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Dyeing of Freshwater Pearls with Potassium Permanganate: Material Transformation and Symbolic Interpretation for Jewelry Design

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ABSTRACT

This study aimed to investigate and develop a dyeing process of freshwater pearls with potassium permanganate ($KMnO_4$) to enhance their suitability for contemporary jewelry design and give them more meaning in that context, tied to the myth of Venus's birth, which links beauty, new beginnings, and nature's strength. In the dyeing process, the pearls were dyed under different pH values, dye concentrations, and immersion durations. The colors were evaluated using CIELAB color measurements, and surface and chemical properties were characterized by using microscopy and Fourier Transform Infrared (FTIR) spectroscopy, respectively. It also includes surface color stability and color durability tests. According to the results, when the pearls were dyed, they turned a nice golden color and kept their original surface texture. The optimal conditions for achieving durable golden-yellow coloration were a $KMnO_4$ concentration of 2.5×10^{-2} to 5.0×10^{-2} M, a pH of 6-7, and a dyeing duration of less than 5 days, resulting in a total color difference (ΔE^*) of 23-25. Moreover, from a design perspective, the modified materials express emotions and cultural ideas. Each component in the prototype of jewelry serves as an interpretive object, showcasing both historical stories and current cultural ideologies. This study showed that the examined materials generate knowledge that links science, culture, and art.

1. INTRODUCTION

In today's design-oriented application of jewelry, materials are no longer only material, physical objects of form; they represent a narrative media, expressing identity, symbolic and cultural concepts, values, and values of tradition as much as technical properties [1]. Thus, jewelry is not only a purely ornamental device but a cultural object and an artefact of culture that is linked with stories, beliefs, and emotional experiences of the wearer. As a result, the search for novel materials and improvement in the quality of material as well as material quality have become key directions for the reinforcement of this conceptual strategy.

Materials used in modern jewelry design go beyond just being beautiful; they also reflect cultural narratives and language-based traditions. In the context of this research, modern jewelry design does not only mean contemporary aesthetic forms but rather a design approach that emphasizes the communication of meaning, identity, experimentation with materials, and the cultural experience of the wearer. The materials function in the design as both physical elements and media for conveying contemporary emotional and symbolic narratives. This aligns with a key trend in 21st-century design that emphasizes identity, symbolic meaning, and cultural values, as well as the technical qualities of materials [2]. In this context, jewelry becomes more than just an ornament; it serves as a cultural product that connects the user to stories, beliefs, and emotions. Therefore, the search for new materials and the enhancement of material quality are important steps in bringing this idea to life. The researcher connects this concept to the pearl industry, especially pearls, which are sustainable and carry deep cultural and emotional significance for those who wear them. Freshwater pearls are quite well-selling but under pressure with regard to the diversity of color of pearls, consistency of quality, adding value to fit the present market need, and storytelling for the pearl product in terms of dimension. Research has shown that the effectiveness, aesthetic value of natural gemstones (NEG), and market presence of raw materials increase significantly through better material production and quality improvements [3]. According to the research from Phlayrahan and Boonchu [4], the market for dyed pearls is growing because of the demand for more colors at an economical price, lower than that of natural pearls. Moreover, to increase aesthetic appearance, market value, catering to fashion trends, and consumer preferences, the researcher usually treats the pearl, such as dyeing, irradiation, bleaching, and optical whitening [5-7]. A lot of the research out there looks at how to color things and make them last. But their studies still lack the technicalities of pearl dyeing, such as limited parametric optimization, limited durability data for dyed freshwater pearls, and a lack of standardized durability testing. In addition, it often misses the deeper meaning. It

doesn't connect these technical details to the broader ideas about culture and what things represent in design.

The Birth of Venus is one of the most famous works that represents the most important symbolic narratives in Western art history associated with beauty, rebirth, and the power of nature. Artists from the Renaissance to modern artworks have reimagined this story, and it continues to hold relevance in contemporary design [8]. Beyond its art historical significance, the story of *The Birth of Venus* has a clear visual composition that can be directly decoded into design elements (i.e., sea, shells, beauty, purity, femininity, and rebirth), and it was mentioned in the context of birth and transition, which are consistent with material conditioning processes, especially freshwater pearls that have been dyed. These meanings are related to the cultural imagery of pearls in art history and contemporary design. Furthermore, Venus is one of the symbols that has been continuously reinterpreted in Western culture, making this narrative suitable as a conceptual anchor for interpreting the transformation of materials in jewelry design.

In this work, design adds symbolism from ocean waves, sponges, and shells to materials, such as dyed pearls, to create a strong connection between the physical characteristics and aesthetic and cultural significance of a material, which can help inform upcoming design trends [9, 10], on the significance of 'storytelling' and 'signs' in establishing value for creative goods, such as crafts and designs originating in ancient cultures. Moreover, this work investigates the material transformation of dyeing freshwater pearls with inorganic materials, creating new shades and color durability, as a material process used as a means of symbolic transformation in contemporary jewelry design.

In this study, material transformation refers not only to physical color alteration but also to the reinterpretation of materials as symbolic and cultural carriers within contemporary jewelry design. Following this idea, the work is regarded as material-led design research from a paradigm standpoint, based on the intersection of materials science with art and cultural interpretation to gain insights at the level of material and artistic knowledge, and new perspectives from the academic and creative industries on an international scale. In this work, experimentation with material is also presented not as a purely instrumental issue, but as a research methodology between science and cultural interpretation. This study, which treats dyed pearls as symbolic materials, aligns itself with a field of humanities-oriented design research that sees materials as carriers of narrative, identity, and emotional meaning. This approach responds to the contemporary design discourse that privileges narratives of value creation through culture, as opposed to materials innovation per se. Within this conceptual framework, this study interprets the changes in color, texture, and material properties as signifiers that can communicate cultural and emotional meanings following semiotics. The results of material experiments are then interpreted symbolically and translated into contemporary jewelry design, including aspects of composition, form, material arrangement, and the creation of aesthetic experiences.

2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

Recent advances in jewelry design research have shifted the emphasis from form and production methods to "material as a meaning carrier". This clearly indicates that jewelry is a cultural artifact and a symbolic medium that weaves the wearer's stories, beliefs, and emotions. Because of this, the current design deliberately integrates knowledge from other fields rather than being separate from historical and cultural contexts and aesthetic interpretations. The following topics are covered in the literature review:

2.1 Materials science of pearls, color processing, and color fastness in the context of jewelry design

Pearls are organic stones. It mainly consists of approximately 95% calcium carbonate ($CaCO_3$), with the polymorphic forms of calcite, aragonite, and vaterite, along with 4-5% of a protein matrix known as conchiolin and about 0.6-0.8% water [11-14]. Cultured pearls are generally classified into two main types: saltwater and freshwater. In recent decades, freshwater cultured pearls have attracted growing attention in the global jewelry market [5, 13]. Freshwater pearls come in many colors. These colors can be natural, coming from organic pigments in the nacre, or they can be made artificially after the pearls are harvested [4]. Based on the microstructure of pearls, microstructure changes even at a small scale of surface or layer level can have a considerable effect on the aesthetic value, and consumers' view about pearls [11]. So, to increase aesthetic appearance, market value, catering to fashion trends, and consumer preferences, the researcher usually treats the pearl, such as dyeing, irradiation, bleaching, and optical whitening [5-7]. In the past, researchers have studied the treatment and testing methods for the pearl; for example, El-Refi et al. [7] reported the use of silver nitrate for dyeing pearls; this technique has been used for many decades to intensify the color of the pearls. which silver nitrate penetrates the nacreous layers and undergoes chemical reactions with light and hydrogen sulfide gas, resulting in a very dark and nearly black coloration of the pearls. Patent No. CN101940395A [15] discloses a pearl dyeing method using crystal violet or lycopene dye, which involves pre-treatment by soaking in hydrogen peroxide and absolute ethanol and dyeing at different dye concentrations, surfactant levels, dyeing temperatures, and dyeing times. Their results showed that before the dyeing process, pearls need to be pretreated by bleaching and dehydration. The best dyeing conditions are 45 °C, a dye concentration of 0.1 mg/ml, and a dyeing time of 7 days. Du Toit et al. [16] investigated the color stability of "Chocolate" pearls produced by Ballerina Pearl Co. under conditions simulating routine consumer use, including exposure to heat, household chemicals, daylight, and common cosmetic products, to assess their influence on pearl color.

Pearl dyeing is not just a procedure of adding color to a natural substance itself, but a way to transform the material using a means of modifying the surface fabric, that is, interference with its nacre layers and surface structure. The color of pearls dyed with inorganic substances, and especially potassium permanganate ($KMnO_4$), is known in gemological research to produce shades from gold, brown, and dark brown, according to the reaction conditions and chemical environment of the dyeing process. This inorganic material may be converted to oxidation, ion exchange, or complex formation with nacre constituents, giving stable colors due to their stability, more than physical adsorption by organic dyes. Related literature also mentions that pH is an important color variable that defines the depth, uniformity, and durability of

the color. Low acidic conditions work better at opening the surface structure and penetrating the dye into the pearl layers than neutral or alkaline conditions. However, harsh dye conditions or immersion in the dye for too long can induce surface unevenness, local deposition of the dye, and degradation of the material structure. Because of this, controlling the dyeing process parameters would be the key performance indicator.

To use pearls in the key elements to produce aesthetically beautiful tones, color durability is a crucial connection between materials science, product development, and customer trust in the jewelry industry. According to the research on the application of gems, the change of color is a major disadvantage of colored pearls, especially in the presence of common chemicals, including cosmetics, perfume, and cleaning agents [6]. To determine whether the material can be utilized commercially, it becomes especially crucial to test the color durability under actual real-world situations. The goal of this study was to examine the relationship between color quality, luster, and color durability for real-world applications and the parameters of dyeing pearls with potassium permanganate (pH, concentration, and dyeing duration). The examination of the subject of material science and the design perspective elevates the dyeing process from the level of improving quality to the level of maximizing the potential of the pearls as a creative material in contemporary jewelry design.

While dyeing pearls using potassium permanganate is not a novel method in materials science, the gem business currently employs other methods. However, using this approach for design research and creating contemporary, cutting-edge jewelry is a concept and material innovation. The color change of the pearls becomes a "material transformation" in the current research, particularly when materials are used as semiotic symbols rather than merely as market value adders, as in this study. This also includes not just physical appearance but also the function and the potential of pearls as a natural element in the context of performing the function in the support of concepts and narratives. To establish the process of dyeing and the logical symbolic explanations of the material, it is vital to examine the materials science of the pearls.

2.2 Symbolic interpretation of *The Birth of Venus* from art history to contemporary design

The story of "*The Birth of Venus*" was one of the great symbols of Western art. It is a symbol of beauty, rebirth, purity, and the power of nature in the form of ocean waves, foam, seashells, and the light of birth. This tradition has been recreated and adapted into artworks in various periods, from the Renaissance to modernism. Artists like Sandro Botticelli, William-Adolphe Bouguereau, Alexandre Cabanel, and Pablo Picasso have mirrored the core meaning, albeit in different styles/gestures, and different art languages [17], and depending on their era, the meaning is equally evident. In semiotics, interpretations of *The Birth of Venus* in the humanities, for example, understand color, form, and material to be like a system of signs that carry cultural and emotional meanings [2, 10]. While their styles differed, the key idea is the same across the generations. But comparative inspection of the narrative reveals that this core symbol still exists: the elegant curves of the body, the shell shapes a space for birth, the movement of ocean waves representing natural power, and light symbolizing the moment that is born anew. The words are to carry the beauty and femininity ideals that have prevailed several times.

The study of design today suggests that adding historical narratives and myths to the design approach allows for semantic and emotional dimensions that are enriched by designs that create a sense of identity and self-differentiation [2]. This idea is consistent with the way design works within the historical symbolism framework: linking the past to the present with the form, materials, and color of the design. Thus, products are not only functional but also media for creating stories and emotional experiences with the user. This research involves weaving the meanings of Venus' birth into the process of material processing, with a focus on pearl dyeing. The colors of such dyed pearls are gold, brown, and purplish brown. It is thought to stand for female skin and the first light of the goddess's birth. Therefore, the color is not just a physical trait of a material but an "emotional language" that carries the message of beauty, rebirth, and vitality. This idea enables the use of dyed pearls as a symbolic material that underpins current jewelry design as an artistic form that integrates materials science with the arts and cultural analysis systematically.

2.3 Symbolic concepts, materials as storytellers, and their integration into jewelry design

Recent work in design over the last two decades has shown a conceptual shift in the understanding of materials to move towards the mediation of meaning, culture, and emotional experience over physical objects. The discourse of "material as narrative medium" describes when the materials can crystallize narratives of history, memories, and symbolic values through their color, texture, and material metamorphoses to create emotional languages that communicate with the user [2]. Within jewelry, in this sense, this idea takes the meaning out of jewelry as a decorative item and extends it to cultural things with a sense of identity.

Semiotics offers an important theoretical basis for understanding this mode of meaning creation. Saussure believed that a sign comprises a signifier and its perceived meaning [9], and Peirce stated that a sign plays roles as form (or its form plus index and symbol) [10]. These theories work hand-in-hand to illustrate the essence of color, form, and materials as sign systems that communicate cultural and emotional significance. As in jewelry design, the color of the materials has an artistic function beyond the cosmetic. But it is also a significant factor that stimulates the perception, feelings, and meaning of the individual doing it. The myth of "*The Birth of Venus*" has been used in the history of Western art as a symbol of beauty, rebirth, and the empowerment of nature. This work looks at artists from the Renaissance to modern art, such as Botticelli, Bouguereau, Cabanel, and Picasso, to illustrate the visual representation of the story. Although their works may differ depending on the era, the story's primary symbols, such as graceful curves, shells, the motion of ocean waves, and the light of birth, remain the same. They are symbols to represent beauty, femininity, and liveliness, which may be used in multiple modern designs.

Accordingly, the experimental outcomes obtained from pearl dyeing in this study were not interpreted solely as material properties, but also as symbolic signs that informed the conceptual and visual development of the jewelry prototypes.

2.4 Conceptual framework

This study uses a research framework as a material-led design that integrates knowledge from materials science, design, and semiotics to study material transformation as physical properties, chemical properties, and cultural conduit. The conditions in the dyeing process of pearls, specifically pH, dye concentration, and dyeing duration, affect the properties of the dyed pearls, including color intensity, surface quality, surface color stability, and color durability when exposed to common household chemicals. These material outcomes are then interpreted through the semiotic concepts of Saussure and Peirce, which look at the pearl color, pearl surface, surface color stability, and color durability with common household chemicals as signifiers conveying emotional and cultural meanings such as beauty, rebirth, mystery, and the power of nature [9, 10]. Then, apply this to contemporary jewelry design expressed through composition, form, color, and material arrangement. Table 1 illustrates the relationship between material science variables, material properties, semiotic interpretation, and the application of results to design decisions. Thus, demonstrating that the design process in this research is not solely driven by artistic inspiration but rather by a systematic connection between material experiment results, cultural interpretation, and design.

Table 1. Conceptual framework linking material transformation and jewelry design

Material Variables	Measurable Properties	Semiotic Signifiers	Design Decisions
pH level	Intensity of golden coloration	Rebirth, vitality	Warm gold color palette
Dye concentration	Darkness and tonal depth	Mystery, femininity	Pearl focal points
Dyeing duration	Surface texture and color gradient	Transformation, emergence	Layered composition
Surface oxidation	Organic surface characteristics	Oceanic movement, natural force	Wave-inspired forms
Color durability	Stability of material appearance	Permanence and value	Material selection for wearable jewelry
Tonal variation	Color gradient	Emergence and movement	Layered pearl arrangement

3. METHODS

This research is an integrated study in the humanities, design fields, and materials science, utilizing a material-led design research framework to investigate materials as a process for creating both the physical properties and symbolic carriers capable of generating cultural meaning through material transformation. The material science results are linked to aesthetic interpretation and contemporary jewelry design. The main material is freshwater pearls, whose characteristics are relatively similar to minimizing variation from their source material (semi-baroque shape, 6 to 7 mm in size, weighing 1.30 to 1.35 carats (1 carat = 0.2 g), and light cream color). The dyeing material was potassium permanganate ($KMnO_4$), an inorganic substance that may stabilize colors. The concentration of $KMnO_4$ solutions was 3.13×10^{-3}, 6.25×10^{-3}, 1.25×10^{-2}, 2.5×10^{-2}, and 5.0×10^{-2} M. Citric acid ($C_6H_{10}O_8$) concentration of 5 %w/w was used as a surface pre-treatment of the pearl before dyeing. Sodium hydroxide (NaOH) was used as a pH adjuster.

The dyeing process, which connects color, material, and meaning, could be thought of as a material metamorphosis. As a pre-treatment, cultured freshwater pearls were immersed in ethanol for 5 minutes to remove surface contaminants. The cultured freshwater pearls were then immersed in a 5 %w/w citric acid solution for 1 minute to enhance porosity and surface area. Following this pre-treatment, the reaction was halted by rinsing the sample with deionized (or clean) water. The second step involved treating freshwater cultured pearls with a dyeing agent ($KMnO_4$). This step was divided into three factors, which included dyeing at various pH values (pH = 2-7), dyeing durations (1-7 days), and dyeing at various concentrations (3.13×10^{-3}-5.0×10^{-2} M), with 5 samples of pearl in each condition and repeating 3 times per condition. The dyeing conditions are shown in Table 2. For the effect of pH conditions: The pH value of the dyeing solution was adjusted by adding a NaOH solution before immersing the freshwater pearls in the dyeing solution.

Table 2. The dyeing conditions of cultured freshwater pearls in $KMnO_4$ solution

Concentration of $KMnO_4$ (M)	pH	Dyeing Duration (Days)
5.0×10^{-2}	2	2 - 7
5.0×10^{-2}	3	2 - 7
5.0×10^{-2}	4	2 - 7
5.0×10^{-2}	5	2 - 7
5.0×10^{-2}	6	2 - 7
5.0×10^{-2}	7	2 - 7
3.13×10^{-3}	7	2 - 7
6.25×10^{-3}	7	2 - 7
1.25×10^{-2}	7	2 - 7
2.5×10^{-2}	7	2 - 7
5.0×10^{-2}	7	2 - 7

CIELAB color measurements were used to assess the colors. The CIELAB color scale (L*, a*, and b* values) was measured using a colorimeter (Linshang LS171). The instrument was calibrated prior to each measurement using the manufacturer-provided white calibration plate to ensure measurement accuracy. For each pearl, three surface points were measured to account for color heterogeneity, and the mean values were used for analysis. The total color difference values (ΔE*) were calculated from the differences between the L*, a*, and b* of the dyed pearl and the standard samples. While microscopy was used to analyze the surface. Fourier Transform Infrared (FTIR) spectroscopy (Bruker optics) was used to analyze the chemical properties, with ATR eco ZnSe mode, scan time of 32, resolution of 4 cm^{-1}, and absorption wave number of 600 – 4,000 cm^{-1}. The surface color stability of pearls under dry wiping is the ability of the color to remain on the pearl surface without peeling, fading, or transferring under mechanical stress. That test simulates the routine cleaning process typically applied after wearing pearl jewelry. A clean microfiber cloth was used as the wiping medium, and a constant normal load of 1.0 N (Similar to the force generated by the user's actual hand) was applied while wiping in a single direction, counting one forward–backward motion as one cycle, for a total of 10 cycles per specimen. The color durability testing of the dyed pearl with common household chemicals included alcohol, acetone, ammonia, household bleach, liquid soap solution, and dishwashing liquid solution.

Colorfastness evaluation and real-world simulated experimental circumstances were all used in the experimental quantification process.

From a design perspective, the experimental outcomes were further interpreted through semiotic and narrative design approaches associated with *The Birth of Venus*. The dyeing process's outcomes were interpreted using semiotic and narrative design frameworks, which connected to the goddess Venus' birth story. Based on explicable and verifiable material results, the hues of the dyed pearls, especially the golden and brown tones, were interpreted as symbolic representations associated with femininity, natural force, oceanic movement, and creation narratives. The experimental outcomes and symbolic interpretations were subsequently translated into jewelry design prototypes to demonstrate the integration of materials science, semiotic interpretation, and contemporary jewelry design practice.

4. RESULTS

4.1 The testing result of pearls dyed with $KMnO_4$

The apparent coloration of dyed pearls following dyeing with 5.0×10^{-2} M $KMnO_4$ solution under various pH conditions (2-7), a dyeing duration of 1-7 days, and at room temperature is presented in Figure 1. During the soaking period of 1–4 days, it was observed that under acidic conditions, the dyed pearls' color exhibited a deeper golden-yellow coloration than the dyed pearls' color under neutral conditions. The pH factor at acidic conditions causes darkening, which may be attributed to the increased oxidation efficiency of $KMnO_4$ in more acidic solutions. The oxidation potential (E^0) increases with decreasing pH, consistent with Eqs. (1) and (2) for neutral and alkaline conditions, and acidic conditions, respectively [18]. In the alkaline condition, MnO_4^- is reduced to MnO_2 through three electrons. On the other hand, in the acidic condition, MnO_4^- is reduced to Mn^{2+} via a five-electron process.

$$MnO_4^- + 2H_2O + 3e^- \rightarrow MnO_2 + 4OH^- + 0.59V(E^0) \quad (1)$$

$$MnO_4^- + 8H^+ + 5e^- \rightarrow Mn^{2+} + 4H_2O + 1.51V(E^0) \quad (2)$$

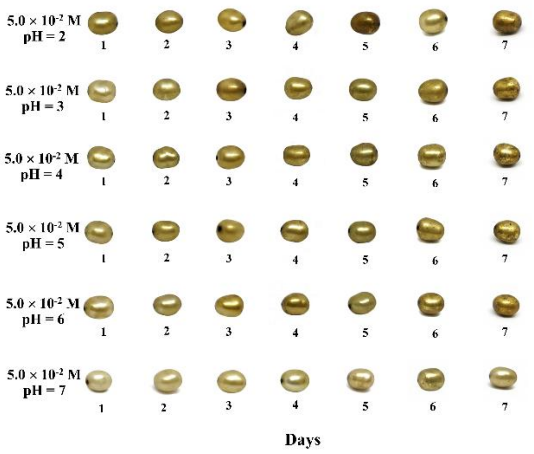

Figure 1. Apparent coloration of dyed pearls after dyeing under different pH values and dyeing durations

Moreover, increasing dyeing duration led to progressively deeper coloration. During the soaking period of 5-7 days, pearls under all pH conditions exhibited surface irregularities, characterized by dark brown spots dispersed on their surfaces due to excessive oxidation of the organic matrix associated with nacre and material degradation resulting from prolonged treatment. Despite these color variations of all samples, the natural luster of the pearls was retained throughout the process.

The apparent coloration of dyed pearls following dyeing with $KMnO_4$ solutions of various concentrations (3.13×10^{-3}-5.0×10^{-2} M), dyeing duration of 1-7 days, at a fixed pH (7), and at room temperature is shown in Figure 2. With increasing prolonged dyeing duration and $KMnO_4$ concentration solution, the dyed pearls' color progressively deepened from golden yellow to deep golden. This deepening of color is attributed to enhanced oxidation of surface organic components by nacre, generating new manganese-containing surface phases (MnO_2) resulting from extended exposure to potassium permanganate. In addition, increasing the dyeing duration and $KMnO_4$ concentration induced the electrostatic attraction forces between the positively charged sites on the pearl surface ($CaCO_3$: Ca^{2+}) and the negatively charged of MnO_4^- [19-21]. These observations are consistent with previous reports, which indicate that organic matrix, organic pigment, metal elements, dye concentration, dyeing duration, pH value, and physical structure influence pearl coloration [19, 22, 23], and these results are also consistent with prior work on pearl dyeing using organic chromophores such as crystal violet and lycopene reported in Patent CN101940395A [15]. Similarly to the previous section, soaking the dyed pearls for five days or longer resulted in the appearance of surface irregularities and the formation of dispersed dark brown spots on their surfaces (Figure 2). So, both pigment deposition and surface oxidation influence dyed pearls' color, leading to variation and, at times, uneven color development.

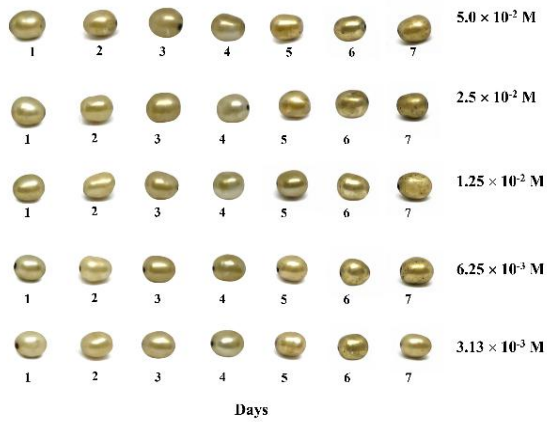

Figure 2. Apparent coloration of dyed pearls after dyeing under different $KMnO_4$ concentrations, dyeing durations, and fixed pH = 7

The total color difference (ΔE*) of dyed pearls after dyeing in 5.0×10^{-2} M $KMnO_4$ solution and under different pH values is shown in Figure 3(a). It was found that the ΔE* values of the dyed pearls were higher in acidic solutions than in neutral ones. In the strongly acidic range (pH = 2-4), the ΔE* value was about 31, whereas in the weakly acidic to neutral range (pH = 5-7), the ΔE* values were between 23 and 25. These results are consistent with the visual appearance of the dyed

pearls shown in Figure 1. The ΔE* value also depended on the concentration of the $KMnO_4$ solution and the dyeing duration. During the dyeing duration of 1 to 4 days, the ΔE* values generally increased with both concentration and dyeing time. At low $KMnO_4$ concentrations (3.13×10^{-3}-1.25×10^{-2} M), the ΔE* values increased rapidly during the first two days and tended to stabilize thereafter. In contrast, at higher concentrations (2.5×10^{-2}-5.0×10^{-2} M), only a slight increase in ΔE* values was observed during the initial stage, followed by stabilization after the second day, as shown in Figure 3(b).

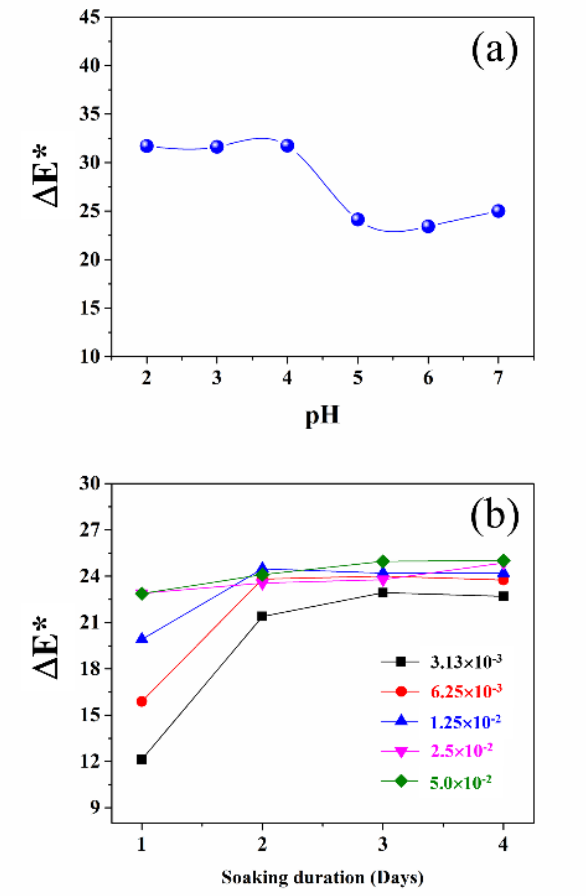

Figure 3. Total color difference (ΔE*) of dyed pearls after dyeing with $KMnO_4$ solution, (a) different pH values and 4 days of dyeing duration, and (b) various concentrations and 1-4 days of dyeing duration

FTIR spectra were used to examine the chemical characteristics of the pearl and dyed pearls to ascertain the sample's chemical makeup. The distinctive FTIR spectra of pearl and dyed pearls are illustrated in Figure 4. Both pearl and dyed pearls exhibited characteristic peaks at approximately 651, 701, and 857 cm^{-1}, corresponding to the aragonite phase. These peaks are attributed to the internal vibration modes of the carbonate ion (CO_3^{2-}), with the ν_4 mode appearing at 651 and 701 cm^{-1} and the ν_2 mode at 857 cm^{-1} [24, 25]. Typically, high-quality freshwater cultured pearls display the aragonite phase [14, 26]. A peak at 1365 cm^{-1} was assigned to MnO_2, representing the surface –OH groups of Mn–OH in colloidal MnO_2 [27]. The absorption band around 1200 cm^{-1} corresponds to C–O stretching vibrations. Peaks associated with $KMnO_4$ were observed at approximately 1744 and 1404 cm^{-1}. As the $KMnO_4$ concentration increased, the intensity of the aragonite peaks decreased, while other peaks became more prominent, which may be due to the higher $KMnO_4$ concentration. Carboxyl, ketone, and ether groups cannot be formed on the pearl surface at low $KMnO_4$ concentrations in limited reaction times [28]. The FTIR spectra correspond to the increasing deep golden color (Figure 2) and the rise in ΔE* (Figure 3(b)) as $KMnO_4$ concentration increases, which is associated with the enhancement of Mn-related FTIR bands and the relative attenuation of aragonite signals. As the spectra of MnO_2 and other Mn-based compounds were increased, maybe due to their forming a thin layer, which modifies light absorption, scattering, and dynamic force at the nacre interface, thus intensifying the golden to brown hues [19, 20, 29].

The results of the surface color stability test under dry wiping conditions for dyed pearls at different pH values and dyeing durations, as well as for samples at different $KMnO_4$ concentrations and dyeing durations at pH 7, are shown in Figures 5(a) and 5(b), respectively. The surface color stability increased with increasing pH, from the minimum at 2 days dyeing for pH 2 to the maximum at 4 days dyeing for pH 6 and 7. Noticeably, slight color removal was observed on dyed pearls at higher pH values and longer dyeing durations, as indicated by the days marked with an asterisk in Figure 5(a). This may be due to the pH of the $KMnO_4$ solution in the dyeing process strongly affecting oxidation potential, concentration of ions, and chemical structure of dye, thereby influencing their substantivity and fastness on materials (i.e., biomineral materials, cellulose-based fabrics) [12, 13, 19]. The surface color stability under dry wiping conditions of dyed pearls, evaluated at various dyeing durations and $KMnO_4$ concentrations, displayed distinct behaviors (Figure 5(b)). Dyed pearls exhibiting visible color removal after testing are indicated with an asterisk. At a $KMnO_4$ concentration of 3.13×10^{-3} M, dyed pearls dyed for 1-6 days exhibited no detectable color removal following wiping, indicating effective dye fixation. In contrast, at higher $KMnO_4$ concentrations ranging from 6.25×10^{-3}-5.0×10^{-2} M, dyed pearls dyed for 1-4 days demonstrated good color stability with no visible color removal. However, when the dyeing duration exceeded 5 days, these samples showed noticeable color detachment and surface fading after dry wiping.

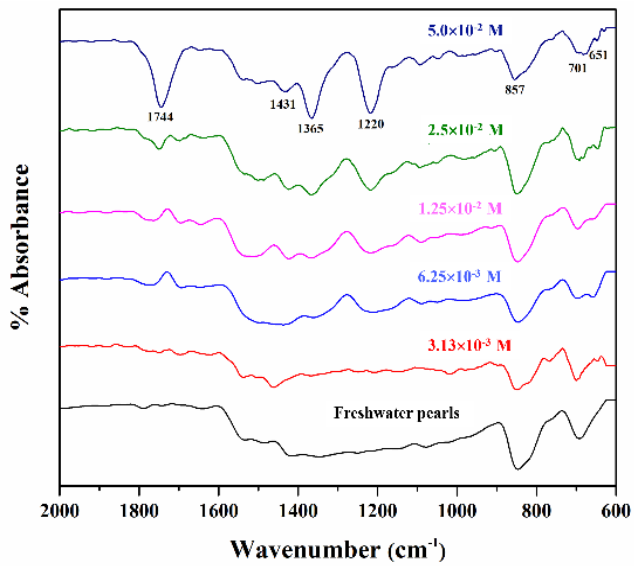

Figure 4. Fourier Transform Infrared (FTIR) spectra of pearl and dyed pearls with different concentrations

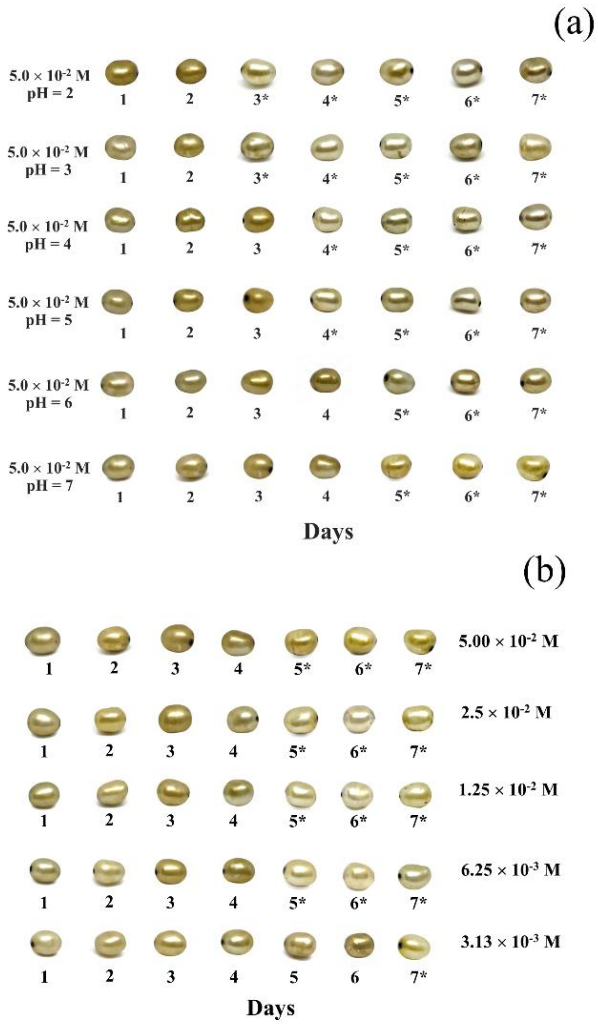

Figure 5. Apparent surface color stability of the dyed pearls after dyeing under dry wiping conditions (a) under 5.0 × 10^{-2} M $KMnO_4$ at different pH values for 1-7 days, (b) under different dye concentrations at pH=7 for 1-7 days

From those results, the appropriate conditions for dyeing pearls with $KMnO_4$ are dyeing concentration 5.0 × 10^{-2} M at pH = 7 for 1-4 days. In comparison with CN101940395A, dyed with crystal violet or lycopene, the reported optimum is at the concentration 0.1 mg/ml, and 7 days yields uniform, stable colors [15]. The contrast observed indicates that the $KMnO_4$ system, which is related to the formation of MnO_2-bearing surface layers, helps to fast-color development but may cause surface defects over a longer dyeing duration, whereas the organic dye systems have slower diffusion, causing the molecular chromophores to enter the nacre and thus requiring a longer dyeing duration for homogenous coloration.

The microscopic images of the freshwater pearl, the pre-treated pearl before dyeing, and the dyed pearls' surfaces are presented in Figure 6(a-l). All samples in Figure 6 exhibit the luster of natural freshwater pearls, while the surface morphology and color distribution gradually become less uniform as dyeing duration increases. After a dyeing duration of 2-3 days (Figure 6(e-h)), the surface color appeared uniform throughout the dyed pearls, with only slight dark spots observed. When the dyeing duration was extended to 3-4 days (Figure 6(i-l)), the dyed pearls' surfaces became less uniform, with some areas showing a lighter color. This could be because some of the pigment came off. There were also a few dark spots on the surfaces, which could be due to flaws that were already there, like pits, pores, and scratches, that are common on natural pearls [4]. They may be due to the impact on dye absorption in those localized regions.

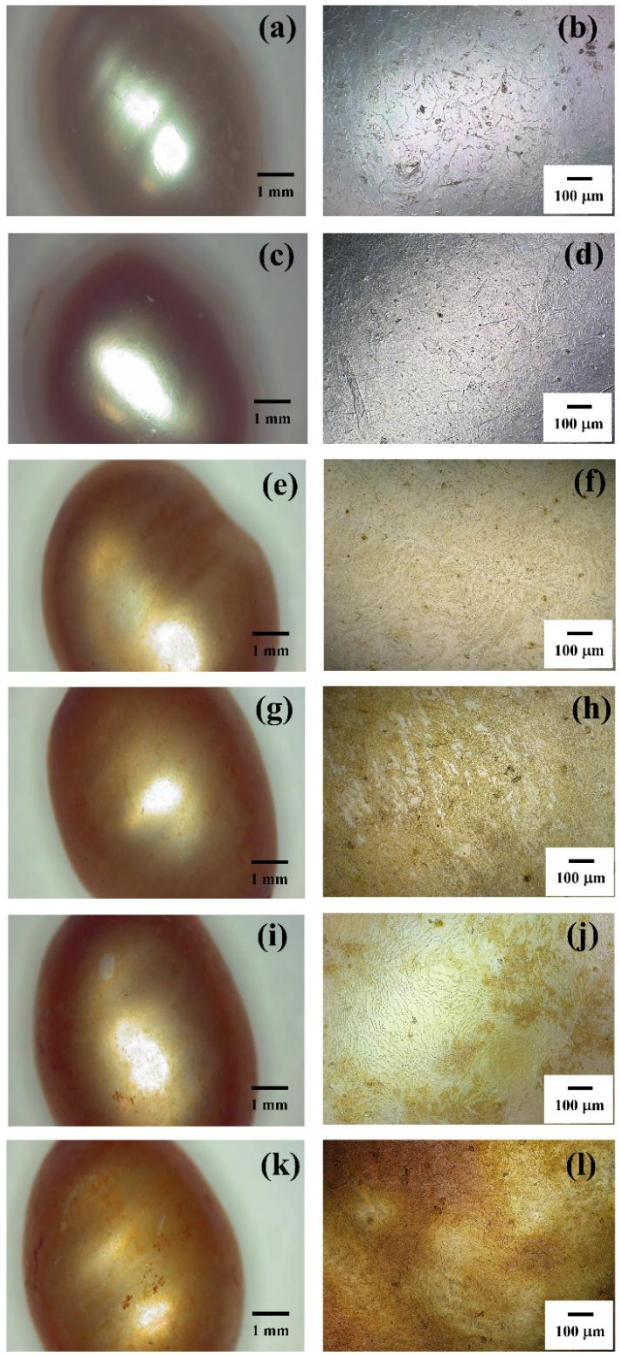

Figure 6. Surface micrographs of pearls: (a-b) untreated freshwater pearl; (c-d) pre-treated pearl before dyeing; and (e-l) pearls dyed in 5.0 × 10^{-2} M $KMnO_4$ at pH 7 for (e-f) 1 day, (g-h) 2 days, (i-j) 3 days, and (k-l) 4 days

The high resolution of the pearls' surface micrographs is shown in Figure 6(b, d, f, h, j, l). It presents the prismatic layers that stack on layers of nacre tablets with an aragonite crystal structure, which corresponds with the FTIR result that shows the aragonite phase of freshwater pearls. Moreover, the pearl surface still shows the pores with the flaws of natural pearls [30, 31]. The surface of the pre-treated pearl before dyeing and

the dyed pearl still show the prismatic layers of an aragonite crystal structure, suggesting that mild acid cleans and smooths the outermost layer without severely etching the underlying aragonite platelets.

The color durability of the dyed pearls in common household chemicals is summarized in Table 3. When the dyed pearls were exposed to different household chemical solvents, they reacted very differently. The dyed pearls that didn't seem to be affected were the ones that had been in alcohol for 5 hours. This shows that the surface is relatively resistant to weak organic acids. In contrast, immersion in acetone caused the color to fade noticeably after 3 hours. This means that stronger organic solvents can partially break down the surface layer and speed up the process of pigments leaching. Also, soaking in ammonia and bleach for 1 hour and 30 minutes, respectively, caused the colors to fade slowly and the samples to look darker. These reactions are consistent with the findings reported by Du Toit et al. [16]. The color of the samples started to fade after 30 minutes, and the coating layer started to peel after 1 hour in liquid soap. After 3 hours, the samples in dishwashing liquid were clearly less colorful. The surfactants and alkaline builders in these detergents probably help the coating come off or separate, and make it easier for dyes to move.

Table 3. Color durability testing of dyed pearls (dyeing condition with 5.0×10^{-2} M $KMnO_4$ at pH 7 for 2 days) with common household chemicals

Common Household Chemical	Condition	Result
Alcohol	Immersed in 95% ethanol for 5 h	No visible color changes were observed on the samples.
Acetone	Immersed in reagent-grade acetone for 5 h	No visible color change was observed within the first 3 h; thereafter, the color of the samples gradually faded with increasing time.
Ammonia	Immersed in 10% ammonium hydroxide for 18 h	No visible color change was observed within the first 1 h; thereafter, the color gradually faded with increasing time, with pronounced fading and the appearance of a dark tone observed in samples.
Household bleach (Hygiene)	Immersed in 6 wt% sodium hypochlorite (bottled, undiluted chlorine bleach) for 1 h	No visible color change was observed within the first 30 min; thereafter, the color gradually faded with increasing time, with pronounced fading and the appearance of a dark tone observed in samples.
Liquid soap (Shokubutsu Monogatari)	Immersed in diluted liquid soap (a ratio of liquid soap and clean water = 1:20 mL) for 1 h	Color fading was observed within the first 30 min., and the coating layer peeling was observed within 1 h.
Dishwashing liquid (Sunlight)	Immersed in diluted dishwashing liquid (a ratio of dishwashing liquid and clean water = 1:20 mL) for 1 h	No visible color change was observed within the first 1 h; thereafter, the color started to fade after 1 h and clearly faded in 3 h.

4.2 Conceptual connection between *The Birth of Venus* and gold-dyed pearls

Analysis has shown that Renaissance and Modern period paintings of "*The Birth of Venus*" present a very similar emphasis on the goddess Venus and use the Venus (or goddess) figure, symbolizing perfection, vitality, and love. Creative artistic objects and unique features add to the atmosphere. Additionally, every work has been created in varying cultural and historical circumstances, making it a space for different purposes, as shown in Table 4, and different interpretations, which are fascinating to viewers, reflecting changes in the cultural and historical times. The study implies that symbolism, beauty, and spiritual conviction are related concepts across "*The Birth of Venus*" and the gold-dyed pearls. The key symbolic, artistic, emotional, and cultural themes identified through the analysis of *The Birth of Venus* artworks are summarized in Table 5. Hall insists that pearls, a "natural" material closely identified with purity, beauty, and rebirth, correspond with Venus's "emerged from the sea inside a seashell" symbol—a classical metaphor for the natural ideal of beauty [32]. Thus, the golden process of dyeing pearls is not just "adding value" from a physical or economic perspective but also acts as a "significance in its symbolic value" and thus turns and makes the material into a symbol for sublime beauty and perfect ideal, such as in today's symbolic design theory about materials. The symbolic interpretation presented in this section was developed through the analysis of experimental material outcomes, particularly color variation, tonal depth, and surface characteristics observed in the dyed pearls.

Table 4. Symbolic, artistic, and cultural analysis of *The Birth of Venus*

Aspect	Summary
Symbolism	Venus serves as the primary symbol for love and beauty in all artwork. A common metaphor for birth, rebirth, and regeneration is the seashell. Venus's celestial and idealized nature is further reinforced by other embellishments like angels and mythological or natural beings that allude to nature and purity.
Artistic Elements	In order to establish harmony and balance, each piece of art uses a variety of compositional techniques, such as the purposeful use of color, dynamic linear movement that boosts visual vibrancy, and the development of depth through light and shadow. Venus is the main subject of every piece, although her importance is highlighted by various artistic techniques and visual hierarchy.
Emotion and Atmosphere	A variety of emotional expressions are evoked by the artworks' general ambiance, from tranquility, beauty, and enchantment to more complicated and violent moods. Despite these differences, the goddess Venus's grace and mystery are consistently portrayed through body language, subtle color use, and facial expressions.
Cultural and Historical Context	The social ideals and cultural surroundings of various historical periods, from the Renaissance to the Modern era, are reflected in all works, which affirm the impact of classical literature and legendary storytelling. These influences have influenced artistic styles including Impressionism, Neoclassicism, and Neoromanticism, which frequently use the figure of Venus to examine the significance, worth, and depiction of femininity.

Table 5. Symbolic, artistic, and theological connections between dyed pearls and *The Birth of Venus*

Topic	Core Concept	Description	Connection to "Dyed Pearls" and "*The Birth of Venus*"
Symbolic Connection	Beauty, Purity, Uniqueness	Gold-dyed pearls symbolize beauty, purity, and feminine skin tones	Venus is born from the sea and a seashell (the origin of pearls); the gold color elevates Venus's value and represents ideal perfection.
Artistic Interpretation Dimension	Transformation and Value Enhancement	Gold-dyed pearls convey both external and internal beauty	Comparable to the multiple interpretations of a painting, "beauty is gold created from the outer shell."
Theological Dimension	Purity, Nobility, Sacredness	Pearls symbolize purity, nobility, and the attainment of a cultural ideal	Venus represents idealized beauty; gold signifies transcendental or supernatural beauty ("beauty is interpreted through symbolic meaning").
Jewelry Design Approach	Inspiration from *The Birth of Venus*	Artistic dimension: warm tones, luxury, gold pearls as focal points \Design: wave motifs, tiered arrangements, diamonds/gemstones \Composition: symmetry, curved lines, gold pearls as the visual center	Visual elements from *The Birth of Venus* are translated into contemporary jewelry design.
Conceptual Summary	Timeless Beauty	Gold-dyed pearls as symbols of beauty, perfection, and sacredness	The integration of "gold-dyed pearls" and *The Birth of Venus* culminates in the concept of "Golden Birth Jewelry."

In terms of artistic interpretation, they resemble the artistic content of *The Birth of Venus*, employing colors, lines, and equilibrium with purpose in terms of portraying external appearance while conveying the internal self of the subject. The gold color of the pearls communicates that value is not inherent but created and enhanced through perception and interpretation, which echoes some of Botticelli's ideas: multiple levels of meaning for the same thing, which can be approached according to the viewer's cultural and aesthetic background [33]. Therefore, beauty originates from the process of perceiving, understanding, and the individual's aesthetic experience rather than being restricted to appearance.

The symbolic significance of gold-dyed pearls relates to concepts of purity, nobility, and idealized beauty within cultural interpretation and jewelry design. That corresponds with the image of Venus as the goddess of love and beauty. The natural origin of pearls reflects the relationship between the material and cultural meaning; therefore, pearls serve as a "symbolic intermediary", a link between inner virtues and outward expression. This is consistent with Hall's research, which states that symbolic intermediaries are a widely discussed concept in the study of sacred symbolism and material culture in art and design [32].

The use of these ideas in the design of gold and pearl jewelry is a clear testament to how classical art can be turned into modern design. The reflection of the aesthetic ideals of the Renaissance consists of warm tones, flowing curves, and harmony. Furthermore, they remain relatable to modern sensibilities. The movement, rhythm, and luxury in design elements convey the meaning from Wave-like shapes, layering, and harmonious gemstone combinations. Meanwhile, the balanced collocation and emphasis on the gold and pearls supported the materials as a primary symbol. That corresponds to the research in position materials, with stories and cultural representations instead of just static parts [34]. These symbolic interpretations provided the conceptual basis for the subsequent jewelry design process, in which experimental material outcomes were translated into compositional structures, color arrangements, and symbolic design elements.

4.3 Application of materials in jewelry design

The use of dyed pearls in the jewelry design is shown in Figure 7. The jewelry design prototypes apply the dyed pearls from the experiment with the concept of *The Birth of Venus*. Moreover, the materials from the experiment were transformed into meaningful and beautiful ones. The jewelry prototypes were developed and designed, including color variation, tonal depth, and surface characteristics. This research informed compositional and symbolic decisions in contemporary jewelry design. The visual and compositional development of the jewelry prototypes was directly informed by the experimental outcomes of the dyed pearls, particularly the tonal variation, pearl surface, and color gradients observed during the dyeing process. Moreover, the experimental materials were translated into symbolic and culturally informed jewelry forms through the design process. The use of dyed pearls in this work is not typical experimentation; instead, it goes beyond the simple application of different-toned dyed pearls. Three jewelry design prototypes, including a brooch converted into a pendant and earrings that are derived from The Birth of Venus picture, are part of the Divine Emergence series. In addition, three creative dimensions were used to define the prototypes as art elements, art composition, and art expression.

Figure 7. Jewelry design prototypes featuring dyed pearls inspired by *The Birth of Venus*, from the collection titled "Divine Emergence"

Art Elements: The goddess's curves, flowing hair, and moving waves all represent movement and softness, and they were inspired by the painting "*The Birth of Venus*." The

subdued shades of gold, pastel shades, and deeper shades like purple and brown represent the mystery. The deep purple, bright gold, and reddish-brown colors, all produced by the $KMnO_4$ dyeing of the pearls, symbolize the mystery and allure of the Venus myth. The wavy shapes of the pearls make them the most important part of the modern jewelry design.

Art Composition: The goddess is typically positioned at the center of artistic compositions depicting Venus, directing the viewer's attention to the focal point through the details presented in the artwork. Similar to the goddess, the pearl functions as a "new Venus" in jewelry design, drawing attention to it with structural shapes and metal lines. Asymmetrical balance, or the waves that surround the goddess, gives the image a sense of rhythm and a contemporary appearance.

Art Expression: Venus represents beauty, rebirth, and nature, while the shell and sea foam represent protection and rebirth. Jewelry design is a form of emotion and expression, and this is all expressed through metaphorically birthing the sea and expressing this in the form of pearls. While settings built on curves that resemble shells or waves convey beauty, warmth, security, and the emotional layers of Venus' mythical birth, deep or iridescent pearl colors convey mystery.

The results are presented in an important aspect of contemporary jewelry design that focuses on telling the story rather than decoration. The different tones of the dyed pearl add dimension to the concept and symbolic connections to femininity, mystery, and rebirth. This result corresponds with that of Alan et al. [35], which shows that the transformation of material can significantly increase a design's narrative efficacy. The Divine Emergence collection's visual language is based on curvilinear shapes, an unbalanced balance, and a strong focal point. All these compositional elements are aesthetic codes of cultural significance that are connected to a story, like patterns related to Venus, such as waves, shells, and the process of emergence. The use of culturally embedded images supports Liu and Zhao's suggestion that cultural codes are incorporated for specific purposes in contemporary design to elicit perception and emotional involvement [36]. The combination of experimental material processes with mythological reading is a prime example of research-oriented design. According to Besten [37], the convergence of technical innovation and cultural meaning-generation is recognized as a key characteristic of modern art jewelry. The pearl's central position and flowing curves combine form and concept, evoking concepts of fluidity and symbolic renewal. Generally speaking, a combination of visual symbolism, myth, and experimental material creates a robust conceptual framework for modern jewelry design, expanding its linguistic, cultural, and intellectual influence.

5. CONCLUSIONS

This study has demonstrated that dyeing freshwater pearls with potassium permanganate ($KMnO_4$) can be utilized in the jewelry industry for both color alteration and material transformation of the pearls. The dyed pearls exhibited a wide range from golden-yellow to deep gold, with different pH, dye concentration, and immersion duration. Under acidic conditions (pH = 2-4), pearls exhibited higher oxidation efficiency and a greater effect on the deeper coloration, compared to lighter tones at near-neutral pH (pH = 5-7). The dyeing duration (more than 5 days) and higher $KMnO_4$ concentrations increase color intensity but cause brown spotting due to $KMnO_4$ solution degradation. Microscopy confirmed that shorter immersion maintained uniform color, whereas longer dyeing duration induced pigment degradation. FTIR analysis indicated the aragonite phase and increased surface manganese species with higher $KMnO_4$ content. The stability testing for everyday usage confirms that dyed pearls produced under appropriate conditions remained suitable for jewelry applications despite all the exposure to strong household chemical agents that caused the fading. The optimal conditions for achieving durable golden coloration were 0.25-0.5 $\times 10^{-2}$ M $KMnO_4$, pH = 5-6, and dyeing periods under five days. These controlled parameters enable the production of stable, aesthetically appealing dyed pearls suitable for innovative jewelry applications.

By positioning dyed pearls as a symbolic rather than decorative material, this work has ramifications not only for material science but also for the humanities and design discourse. According to semiotics and storytelling design, the golden and brownish colors that $KMnO_4$ dyeing made were thought to be connected to the myth of *The Birth of Venus*, which stands for beauty, rebirth, femininity, and the power of nature. According to semiotic and storytelling design approaches, the golden and brownish tones produced through $KMnO_4$ dyeing were interpreted as symbolic representations associated with *The Birth of Venus*, particularly in relation to rebirth, femininity, and cultural meaning. In this context, color becomes an emotional and cultural language. Pearls are used to tell stories and share their history that goes beyond physical color. These findings form the basis for the development of jewelry design prototypes, demonstrating how innovative material techniques can yield culturally significant design products. These prototypes further demonstrate the significance of material-led design research as a knowledge-generation process capable of connecting scientific experimentation with artistic interpretation through material transformation. Although the scope of this study is restricted to freshwater pearls and a single inorganic dye, the general methodology can be applied to various natural materials and cultural narratives in future investigations. Lastly, the study demonstrates how modern design may create jewelry that is both technically exceptional and culturally significant by combining an emphasis on materials science, meaning-interpretation, and design. This study contributes to contemporary jewelry design research by demonstrating how experimental material processes can be systematically integrated with semiotic interpretation and cultural storytelling to generate both material and design knowledge.

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