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Innovation from Pearl Oysters: The Development of a New Sustainable Multifunctional Pearl Powder

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1. Introduction and Objectives

In recent years, in response to rapid environmental changes on a global scale, human society has been increasingly required to adopt a global perspective and coordinated action to address these challenges [1, 2]. The cosmetics industry is no exception, with environmentally conscious initiatives such as regulations on the use of UV absorbers and microplastics gaining traction worldwide. Consequently, there is a growing search for alternative raw materials that can perform functions equivalent to those of the regulated substances, particularly from natural biological resources. Pearls, produced by living organisms, represent an appealing material expected to align with environmental goals not only due to their aesthetic value but also because of their potential for CO_2 fixation through biomineralization [3].

In anticipation of the Sustainable Development Goals (SDGs), we have developed a system to fully utilize materials derived from the pearl oyster *Pinctada fucata* and apply them in cosmetics and health foods (Figure 1).

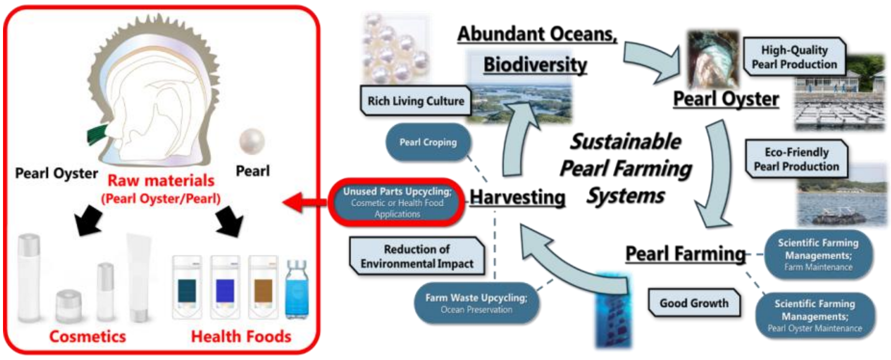


Figure 1. Sustainable zero-emission pearl oyster farming system and upcycling mechanism to convert unused parts into cosmetic raw materials. The red box shows an image of the advanced use of unused components of pearl oysters/pearls in cosmetics or health foods.

The nacreous layer of the pearl oyster shell is known to exhibit a unique brick-and-mortar structure, composed of alternating layers of calcium carbonate and thin protein sheets, similar to that of pearls [4]. The optical properties of light, the reflected light produced by irradiating light onto the nacreous layer, and the interference light produced by light entering the nacreous layer give the nacreous layer a unique and attractive glow [5]. The nacreous layer is composed of various soluble and insoluble proteins that are involved in the formation of calcium carbonate crystal structures [6, 7].

In this study, by focusing on the ability of pearl oysters to form nacreous layers and the process of processing nacreous layers, we have developed an innovative and multifunctional white powder (pearl powder) that produces pearly spherical crystals from demineralized liquid containing nacre-forming components. In this presentation, we introduce the physical properties and functionality of this pearl powder, as well as examples of its application in cosmetics.

2. Materials and Methods

2-1. Materials

After grinding and removing the ridge column layer of the pearl oyster *Pinctada fucata*, the shell nacre layer was demineralized by adding a strong acid, and solid-liquid separation was performed by centrifugation and filtration. The resulting aqueous solution is hereafter referred to as the demineralized solution. To obtain the demineralized solution, an aqueous solution of basic salt was added and stirred, and the solids produced were collected by filtration, washed with water, and dried to obtain a pearl powder (Figure 2).

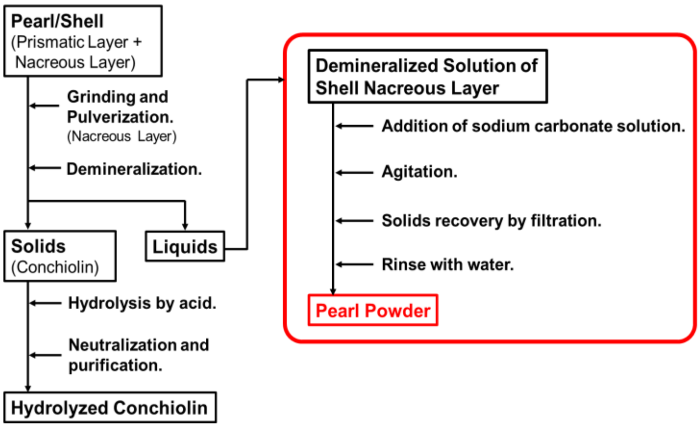


Figure 2. Pearl powder manufacturing process. The area in red border shows the flow of the pearl powder manufacturing process. This flow effectively utilizes the demineralized liquid produced during the manufacturing process of conchiolin, the active ingredient obtained from the nacreous layer of pearls and shells.

2-2. Physical Properties Analysis

The physical properties of the obtained pearl powder, such as the particle shape, crystal structure, and size distribution, were analyzed using a scanning electron microscope (SU3500, HITACHI), an X-ray diffraction (XRD) system (Ultima IV, Rigaku), and a particle size distribution analyzer (SALD-7500nano, SIMADZU).

2-3. Comparison of Powder Raw Material Characteristics

To investigate the usefulness of pearl powder as a cosmetic ingredient, we measured the oil absorption (ISO 787-5:1980) of four types of oils (oleic acid, triolein, liquid paraffin, and

Table 1. Types of samples used in evaluation tests. The effects of the different crystal shapes and properties of each $CaCO_3$-derived powder and microplastic powder were compared.

Samples	INCI	Shapes	Origin/Features
Control	Calcium carbonate	Plate crystal	Shell nacreous layer (Mainly $CaCO_3$). No microporous structure.
Pearl Powder	Calcium carbonate	Spherical crystal	Shell nacre demineralized solution (Mainly $CaCO_3$). Microporous structure.
Sample A	Hydroxyapatite	Plate crystal	Synthesis of shell nacre (mainly $CaCO_3$) and $Ca_3(PO_3)_2$. Microporous structure.
Sample B	Hydroxyapatite	Spherical crystal	Synthesis of $CaCO_3$ and $Ca_3(PO_3)_2$. Microporous structure.
Sample C	Calcium carbonate, Sodium metaphosphate	Spherical crystal	Spherical calcium carbonate crystals. Microporous structure.
Sample D	HDI/Trimethylol Hexyllactone Crosspolymer, Silica	Spherical crystal	A kind of microplastic powder. No microporous structure.

squalene), including sebum components. In addition, the friction properties were measured using a KES-SE friction tester (KatoTech), and the optical properties were measured using an angle-difference photometer (GP-5, MURAKAMI COLOR RESEACH LABORATORY). For the above measurements, various powders listed in Table 1 (including plastic powders that were once commonly used in cosmetics) were used as test products, and powders with different physical properties were measured from various angles and compared with the pearl powders.

2-4. Clinical Trial

To investigate the application of pearl powder in cosmetics, the pore-hiding properties of pearl powder formulated on a liquid foundation were examined. The test products are listed in Table 2 (approved by the Ethics Committee). Ten subjects (5 males and 5 females, mean age: 42.0±11.3 y.o.) who were concerned about the appearance of pores were selected, and the purpose of the study was explained and agreed upon. The number of pores in a 3 cm × 6 cm area on the left and right cheeks of each subject was counted using VISIA system (Integral Corporation) before the application of the test products. The number of pores was compared 5 min after 0.04 g of each test product was applied to the same area.

Table 2. Composition of the test substance used in the clinical trial.

Components	Composition ratio (%)	
	Control	Experimental product
Water	23.23	22.73
Silicone	21.00	21.00
Pigment	19.64	19.64
Preservative	11.00	11.00
Emollient	7.77	7.77
Solvent	7.00	7.00
Hydrocarbon agent	5.00	5.00
UV absorber	4.00	4.00
Chelating agent	0.05	0.05
Thickener	1.30	1.30
Calcium Carbonate (Pearl Powder)*	**0.00**	**0.50**
Powder	0.01	0.01
Total	100.00	100.00

*Pearl Powder safety tests for skin irritation, eye irritation, and skin sensitization were conducted using OECD TG439, TG491, TG492, and TG442C alternative animal testing methods, respectively, and all were found to be negative, followed by human studies (RIPT) to confirm no safety issues.

3. Results and Discussion

3-1. Physical Properties of Pearl Powder

Figure 3 shows the results of the various physical property analyses of the pearl powder. The powdered particles are spherical and porous (Figure 3A). XRD analysis also showed that the pearl powder was calcium carbonate with a vaterite-type crystal structure (Figure 3B). Next, the particle size distribution was measured, showing that the particles were relatively uniform in size, with an average diameter of 6.592±0.304 μm, a median diameter of 7.442 μm, and a mode diameter of 8.131 μm (Figure 3C).

These results suggest that pearl powder is smooth to touch and easily adsorbs sebum and dirt and has soft-focusing properties by penetrating pores and other areas. The demineralized solution from which the pearl powder contained soluble proteins among the proteins in the nacreous layer, as mentioned at the beginning of this paper, and $CaCO_3$ without these factors, did not produce uniform spherical crystals (data not shown). This suggests that the components of the nacreous layer may be involved in the formation of the spherical crystals of the pearl powder. If the control mechanism of the crystal shape of pearl powder can be clarified, it will be possible to develop various powder materials with different functions for different applications.

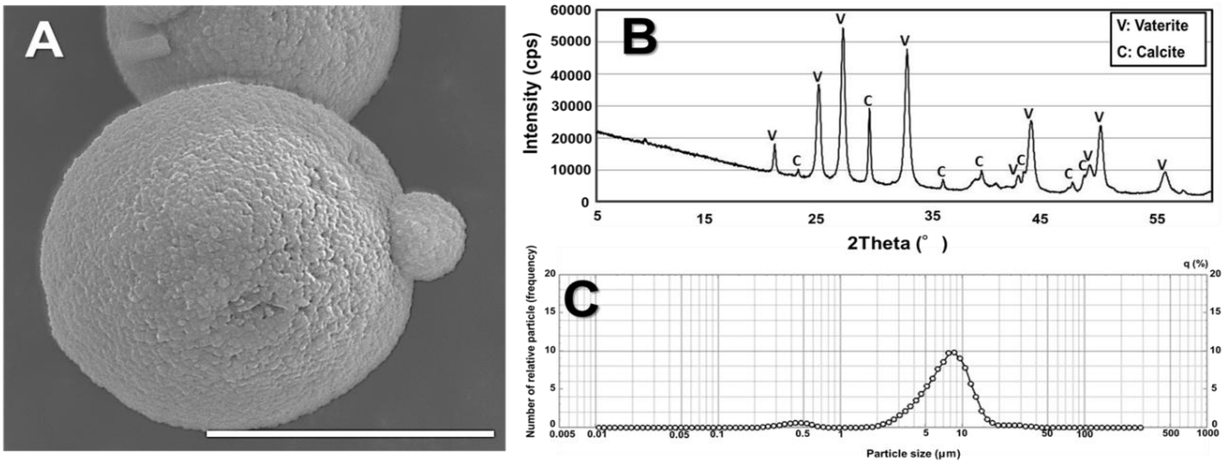


Figure 3. Physical analyses of pearl powder. **A**: Electron microscope image of pearl powder at 10.0 k × magnification. The scale bar indicates 10 μm. **B**: XRD analysis of pearl powder. V and C indicate vaterite and calcite crystal structures, respectively. **C**: Particle size distribution of pearl powder. The mean particle size of the pearl powder was 6.592±0.304 μm, median diameter 7.442 μm, and mode diameter 8.131 μm.

3-2. Comparison of Pearl Powder and Other Powder Materials

The oil absorption results for each oil type for each powder and pearl powder are shown in Figure 4. The pearl powder exhibited the highest oil absorption for oleic acid, followed by liquid paraffin, squalene, and triolein. This trend was also observed in Sample C, which had the same spherical $CaCO_3$ particles as the pearl powder, but the oleic acid oil absorption was higher in the pearl powder. These results suggest that both have selective oil absorption properties that specifically adsorb oleic acid. Oleic acid is an unsaturated fatty acid and a component of sebum. Exposure to ultraviolet light generates reactive oxygen species on the skin, which oxidize oleic acid and produce lipid peroxides [8].

As this accelerates skin inflammation and causes skin aging, these powders, which can selectively adsorb oleic acid, are expected to suppress skin inflammation caused by UV irradiation. Sample A exhibited the highest oil absorption across all oil types among the tested products, followed by Sample B. However, the types of oil adsorbed differed between Samples A and B. Although both are hydroxyapatite, their particle shapes vary. Sample A is derived

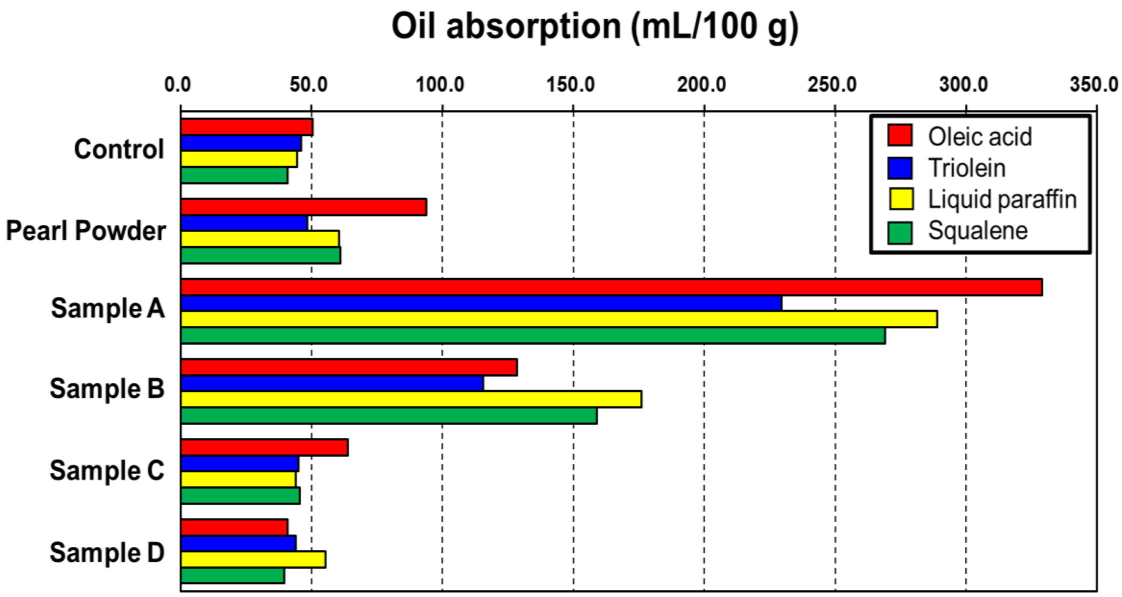


Figure 4. Composition of oil absorption for different types of oil for each powder (n=3).

from the nacreous layer of the pearl oyster shell and contains a small amount of protein, while Sample B is derived from inorganic $CaCO_3$. These differences in particle shape and composition may account for the variation in oil absorption. Sample D, a plastic powder, consistently showed the lowest oil absorbency across all fats.

Figure 5 presents the results of frictional property tests for each powder (excluding pearl powder). Sample D demonstrated the best performance in terms of smoothness and low

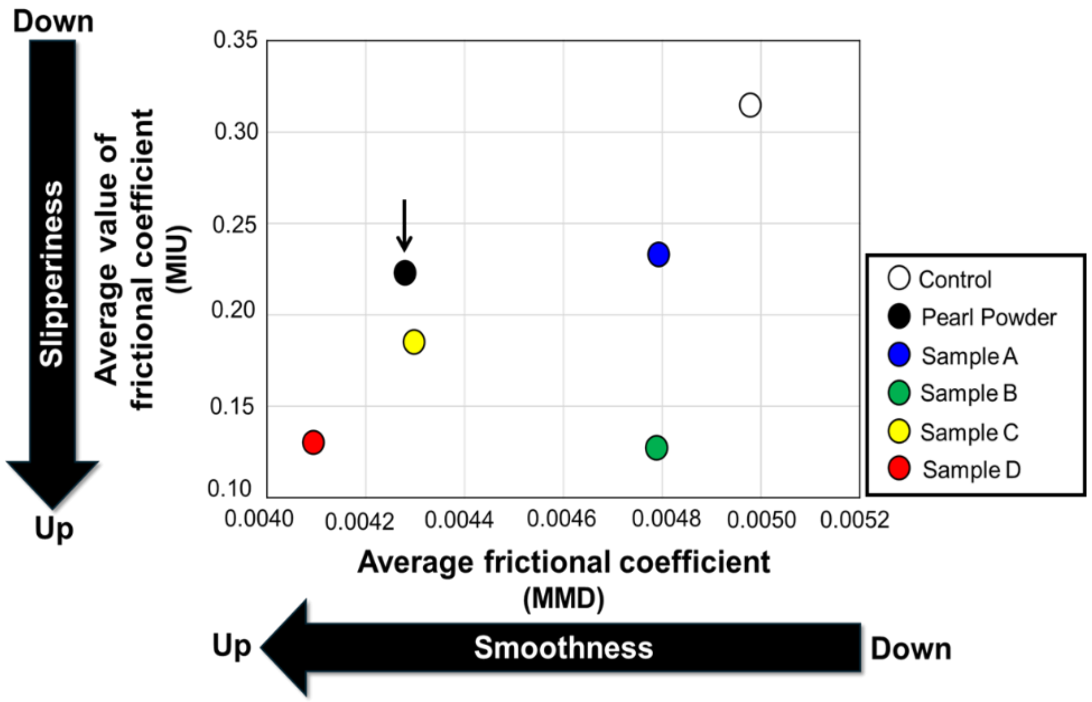


Figure 5. Comparison of frictional properties of each powder (n=5). MIU and MMD indicate slipperiness and smoothness, respectively, with lower values indicating greater effectiveness. Arrows indicate the frictional properties of pearl powders.

roughness, followed by Sample C and the pearl powder. The performance differences between Samples A and B may again be attributed to their differing particle shapes.

The measured optical properties of the powders are shown in Figure 6. In the retroreflective region, Sample D tended to show the highest reflection intensity at a particular angle, but overall, pearl powder and Sample B showed the flattest and highest reflection intensities. Samples C and A followed this order, suggesting that the shape of the crystals had a significant effect on the reflection intensity in retroreflection. Although there was a slight difference in the retroreflectance intensity between the powders, they were almost identical.

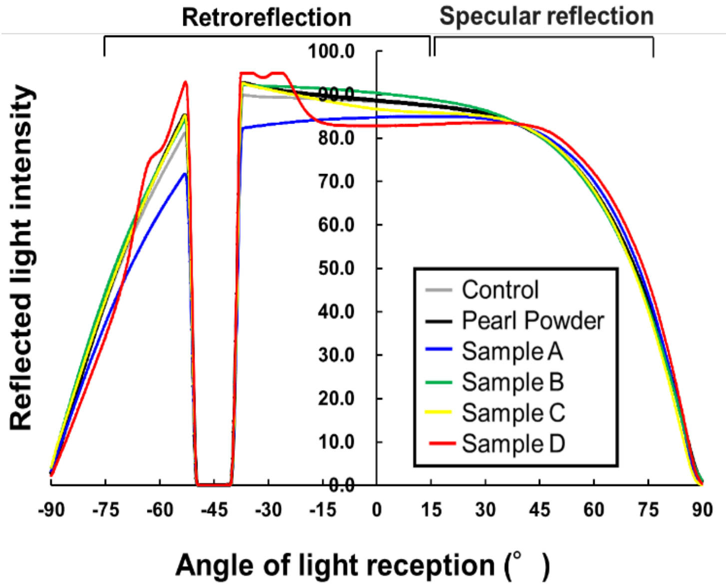


Figure 6. Comparison of the optical properties of each powder (n=3). The retroreflective area (-75° to 15°) is an indicator of soft focus when the powder is applied to the skin. The retroreflective area (15° to 75°) is an indicator of smoothness when the powder is applied to the skin. The higher the intensity of these reflections, the smoother the powder is with soft-focus properties.

The particle shapes and size distributions of the powders are shown in Figure 7 and Table 3. The control and Sample A exhibited a plate-like particle shape; however, the former lacked a

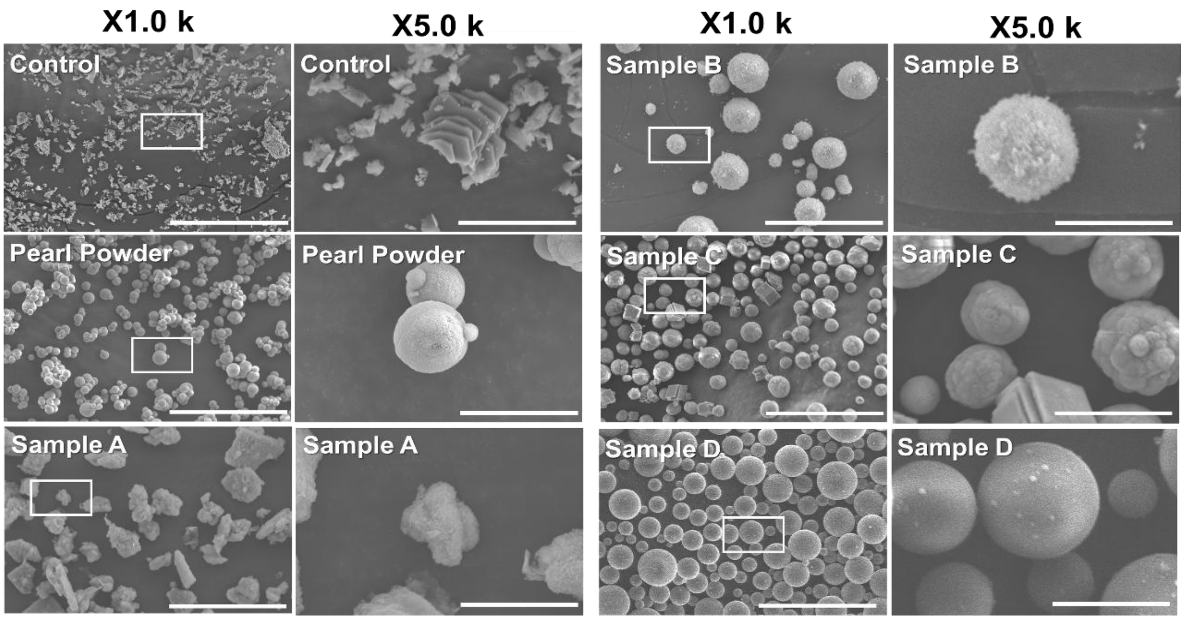


Figure 7. Comparison of particle shape for each powder. Each SEM image is of each powder material at 1.0 k × magnification and 5.0 k × magnification, with the area squared in the 1.0 k × magnification image magnified at 5.0 k × magnification. 1.0 k × magnification and 5.0 k × magnification, the scale bars indicate 10.0 μm and 50.0 μm, respectively.

fine porous structure, whereas the latter exhibited a scaled, layered, porous structure. Pearl powder and Samples B, C, and D each exhibited a spherical particle shape; however, only Sample D showed no microporous structure. Sample B had a slightly non-uniform particle shape compared to pearl powder and Sample D. On hand, sample C was found to have the most uniform particle size among the powder materials evaluated in this experiment. These results indicate that the pearl powder exhibits oil absorption, friction, and optical properties comparable to or better than those of existing raw powder materials.

These results indicate that pearl powder is not only complement the challenges posed by plastic powder formulation regulations in cosmetics, but also that its production process makes it an environmentally friendly, sustainable, and innovative raw material.

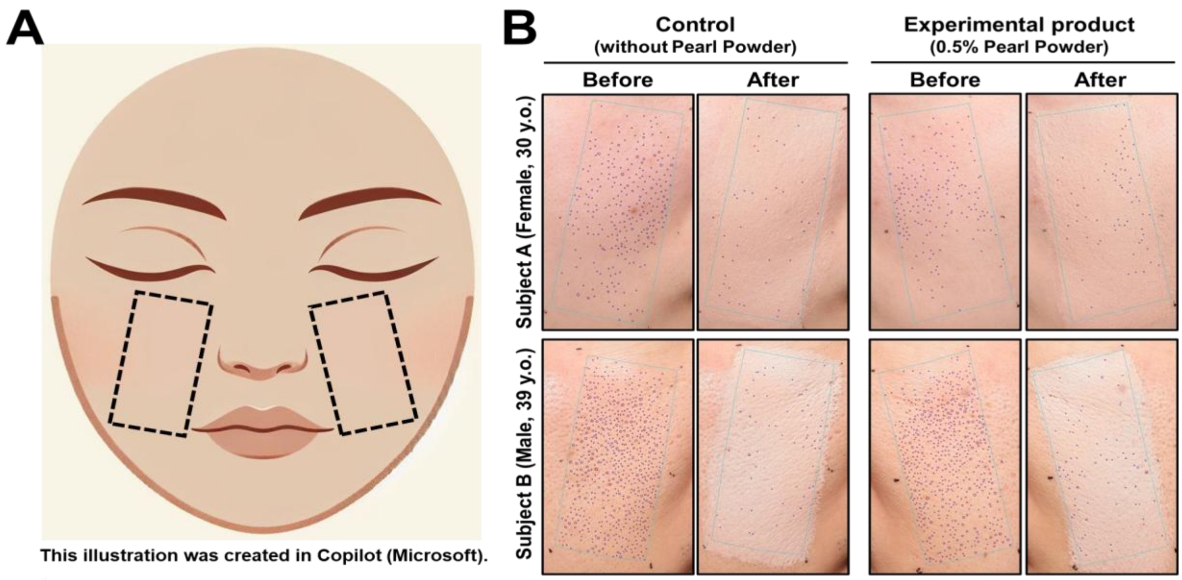
Table 3. Comparison of particle size distribution for each powder raw material.

Samples	INCI	Particle size distribution (μm)		
		Average particle diameter	Median diameter	Mode diameter
Control	Calcium carbonate	3.760 ± 0.656	4.386	18.548
Pearl Powder	Calcium carbonate	6.592 ± 0.304	7.442	8.131
Sample A	Hydroxyapatite	13.989 ± 0.327	15.319	15.092
Sample B	Hydroxyapatite	11.970 ± 0.388	14.786	18.548
Sample C	Calcium carbonate, Sodium metaphosphate	9.209 ± 0.091	9.258	9.992
Sample D	HDI/Trimethylol Hexyllactone Crosspolymer, Silica	11.516 ± 0.295	12.872	12.280

3-3. Functionality of Pearl Powder in Foundations

Figure 8 shows the pore-concealing properties of pearl powder blended in a liquid foundation. There were no significant differences between the control and test products, and both showed comparable pore-concealing properties. However, although there were significant individual differences, both men and women tended to show better pore-concealing properties with pearl powder than with fewer pores. This suggests that a clear difference in pore concealment may be observed if the amount of pearl powder in the formulation is increased, but at the same time, the compatibility of usability as a formulation is also an issue to be considered.

In this study, we verified the functionality of pearl powder as a cosmetic product using its pore-concealing property as an indicator in a liquid foundation, where the difference in formulation could be observed in a relatively short period of time. In the future, it will be necessary to further examine the functionality of pearl powder when blended with basic cosmetics such as facial cleansers.



C

Subjects	Relative values to average pores of skin count: Control		Experimental product (0.5% Pearl Powder)	
	Before	After	Before	After
Female	1.00	0.33	1.00	0.36
Male	1.00	0.21	1.00	0.17
Total	1.00	0.25	1.00	0.23

Figure 8. Pore coverage with liquid foundation containing pearl powder. **A**: Areas measured in VISIA (dotted squares, 3 cm × 6 cm). The left side is the control and the right side is the test area. **B**: Pore images before and after application of the control and test liquid foundations. Circles indicate the number of pores. **C**: Relative pore counts of the control and test product before and after application of the liquid foundation.

4. Conclusion

In this study, we successfully developed a new cosmetic raw material, pearl powder, from demineralized liquid containing calcium or protein derived from nacreous layer, which is produced in the manufacture of conchiolin powder, a cosmetic raw material. This demineralized liquid has not been used effectively as a cosmetic ingredient for several years. However, by upgrading it as a cosmetic raw material in this study, we were able to transform it into a new, innovative, and sustainable cosmetic raw material that minimizes the risk of releasing residues constantly generated during the raw material production process into the environment. This new raw material has a high functionality equivalent or superior to that of existing powder raw materials. These properties are complement the challenges posed by restrictions on the incorporation of plastic powders in cosmetics [9] and are expected to expand their use in cosmetics.

The results of this study provide a good example of the sustainability of both systems for utilizing pearl oysters as a resource and the efforts to utilize them as a material for beauty and health that have been developed by our predecessors. Based on the wisdom of our predecessors and the new discoveries and ideas that can be obtained from pearls, we will continually address new challenges. We also believe that the spread of such initiatives worldwide will lead to the preservation of the global environment and harmony with human activities. Through these efforts, we will continue developing attractive materials and strive to create a recycling-oriented society.

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