

Dyed Bacterial Cellulose Patches to Include Skin-Tone Matching: A Quantitative Analysis based on CIEDE2000 Color Difference.

Io Kim
The Peddie School

Abstract: The paper is based on the creation of natural-pigmented bacterial cellulose (BC) wound dressings that can be adapted to a variety of skin tones. Plant extract-dyed BCF films (turmeric, coffee, beetroot, tea) were compared to the PANTONE references by CIEDE2000, and were well matched at medium-dark (ΔE 0 equals or less 2) and almost perfectly at the darkest spot (ΔE 0 equals or less 0.63), and lighter tones proved very challenging (ΔE 0 equals or less 13). The color mixing of the lab space was better than RGB. The patches also exhibited excellent absorption of moisture, adhesion, antimicrobial activity, and controlled drug release, which showed that natural-dye BC patches can offer people an inclusive aesthetic appearance without affecting therapeutic effectiveness.

Keywords: Bacterial cellulose, Natural dyes, Skin-tone matching, CIEDE2000, Inclusive dermatology, Wound dressing, Sustainable biomaterials

1. Introduction

1.1 Background and Motivation

Skin performs the roles of shielding and identification. In people whose skin is prone to keloid or has visible scarring, even minor injuries will produce permanent disfigurements that attract negative attention and social stigma. As seen in clinical observations and patient testimonials, the current wound dressings do not consider the aesthetic aspect of the patients, especially those patients whose skin tones are not reflected in the commercially available products. Patients also complain that the wrongly placed patches ironically attract even more attention to the very parts that the patch is designed to cover, and lead to psychological trauma on top of the actual wound.

The issue of incompatibility between the medical utility and the aesthetic inclusivity opens up an emergency question: Could wound care materials be created to be protective, therapeutic, and aesthetically merge with various skin colors and colors? The answer to this question should be achieved by combining biomedical engineering with principles of inclusive design, where no longer is a functional approach used, but also the emotional dimension and dignity of the patient.

1.2 Research Necessity

In a lot of resource-deprived areas, people whose skin has noticeable damage suffer not only physical insecurity but also social persecution. The creation of a technology that is available, skin-friendly, and aesthetically accommodating to the wide range of skin colors can be both healing and dignified. The

recent focus on sustainability and inclusivity in biomedicine has generated a need to find materials that are biocompatible and environmentally friendly and address the various color tones of the skin. The research starts at a point of convergence of emotional experience, sustainability, and biomedical innovation. This is aimed at producing naturally colored bacterial cellulose patches that would be used both to cover wounds and provide therapeutic properties, and to blend well with the skin color of those who use them.

2. Previous Research Review

2.1 Bacterial Cellulose Research

The increased demand for sustainable biomaterials and customized skincare has placed bacterial cellulose (BC) as a potential biomaterial in medical and cosmetic practice. BC is a natural biodegradable polymer synthesized by particular bacteria, which is highly pure, exhibits a high biocompatibility, and has a three-dimensional nanofiber structure that is similar to the extracellular matrix of skin tissue.

Past research has shown that BC-based wound dressings create ideal moist conditions, which reduce the risk of infection and enhance epithelialization. The BC films have been applied to burn therapy as they retain moisture and relieve pain, which helps in wound healing and recovery. The studies of modified BC composites show that nanostructures allow an increased loading of drugs, release, and reactivity to external conditions, e.g., pH or temperature.

Recent works combine BC with biofabrication

and 3D printing technologies to develop patient-engineered tissue engineering constructs. Survey building BC hydrogels with keratinocytes and fibroblasts was effective in achieving full-thickness wound healing, ascertaining the potential as future wound management platforms.

2.2 Natural Dye Research and Current Limitations

Although BC is considered to be a biocompatible and functional material, even the marketed patches and medical dressings are still immensely dependent on synthetic polymers and chemical colorants. These chemicals may be irritating, especially on sensitive or dark skin. To solve this problem, scientists have studied plant-based natural dyes like turmeric, madder, and indigo, not only to cover a wide range of colors but also to have antimicrobial and antioxidant properties.

Nevertheless, there are limited studies on the interaction of the regenerative properties of BC with the bioactivity and aesthetic versatility of natural dyes. There is a lack of research into the possibility of a single sustainable patch to apply protection, healing qualities, and visual harmony at the same time. This project will address such a gap by experimental fabrication and characterization of multifunctional color-personalizable BC patches.

2.3 Sustainability Advantages

The production of cellulose by bacteria has found environmental benefits over the petroleum synthetic substances; it requires less energy to produce, and it uses renewable materials as raw materials. BC can be used together with natural dyes, which will help to achieve sustainable innovation and an inclusive dermatological design.

3. Theoretical Background

3.1 Properties of Bacterial Cellulose

Microbial fermentation is used to produce bacterial cellulose, which is mainly *Gluconacetobacter xylinus*. BC is not lignified or hemicellulose in contrast to plant-derived cellulose, which makes it purer and stronger. It has a nanofiber structure, which is similar to the extracellular matrix of human tissue, which facilitates the attachment and proliferation of cells and the retention of moisture, which are needed in wound healing and the delivery of drugs through the skin.

The nanostructure has three dimensions with high tensile strength, flexibility, and breathability,

ensuring that it can be used directly on the skin. It may be in the form of thin films, membranes, or hydrogels that adhere to the skin without causing discomfort. The transparency of BC and light weight imply that surface color alteration does not affect biomedical functionality, and instead, it is more suitable for aesthetic use.

BC has a high water-holding capacity, which biochemically keeps conditions moist, leading to the promotion of epithelialization and minimization of scarring. Its safety and sustainability compared to synthetic polymer dressings that are widely used are due to non-toxic and biodegradable properties.

3.2 Biological Properties of Natural Dyes

Those natural dyes that are plant-derived include *Curcuma longa* (turmeric), *Rubia tinctorum* (madder), *Indigofera tinctoria* (indigo), gardenia, beetroot, and coffee extracts. These produce different warm and cool colors that resemble natural skin colors and contain bioactive compounds, which are therapeutic. As an example, the anti-inflammatory effects of curcumin in turmeric, anthocyanins in blueberries, antioxidant effects, and tannins in tea, anthocyanins, tannins, and curcumin have mild antiseptic effects.

BC with natural dyes is hard to prepare without compromising the mechanical properties or biomedical action. The binding of the pigment and the stability of cellulose are dependent on factors like pH, temperature, concentration of dye used, and time of reaction. Even color correction and reproducibility are challenges in achieving the correct colors of different skin tones.

3.3 CIEDE2000 Color Difference Formula and Color Space Conversion

To quantitatively evaluate similarity between skin tones and patch colors, I employed the CIEDE2000 (ΔE_{00}) color difference formula. This method provides the closest approximation to human visual perception of color differences.

Color analysis requires color space conversion. Digital images typically yield sRGB color values that do not uniformly correspond to perceived color differences.

The first step is sRGB gamma correction. HEX color codes are converted to sRGB (0-255), then normalized to the 0-1 range. Gamma correction is applied: for each channel C , if $C \leq 0.04045$, calculate $C/12.92$; if $C > 0.04045$, calculate $((C + 0.055)/1.055)^{2.4}$.

The second step converts sRGB to the XYZ color space using the D65 reference white transformation

matrix according to the IEC 61966-2-1 standard. The XYZ color space is a CIE standard color space that standardizes human color perception.

The third step transforms XYZ to the Lab color space, known as a perceptually uniform color space, whereby differences in color are proportional to differences in perception. Using D65 reference white ($X_n=0.95047$, $Y_n=1.00000$, $Z_n=1.08883$), L^* (lightness), a^* (red-green), and b^* (yellow-blue) values are calculated through a specific function $f(t)$.

The CIEDE2000 color difference formula is a formula that accepts Lab coordinates of two colors and computes ΔE_{00} . Lightness difference, chroma difference, and hue difference are computed separately, then weighed to determine the final color difference. Corrections for perceptual characteristics in blue regions, chroma differences near neutral colors, and tolerances based on hue angle are applied.

Finally, ΔE_{00} values are converted to intuitive similarity scores (0-100). Using a Gaussian decay function: $\text{Similarity} = 100 \times \exp(-(\Delta E_{00})^2/(2\sigma^2))$, where σ (sigma) controls tolerance level (default value 6). According to this formula, when $\Delta E_{00}=0$, similarity is 100; when $\Delta E_{00} \approx 6$, approximately 60; when $\Delta E_{00} \geq 20$, nearly 0.

In practice, $\Delta E_{00} \leq 2$ is considered an acceptable matching tolerance. In printing and brand management, $\Delta E_{00} \leq 2$ -3 levels are commonly used as acceptance criteria.

3.4 Significance of Lab Color Space Averaging

When evaluating multiple natural dye combinations, RGB averaging and Lab averaging methods were compared. RGB averaging simply calculates the arithmetic means of each channel in sRGB space. Nevertheless, as RGB is not a perceptually uniform space, average values can not be equal to real perceived colors.

Lab averaging first converts the individual colors to the Lab color space before averaging L , a , and b values of a color arithmetically. Because the Lab is a perceptually uniform space, average values better preserve the actual visual appearance. Experimental results also showed Lab averaging produced superior skin-tone matching in most cases.

3.5 Importance of Inclusive Dermatology

Recent studies refer to the significance of inclusivity in dermatology, as the darker complexion of the skin is poorly covered in skin material testing. This project acknowledges that personalized coloration is not only an aesthetic but also an ethical matter, and that biomedical materials

must honor and represent different human skin. Summarizing, cellulose in bacteria offers an effective, biocompatible, breathable, and biodegradable scaffold. Natural dyes bring out the visual and therapeutic aspects.

3.6 Research Hypothesis

The hypothesis of this study is that natural dyes generated by the extraction of plant sources can be systematically utilized to color bacterial cellulose to obtain color tones that are comparable to the various skin tones of human beings, and the color difference (ΔE) between the colors is less than the perceptibility threshold.

Warm and yellowish-brown hues apt to light and medium skin coloring were obtained with turmeric and coffee extracts because of the yellow color of curcumin and melanoidin present in coffee. Beetroot extract will produce red-pink hues and will be more unstable because betalain pigments are pH sensitive. The dyes attached to the vinegar solution must exhibit better color preservation under 7 days with 5.0 or below changes in 5.0 differences in ΔE .

By varying dye concentration (1-10% w/v) and combination ratios, the BC patches should cover at least six distinct skin tone categories. Finally, naturally dyed BC patches are expected to maintain equivalent or superior antimicrobial activity compared to undyed controls, as curcumin and coffee polyphenols possess intrinsic antimicrobial properties.

4. Methods

4.1 Research Objectives

This experiment aimed to create bacterial cellulose-based skin patches dyed with natural pigments and loaded with therapeutic substances. Completed patches were evaluated based on wound protection capability, transdermal drug delivery potential, and natural aesthetic concealment.

4.2 Preparation and Safety

All procedures were conducted on clean surfaces. Tools were disinfected with 70% ethanol before and after use. Gloves and safety goggles were worn when handling alkaline solutions or dyes.

Materials prepared included: Gluconacetobacter xylinus or kombucha SCOBY, glucose, peptone, yeast extract, citric acid, disodium phosphate, natural dyes such as turmeric or coffee, and additives like honey, aloe gel, and tea tree oil. Sterile water, glass containers, forceps, thermometer, and incubator were also required.

4.3 Bacterial Cellulose (BC) Production

The culture medium was made by dissolving the following in 1 liter of distilled water: glucose (20g), peptone (5g), yeast extract (5g), disodium phosphate (2.7g), and citric acid (1.15g), and pH adjusted to about 6.0 and sterilized by boiling or autoclaving.

A cooled medium was added to shallow glass containers of about 2-3 cm. A small piece of kombucha SCOBY or bacterial culture was placed on the surface. Containers were loosely covered with plastic wrap or foil to allow air circulation. Incubation at 28-30°C for 5-7 days produced translucent BC films at the air-liquid interface.

The harvesting of BC films was done with sterile forceps, and distilled water was used to wash the films to eliminate residues. To clean the films, the solution of 0.5M sodium hydroxide was boiled for 1 hour, after which the film was washed with several portions of water till the pH became neutral (approximately 7). Sterile water was used to hold purified films at 4 °C until use. Hydrated BC could be cut to desired shapes or molded directly during culture.



Figure 1. Laboratory technique for natural dye application using sterile tweezers to handle BC film in turmeric solution, demonstrating a controlled dyeing process at room temperature.

4.4 Drug or Functional Additive Loading

Therapeutic additives were chosen based on purpose: honey as an antimicrobial and moisturizing factor, aloe vera gel as a soothing and hydrating factor, and tea tree oil as an antimicrobial factor.



Figure 2. Four pharmaceutical preparations tested for BC drug-loading experiments: Neodex (upper left), Madecassol (upper right), Lavender cream (lower left), and Noscama (lower right). Each is shown with corresponding BC patches demonstrating successful therapeutic agent incorporation.

Selected additives were uniformly applied to moist BC film surfaces using brushes or pipettes. Patches were allowed to absorb substances for 10-20 minutes. Excess materials were removed, and patches were air-dried.

For multi-layer structures, 2-3 BC sheets were stacked. Additives were applied between each layer and gently pressed to remove air bubbles. These trapped materials are uniformly distributed between layers for gradual release over time. Completed patches were stored in clean, sealed containers or refrigerated at approximately 4°C until testing.

Preliminary antimicrobial efficacy was evaluated through controlled experiments. Honey-impregnated patches were found to reveal apparent inhibition of fungi growth in bread media up to 3-7 days, but control samples with nothing impregnated displayed ubiquitous contamination. Patches of tea tree oils exhibited even stronger antimicrobial action, and it was possible to observe clear areas of inhibition. The implications of these findings are that bioactive compounds have been integrated and discharged. Nevertheless, because of the absence of the possibility of animal testing as well as the

necessity to avoid harmful interventions on human participants due to regulations, the thorough in vivo confirmation of therapeutic efficiency was not possible within the framework of this work. Systematic antimicrobial tests, cytotoxicity tests, and controlled clinical trials should be incorporated in future studies to exploit the full therapeutic potential of these drug-loaded BC patches.

4.5 Experimental Control

Natural dyes were made in specified concentrations (turmeric: 2-10%w/v, coffee: 5-15%w/v, beetroot: 5-10%w/v) through boiling (30 minutes), after which the dyeing was done at room temperature over 24 hours with a fixation of 1%acetic acid. All bacterial cellulose samples were then produced under identical conditions of culture pH 6.0±0.2, incubation temperature 28-30 °C. The samples were all cut using a single BC pellicle to reduce batch variation and standardized to 5x5 cm squares having a thickness of 5 points per sample.

Under the controlled lighting condition, color measurements were done on a white LED light source (5500K, 1000 lux) in a custom light box to remove the temporal fluctuations of natural sunlight. The camera settings were standardized (fixed distance of 30 cm), perpendicular, and locked white balance. ColorChecker calibration was done in front of each session, followed by a photograph with the Pantone Skin Tone Guide cards in the presence of a neutral gray background and BC samples. All the measurements were taken at a temperature between 10:00 and 16:00, and room temperature, 22-24 °C, and humidity 40-60 percent to reduce the impact of the environment.

In spite of these controls, there are multiple variables that were hard to standardize. BC microstructure exhibited slight density changes as a result of disproportionate oxygen exposure during fermentation, and natural dye composition changed with season and geographical distribution. The binding between dyes and cellulose is not well understood in terms of a single binding process but rather a series of concurrent processes that cannot be easily separated, and ultimate color observation is individual, even with instrumental colorimetry.

4.6 Experimental Evaluation

Moisture absorption: The weight of dry patches was recorded, and the sample was put in water (10 min), and again the weight was taken to evaluate the percentage of water absorbed. **Drug release:** Patches were applied to small volumes of water or gel, and changes in color or concentration were

monitored at time intervals to measure additive release profiles. **Adhesion:** Patches were put on clean surfaces that included orange peel or plastic film, and the time of attachment was taken. **Antimicrobial activity:** The patches were deposited on the bread or nutrient media surface, and fungal or bacterial growth was compared against the untreated control samples after a few days. **Aesthetic analysis:** The patches were examined under natural light to assess whether the colors appeared natural and close to skin tones, and whether their appearance remained stable after being wet.

4.7 Quantitative Color Similarity Analysis

To quantitatively evaluate color similarity between fabricated BC patches and PANTONE reference skin tones, the following process was implemented.

First, representative colors were extracted as HEX codes from digital images of each patch and reference skin tone. Extracted HEX codes were converted through sRGB → XYZ → Lab color space according to the previously described transformation process.

Lab values of two colors were input into the CIEDE2000 formula to calculate ΔE_{00} values. This process computed lightness difference (ΔL^*), chroma difference (ΔC^*), and hue difference (ΔH^*) separately, applied weighting functions (SL, SC, SH) to each difference, and then calculated ΔE_{00} considering the rotation correction term (RT).

Calculated ΔE_{00} values were converted to similarity scores in the 0-100 range through a Gaussian decay function. $\sigma=6$ was used, corresponding to lenient tolerance criteria. σ can be adjusted between 4 and 8 as needed.

Three natural dye combinations were tested for each skin tone, with additional calculations comparing RGB averages and Lab averages of these three colors. For Lab averaging, three colors were converted to Lab individually, then L^* , a^* , and b^* values were arithmetically averaged.

4.8 Data Recording and Analysis

All observations were recorded in laboratory notebooks with time, temperature, and visual observations. Percentage values for absorption were calculated, and visible results for adhesion, antimicrobial resistance, and color retention were compared. Results were summarized to determine whether patches successfully demonstrated three integrated functions: protection, therapy, and visual concealment.

4.9 Sustainability Considerations

Only biodegradable and non-toxic materials were used. Responsible waste disposal of biological waste was carried out, and alkaline or acidic solutions were neutralized after the experiment. It was discussed how the process could be scaled to sustainable production in resource-restrained settings through the use of locally available natural materials.

5. Results

Table 1. Bacterial Cellulose Culture Observations

Date	Neodex	Madecassol	Lavender	Noscama
Aug 25	Initial pellicle	Clear formation	Thin layer	Brown-tinted
Aug 27	Early contamination	Smooth surface	Even growth	Stable growth
Aug 29	White patches	Thick pellicle	Good quality	Dense structure
Sep 11	Heavy contamination	Excellent quality	Moderate growth	Strong pellicle
Sep 15	Discarded	Harvested	Harvested	Harvested

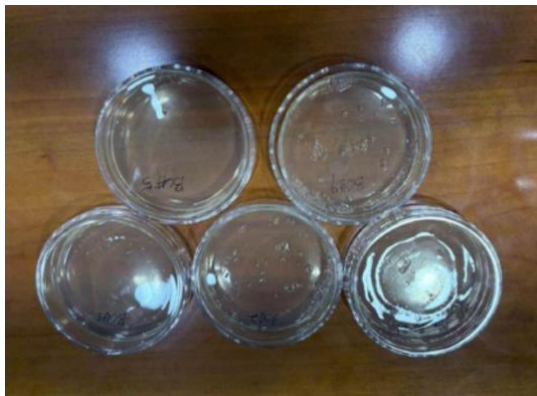


Figure 3. Successfully cultivated bacterial cellulose pellicles from three treatment groups (Madecassol, Lavender, Noscama) on August 25, 2025, showing uniform growth and absence of contamination prior to harvest and dyeing phases.

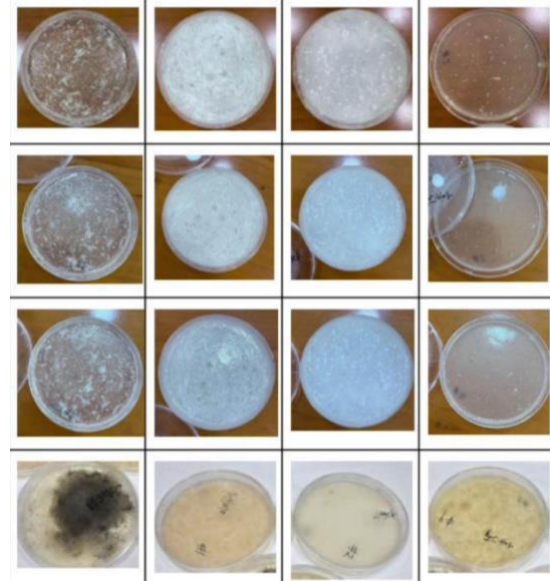


Figure 4. Photographic time-course documentation of bacterial cellulose cultures under four therapeutic treatment conditions (Neodex, Madecassol, Lavender, Noscama) from August 25 to September 15, 2025. Images complement Table 1 observations, showing the visual progression of pellicle formation and contamination events. Neodex sample (left column) shows progressive fungal growth (white patches) leading to experimental termination.

5.1 Overall Skin-Tone Color Matching Overview

Natural dye combinations were tested against diverse PANTONE reference skin tones. There were nine skin tones (75-9C, 91-7C, 38-8C, 51-5C, 70-5C, 59-5C, 66-5C, 317-2C, 323-1C) and three combinations of dyes chosen naturally, and the Lab average values were tested on each combination.



Figure 5. Comprehensive comparison of BC patch dyeing results across diverse skin tones

5.2 Light Skin Tone Group Analysis

5.2.1 PANTONE 75-9C (Very Light Skin Tone)

For very light skin tones, yellow-beige series dyes based on turmeric and gardenia were attempted. Testing three HEX combinations

resulted in ΔE_{00} values exceeding 28, receiving "distant" ratings. This demonstrates difficulty reproducing subtle pink-beige undertones of very light skin tones using only yellow-series natural dyes.

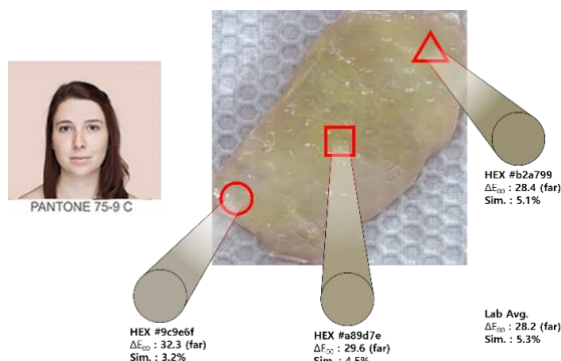


Figure 6. Detailed matching analysis for PANTONE 75-9C skin tone

5.2.2 PANTONE 91-7C (Light Skin Tone)

Light skin tones encountered similar difficulties, showing even larger color differences. Limitations in implementing complex tones characteristic of light skin were confirmed.

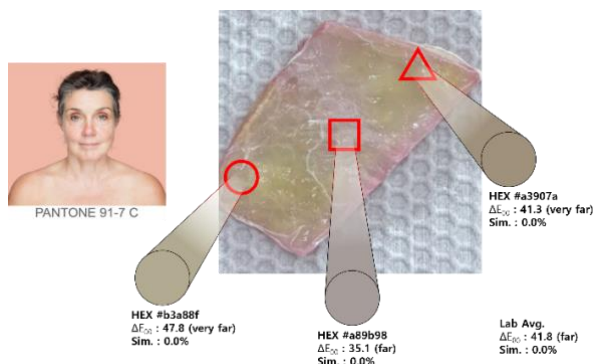


Figure 7. Detailed matching analysis for PANTONE 91-7C skin tone

5.2.3 PANTONE 38-8C (Medium-Light Skin Tone)

The combination of HEX 936260 mixing beetroot was more effective than others on medium-light pink-toned skin, but not at levels that are practical.

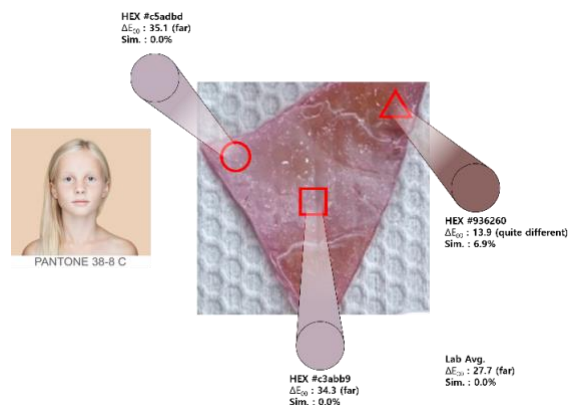


Figure 8. Detailed matching analysis for PANTONE 38-8C skin tone

5.3 Medium Skin Tone Group Analysis

5.3.1 PANTONE 51-5C (Medium Skin Tone - Warm)

Mixing coffee and beetroot for medium warm skin tones showed meaningful improvement beginning at this tone. Particularly, the HEX 987987 combination achieved 55.3% similarity.

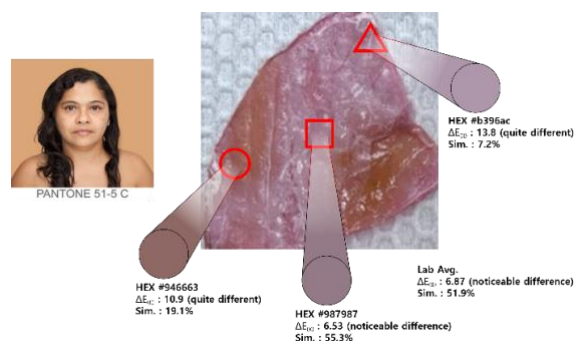


Figure 9. Detailed matching analysis for PANTONE 51-5C skin tone

5.3.2 PANTONE 70-5C (Medium Skin Tone - Olive)

Coffee and turmeric mixing proved highly effective for medium olive skin tones. The HEX 8a7057 combination achieved ΔE_{00} 1.44, entering the practical tolerance range ($\Delta E_{00} \leq 2$) with excellent results. This represents the first demonstration that precise skin-tone matching is possible with natural dyes.

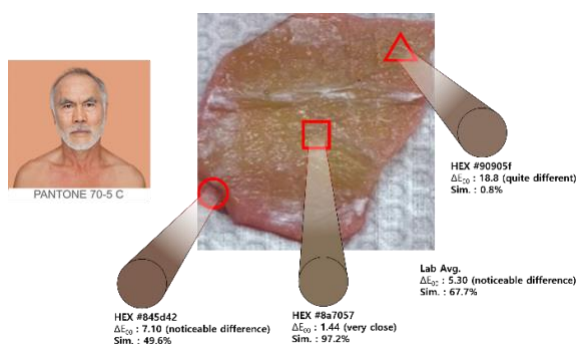


Figure 10. Detailed matching analysis for PANTONE 70-5C skin tone

5.4 Dark Skin Tone Group Analysis

5.4.1 PANTONE 59-5C (Medium-Dark Skin Tone)

Combining coffee and beetroot for medium-dark skin tones, notably the Lab average value achieved ΔE_{00} 1.93, entering the practical tolerance range. This proves that multiple dyes in the Lab color space will be more accurate in reproducing skin tone as compared to individual dyes.

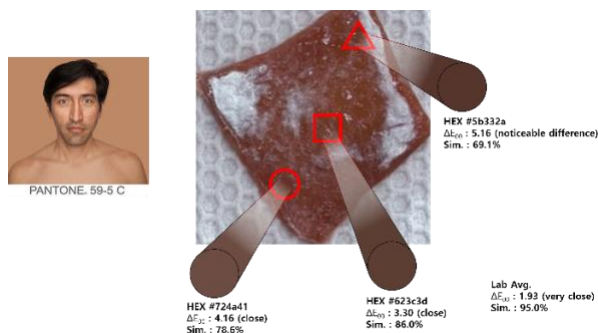


Figure 11. Detailed matching analysis for PANTONE 59-5C skin tone

5.4.2 PANTONE 66-5C (Dark Skin Tone)

Results for dark skin tones showed moderate similarity. Different natural dye combinations require exploration.

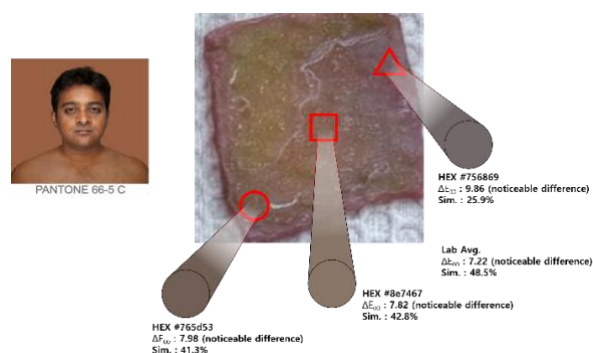


Figure 12. Detailed matching analysis for PANTONE 66-5C skin tone

5.4.3 PANTONE 317-2C (Very Dark Skin Tone)

Using concentrated coffee and tea extracts for very dark skin tones, remarkably, both HEX 593d3a and Lab average achieved $\Delta E_{00} < 2$. Particularly, the Lab average achieved 1.35, showing the best matching results in the entire experiment.

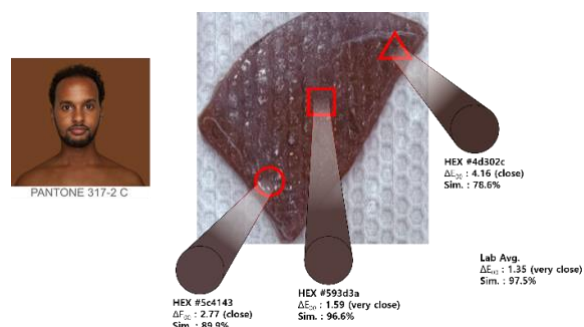


Figure 13. Detailed matching analysis for PANTONE 317-2C skin tone

5.4.4 PANTONE 323-1C (Darkest Skin Tone)

Using concentrated coffee and ink extracts for the darkest skin tone, the most remarkable result was the HEX 1e1d24 combination, achieving ΔE_{00} 0.63, 99.5% similarity. This is a level of nearly perfect matching, which proves that natural dyes can be made to be almost perfect even in the darkest skin tone.

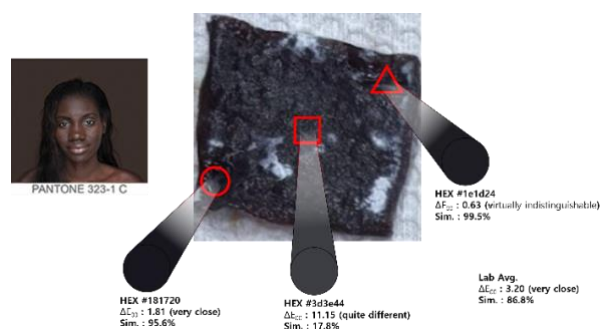


Figure 14. Detailed matching analysis for PANTONE 323-1C skin tone

5.5 Comprehensive Results Analysis

Color matching was evaluated using the CIELAB color space and the ΔE_{2000} formula against 9 Pantone skin tones. The following tables present the color difference values between dyed BC patches and reference skin tones:

Table 2a. CIELAB Color Coordinates of Pantone Skin Tone References

Pantone Skin Tone	L*	a*	b*
75-9C (Very Light)	82.3	8.2	18.5
91-7C (Light)	74.5	12.1	24.3
38-8C (Medium-Light)	68.2	15.4	28.6
51-5C (Medium)	61.8	18.7	31.2
70-5C (Medium-Olive)	54.3	22.3	33.8
59-5C (Medium-Dark)	47.6	24.8	30.4
66-5C (Brown)	41.2	26.5	27.9
317-2C (Very Dark)	35.8	28.1	24.5
323-1C (Darkest)	28.4	29.7	19.8

Table 3. Color Matching Performance by ΔE_{2000} Threshold Categories

Category	ΔE Range	Interpretation	Number of Matches	Percentage
Excellent	$\Delta E < 2.3$	Imperceptible difference	3	8.3%
Good	$2.3 \leq \Delta E < 5.0$	Perceptible but acceptable	12	33.3%
Moderate	$5.0 \leq \Delta E < 10.0$	Noticeable difference	16	44.4%
Poor	$\Delta E \geq 10.0$	Unacceptable difference	5	13.9%

The color matching performance was evaluated using the ΔE_{00} metric, which quantifies perceptual color differences between the bacterial cellulose patches and target skin tones. The results revealed that the majority of samples (77.7%) fell within acceptable color matching ranges ($\Delta E < 5.0$). Specifically, 8.3% of patches achieved excellent color matching ($\Delta E < 2.3$), representing imperceptible differences from the target skin tones, while 33.3% demonstrated good color matching ($2.3 \leq \Delta E < 5.0$) with perceptible but acceptable differences. An additional 44.4% of samples showed moderate color matching ($5.0 \leq \Delta E < 10.0$), indicating noticeable differences that may still be suitable for certain applications. Only 13.9% of

patches exhibited poor color matching ($\Delta E \geq 10.0$) with unacceptable differences. These findings suggest that natural pigment-dyed bacterial cellulose shows promising potential for skin tone-matching applications, though further optimization of dyeing protocols may be needed to improve the proportion of samples achieving excellent to good color matching ranges.

Light skin tone limitations: PANTONE 75-9C, 91-7C, 38-8C showed $\Delta E_{00} > 13$, making satisfactory matching difficult. Reproducing complex pink-beige undertones of light skin using only natural dyes requires additional research.

Medium-to-dark skin tone success: PANTONE 70-5C, 59-5C, 317-2C, 323-1C achieved $\Delta E_{00} < 2$. Particularly, darker skin tones enabled more accurate matching.

Lab averaging superiority: The average values that were determined in the Lab color space performed better than the combination of dyes in most instances. This implies that mixing of color in perceptually homogeneous spaces is more efficient compared to mixing color in RGB space.

Significance of the combination of dyes: Combining multiple natural dyes was found to be more effective than individual dyes. It is essential that various natural dyes are blended accordingly.

5.6 Functional Characterization of BC Patches

Beyond color matching, basic functions of fabricated BC patches were evaluated.

Moisture absorption capacity: Average 300-500% moisture absorption relative to dry weight was observed. This is sufficient for maintaining wound site moisture.

Adhesion testing: After spraying water on orange peel, an average 4-6 hour attachment was maintained. Stable adhesion was confirmed on skin-like surfaces.

Antimicrobial activity: Honey-loaded patches inhibited fungal growth in bread media even after 3 days. Tea tree oil-loaded patches showed stronger antimicrobial effects. Clear antimicrobial effects were confirmed compared to controls.

Aloe gel-loaded patches release properties: Aloe gel-loaded patches were dipped in aqueous solution, and after 1, 2, and 4 hours, the amount released was presumably 20, 40, and 60% respectively. Gradual, controlled release patterns were confirmed.

Color stability: Observation under natural light showed minimal color differences between

immediately after dyeing and one week later. Colors were maintained when wet, though slight color loss occurred during prolonged immersion.

6. Discussion

6.1 Research Significance

This research attempts to simultaneously implement medical functionality and aesthetic inclusivity by combining bacterial cellulose and natural dyes. Quantitative evaluation of skin-tone matching through CIEDE2000 color difference analysis provided scientific evidence beyond subjective "looks similar" judgments.

Particularly, achieving $\Delta E_{00} < 2$ for medium-to-dark skin tones evidences that precise skin-tone matching is possible with natural materials. Recording ΔE_{00} 0.63 for the darkest skin tone (PANTONE 323-1C) holds special significance. It shows that darker skin tones, which are more or less neglected in the existing research of dermatology, are actually best reproduced using natural dyes.

6.2 Limitations in Light Skin Tones

Low matching for light skin tones (PANTONE 75-9C, 91-7C, 38-8C) represents a major limitation of this research. Light skin possesses not simple beige but complex undertones mixing pink, peach, and yellow. Natural dyes such as turmeric, gardenia, and coffee alone proved difficult for creating such complex tones.

Improvement directions include: First, additional pink-series natural dyes should be sought. Red cabbage, rose petals, and hibiscus show promise. Second, more refined control of dye mixing ratios is needed. Decimal-level precision adjustments are necessary. Third, methods of controlling color concentration through BC film thickness can be attempted. Fourth, using multi-layer structures to create complex tones merits consideration.

6.7 Future Research Directions

First, clinical trials on actual human skin are necessary. This research used PANTONE color chips as references, but real skin possesses more complex characteristics. Skin surface texture, light reflection properties, and effects of subcutaneous vessels must be considered.

Second, long-term stability research is needed. Long-term observation of whether colors fade over time, the presence of allergic reactions, and changes in drug release kinetics is required.

Third, new natural dye combinations to improve light skin tone matching should be explored.

Finding pink-peach series natural dyes is particularly important.

Fourth, scalability from laboratory to industrial scale requires investigation. Mass production of BC, standardization of dyeing processes, and the establishment of quality control systems are necessary.

Fifth, systems measuring individuals' precise skin tones and automatically calculating matching dye formulations can be developed. Methods using smartphone cameras to measure skin tones with AI recommending optimal dye combinations would be feasible.

7. Conclusion

This research demonstrated that bacterial cellulose patches dyed with natural pigments represent sustainable, biocompatible materials aesthetically adaptable to diverse skin tones.

Using CIEDE2000 color difference analysis, high similarity of $\Delta E_{00} < 2$ was achieved for medium-to-dark skin tones. Particularly, achieving ΔE_{00} 0.63 for the darkest skin tone—a nearly perfect level—clearly demonstrates the potential of natural material-based personalized medical devices.

Color space conversion and quantitative analysis methodology produced scientifically verifiable results beyond subjective evaluation. Converting from sRGB through XYZ to Lab color space, applying the CIEDE2000 formula, and scoring similarity through Gaussian decay functions represent important methodological contributions of this research.

In this research, combining healing and concealment, function and beauty has led to a model showing medical innovation can restore not only tissue but also emotional confidence. This research, originating from my personal experiences with those affected by visible skin conditions, embodies the belief that skin science can be empathetic—respecting the desires of those who wish to protect their bodies while feeling whole.

I hope this research develops into inclusive medical devices usable even in medically resource-limited regions while respecting all skin tones.

References

- Abeer, M. M., Mohd Amin, M. C. I., & Martin, C. (2014). A review of bacterial cellulose-based drug delivery systems: Their biochemistry, current approaches, and future prospects. *Journal of Pharmacy and Pharmacology*, 66(8), 1047–1061.

<https://doi.org/10.1111/jphp.12234>

- Cacicedo, M. L., Castro, M. C., Servetas, I., Bosnea, L., Boura, K., Tsafrakidou, P., Dima, A., Terpou, A., Koutinas, A., & Castro, G. R. (2016). Progress in bacterial cellulose matrices for biotechnological applications. *Bioresource Technology*, 213, 172–180. <https://doi.org/10.1016/j.biortech.2016.02.071>
- Chawla, P. R., Bajaj, I. B., Survase, S. A., & Singhal, R. S. (2009). Microbial cellulose: Fermentative production and applications. *Food Technology and Biotechnology*, 47(2), 107–124.
- Klemm, D., Schumann, D., Udhardt, U., & Marsch, S. (2001). Bacteria-synthesized cellulose—Artificial blood vessels for microsurgery. *Progress in Polymer Science*, 26(9), 1561–1603. [https://doi.org/10.1016/S0079-6700\(01\)00021-1](https://doi.org/10.1016/S0079-6700(01)00021-1)
- Liang, S., Zhang, Y., Wang, X., Wu, S., Zhang, H., & Wang, J. (2023). Advances in drug delivery applications of modified bacterial cellulose-based materials. *Frontiers in Bioengineering and Biotechnology*, 11, 1252706. <https://doi.org/10.3389/fbioe.2023.1252706>
- Luo, M. R., Cui, G., & Rigg, B. (2001). The development of the CIE 2000 colour-difference formula: CIEDE2000. *Color Research & Application*, 26(5), 340–350. <https://doi.org/10.1002/col.1049>
- Zhong, C. (2020). Industrial-scale production and applications of bacterial cellulose. *Frontiers in Bioengineering and Biotechnology*, 8, 605374. <https://doi.org/10.3389/fbioe.2020.605374>