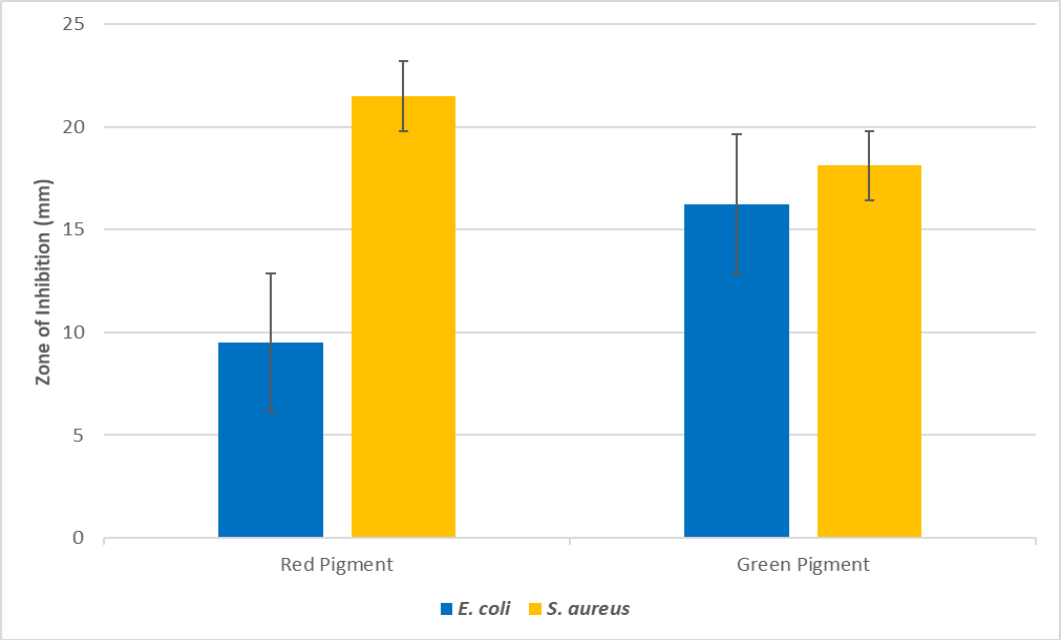

Figure 5: *Antibacterial potential of two pigmented extracts obtained from Chlorobium sp. and Chromatium sp. applied to woven fabrics. Error bars represent the standard deviation (±SD) of two independent replicate (n = 2).*

namely continuous and exhaustive. The first method includes padding, where the fabric is immersed in a dye vat, packed, and dried until complete absorption. The exhaustive method is carried out in batches and includes the mechanical movement of a fabric or dye vat to promote dye absorption in the dyeing machine (Clark, 2011). Dye dissolution is also a crucial stage in the dyeing process, which depends on the properties of the compound. A previous study reported that the bacterial pigments were soluble in methanol and acetone (Kramar and Kostic, 2022). The current results provided important information for developing a functional natural dye, since both pigments had the ability to maintain antibacterial activity after being fixed on a solid medium such as textile fabric. Consequently, *Chromatium* sp. and *Chlorobium* sp. pigments can be used as candidates for sustainable bioactive dyes in traditional textile such as Tembe Nggoli woven fabric from Bima, West Nusa Tenggara.

The application of *Chromatium* sp. and *Chlorobium* sp. pigments in the textile dyeing process represents a remarkable novelty in this study. While these phototrophic bacteria are well-known for their roles in anaerobic ecosystems, their potential as a source of fabric dyes has not been previously reported. Due to the lack of existing literatures on the specific application of these bacterial species in textile technology, this study provides a pioneering baseline for future researches. This finding opens new possibilities for utilizing the anaerobic bacteria as sustainable alternatives to synthetic dyes, which has not been explored in earlier pigment-related studies.

Conclusions and Recommendations

In conclusion, this study showed that pigments obtained from *Chromatium* sp. and *Chlorobium* sp. are potential sources for sustainable applications in textile dye. The products obtained displayed clear coloring on traditional "Tembe Nggoli" textile fabrics. Additionally, both pigments demonstrated measurable antibacterial activity against *Escherichia coli, Staphylococcus aureus,* and *Streptococcus mutans,* and high antioxidant activity using the DPPH assay. These results confirm that application of the anoxic photobacterial pigments enriches the functional value of textile and strengthens the cultural significance of Tembe Nggoli textile fabric as a locally developed, scientifically and ecofriendly heritage. Moreover, further future studies are highly recommended to comprehensively evaluate the stability, fixation efficiency, and functional activity resistance of the treated textile fabric under the used conditions.

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Novelty Statement

This research presents an innovative approach by utilizing biopigments from photosynthetic bacteria, namely *Chromatium* sp. and *Chlorobium* sp., as functional dyeing agents for traditional Tembe Nggoli woven fabrics. Unlike previous studies that generally focused on plant extracts or synthetic compounds, this study integrated the microbial bioresources with ethnic textile materials to produce colored fabrics, which also have a potential antibacterial activity *against Escherichia coli* and *Staphylococcus aureus*. In addition, this study also provided a new contribution for the manipulation of insoluble biopigments as functional dyes based on their chemical interactions with textile fibers, thus opening up new opportunities for the development of ecofriendly and high-valued textiles.

Author's Contribution

Ruslan: Conceptualization, methodology.
Muh. Nasir: Investigation, data curation.
Muhammad Azdy Faroby: Formal analysis, visualization.
Wanda Qoriasmadillah: Investigation, writing original draft.
Faturrahman: Conceptualization, supervision, writing review and editing. All authors have read and agreed to the published version of the manuscript.

Ethical approval
This study was conducted in accordance with ethical standards for the use of experimentals. All procedures were reviewed and approved by the Academic Integrity Committee of University of Nggusuwaru, Indonesia, under an approval code number 011/KI-Ak.I/X/2025.

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Generative AI and AI assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interests
The authors have declared that there are no conflicts of interest regarding the publication of this paper. The authors have no financial, personal, or professional relationships that could have influenced the work reported in this study.

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