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Innovation and Application of Natural Organic Cosmetic Formulations: A Case Study of Bochu Cosmetics

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Abstract

Amidst the global clean beauty market's annual growth rate of 11.2%, natural organic cosmetics still face common bottlenecks such as the easy deactivation of plant actives, insufficient cleansing power of sulfate-free systems, and distortion of green processes during scale-up. This paper, using the continuous industrial data from Guangzhou Bochu Cosmetics Co., Ltd. from 2018 to 2024 as the sole sample chain, constructs a quaternary synergistic framework of "plant efficacy module - green surfactants - biopreservation - energy module." The consistency of "activity - efficacy - scale-up" is verified at a 10 t scale. Low-temperature instantaneous cell disruption (≤40°C, 30 MPa) increases the yield of cinnamon polyphenols by 32%. The sulfate-free ternary micelle of "amino acids + APG + avena alkaloids" reduces MIT irritation by 62% with only an 8% decrease in foam height. The synergistic biopreservation system challenges a bacterial total count of <10 CFU g^{-1} over 28 days, and the microbial ecology remains balanced within 60 days after opening, as confirmed by 16S rRNA.

Keywords: natural organic cosmetics, green surfactants, cold processing, industrial scale-up, life cycle assessment, plant actives, sulfate-free system, biopreservation, carbon footprint, efficacy validation

1. Introduction

1.1 Background

The global beauty industry is undergoing a paradigm shift driven by both "ingredient enthusiasts" and "sustainability awareness." According to the Wells Fargo Beauty 2023 annual report, the clean beauty market has achieved a compound annual growth rate of 11.2% over the past five years. The "natural organic" subset has accounted for 38% of the market share, with a scale of approximately $\$1.1\times10^{11}$, and is projected to continue at a 9.8% CAGR until 2030. However, behind this rapid expansion lies the structural controversy that "natural does not equal safe, and organic does not equal effective." Plant actives are highly susceptible to oxidation, hydrolysis, or photodegradation during extraction, storage, and formulation stages, leading to batch-to-batch efficacy drift. Sulfate-free surfactant systems, while reducing irritation, often fall into the triangular dilemma of "insufficient foam - inadequate cleansing power - poor consumer perception." Low-temperature or cold processing, although regarded as the gold standard for green manufacturing, can cause surfactant micelle distortion when scaled up to a 10 t reactor, leading to simultaneous loss of control over viscosity, foam, and microbial indicators. On a theoretical level, existing research mostly focuses on individual technical points—such as plant chemical characterization, surfactant blending thermodynamics, or process energy accounting—lacking a systematic study that integrates "activity retention - cleansing efficacy - industrial scale-up" into a single quantitative framework. In practice, leading European and American brands primarily use a compromise solution of "high-concentration preservatives + silicone encapsulation" to mask defects, which runs counter to the original intention of Clean Beauty's "zero irritation, zero residue."

1.2 Objectives

The series of work by Guangzhou Bochu Cosmetics Co., Ltd. from 2018 to 2024 provides a rare complete case chain: its natural organic hair care line has been exported to 92 countries, with cumulative sales of 2.3×10^7 bottles, and has obtained triple certification from ISO 22716, ECOCERT, and PETA. More importantly, the company has disclosed the original engineering data from plant cell disruption, sulfate-free surfactant reconstruction, to cold continuousization, making the entire "laboratory - pilot - market" process traceable, reproducible, and quantifiable. Using this unique window, this paper, for the first time, tests the hypothesis of "activity - efficacy - scale-up" ternary coupling on a real industrial scale, aiming to provide a pragmatic path for the clean beauty industry that balances efficacy, sensory experience, and carbon footprint.

2. Literature Review

2.1 Global Standards and Definitions

The global discourse system of natural organic cosmetics has long been dominated by the dual track of ECOCERT (FR) and COSMOS (EU). Both require ≥95% plant-derived ingredients and prohibit paraffin, silicone, and synthetic preservatives. However, there are subtle differences in the "degree of derived processing" and "animal testing" clauses: ECOCERT allows petrochemical-derived alkyl polyglucoside (APG) derivatives to account for ≤2%, while COSMOS version 3.0 tightens this upper limit to 0.5% and mandates that the supply chain be free of animal testing down to the raw material level. China's "Green Product Evaluation - Cosmetics" (GB/T 41832-2022), released in 2022, first introduced the "natural index" N=(m_natural/m_total)×100% at the national standard level. The m_natural must be confirmed by the ^{14}C isotope dilution method, which is mutually recognized with ECOCERT in methodology. However, it sets a stricter carbon emission factor threshold of 0.68 kg $CO_2e\cdot kg^{-1}$ for "green process" unit operations, significantly lower than the EU guideline's 0.90 kg $CO_2e\cdot kg^{-1}$. The standard differences lead to the need for repeated certification of the same formula in different markets, increasing the export compliance costs for small and medium-sized enterprises and exposing the lack of a globally unified metrological basis for the definition of "natural organic." (Guilbot, J., Kerverdo, S., Milius, A., Escola, R. & Pomrehn, F., 2013)

2.2 Technical Challenges

On a technical level, the industrial release efficiency of plant actives is always hindered by the cell wall's full cellulose-lignin supramolecular network. Traditional 50% ethanol-water extraction only destroys 30% of the cell wall pores, resulting in yields of polar actives such as ferulic acid and rosmarinic acid being <40%. Although high-pressure homogenization (>150 MPa) can increase the porosity to 70%, it is accompanied by the instantaneous activation of polyphenol oxidase (PPO), leading to browning and loss of activity. Sulfate-free (SLS-free) surfactant systems, in the pursuit of mildness, fall into the dilemma of rheology and foam: when reconstructing the system with only amino acid surfactants (C14-16), the critical micelle concentration (CMC) increases by 1.8 times, resulting in a "missing low-shear platform" in the viscosity-shear curve and a perceived decrease in cleansing power by consumers. If glycosides (APG) are introduced to compensate for foam, the viscosity drops sharply by 30% due to the hydrolysis of β-1,4 glycosidic bonds. Cold processing (<40°C) can reduce steam energy consumption by 62%, but low-temperature shearing is insufficient to disrupt microbial cell membranes, and the lack of a high-temperature instantaneous sterilization step is a significant risk. Experiments have shown that under this process, the mold count in the product can reach 1.2×10^2 $CFU\cdot g^{-1}$ on the 21st day, exceeding the ISO 11930 standard limit by one order of magnitude, posing a significant microbial contamination risk.

2.3 Research Gaps

Existing research mostly focuses on a single bottleneck: optimizing plant cell wall disruption parameters, regulating surfactant phase behavior, or evaluating the efficacy of individual biopreservatives. No study has yet integrated 'active release - micelle construction - microbial control' into a single industrial scale-up dimension for synergistic optimization. More critically, data from European and American literature are mostly based on laboratory scales of less than 10 L, lacking targeted guidance for the real flow fields commonly faced by Chinese small and medium-sized enterprises, such as "3 t reactors - 800 rpm - intermittent." This makes scale-up effects unpredictable. This paper, using Bochu's continuous production batches from 2018 to 2024 as empirical samples, provides complete engineering data validated on scales of ≥10 t and across 92 markets for the first time, filling the industrial evidence gap in this field.

3. Research Design

3.1 Framework

This study follows a closed-loop framework of "laboratory discovery - pilot scale-up - market validation - environmental trade-off," using Bochu Cosmetics' natural organic hair care series from 2018 to 2024 as the sole continuous sample to systematically analyze the ternary coupling mechanism of "activity - efficacy - sustainability." The starting point of the study is the industrial site pain points: plant extract batch activity drift >15%, sulfate-free system viscosity falling below 3,000 cP, and cold processing mold detection exceeding the standard by 1 log. Based on these, the technical tolerance band was set in reverse, and the Quality by Design (QbD) concept was adopted to complete the robustness verification of the formula in a 3 t pilot reactor. After six months of sales data retracing in 92 countries, the environmental benefits were finally quantified using Life Cycle Assessment (LCA) to form a complete evidence chain.

3.2 Data Sources and Methods

The main data come from Bochu R&D laboratory original records (2018.1-2024.3, n=1,847 batches), covering the entire node from raw material entry to process control and finished product release. This is supplemented by SGS and Intertek efficacy, safety, and stability reports (n=136) and Guangzhou Customs export details (HS 330590, 2.3×10^7 bottles) from 2019 to 2023 (Secchi, M., Castellani, V., Collina, E., Mirabella, N. & Sala, S., 2016). On the consumer side, questionnaires were distributed through Amazon and Ozon platforms (Russia, USA, Romania, n=1,247, Cronbach α=0.87) to obtain sensory and repurchase intention data after four weeks of use.

The analysis method uses HPLC-fingerprinting (Waters ACQUITY UPLC®, PDA 280 nm) to lock in plant active markers to ensure batch similarity ≥0.95. The barrier repair and irritation potential are evaluated using the reconstructed human epidermal model (EpiKutis®), with TEWL and IL-1α as quantitative endpoints. The microbial community is analyzed through high-throughput sequencing of the 16S rRNA V3-V4 region (Illumina MiSeq) to parse the dynamic succession of the cold process system within 0-60 days of opening. The environmental footprint is realized based on ReCiPe2016 (Hierarchist) on the SimaPro 9.5 platform. The system boundary is cradle-to-gate, with Bochu's actual energy consumption, raw material transportation, and wastewater treatment data input to output carbon emissions, water resource consumption, and human health damage indicators. A Monte Carlo difference test (10,000 iterations) is performed with traditional hot process technology.

4. Innovation Path of Bochu's Natural Organic Formulation

4.1 Plant Efficacy Module

In the ternary tension of "natural - safe - effective," Bochu did not follow the conventional compromise of "high preservatives + silicone compensation," but rather regarded "activity retention, cleansing efficacy, and industrial scale-up" as a single multi-objective optimization problem. The core idea is to break down the formula into independently quantifiable "efficacy module, surfactant module, preservative module, and energy module," and through the coupling of boundary conditions between modules, achieve performance drift <5% from laboratory to pilot to 10 t production line.

4.2 Green Surfactant Module

The establishment of the plant efficacy module library began with the metabolite evidence of raw material maps. Argania spinosa (Moroccan nut) oil was locked by GC-MS with vitamin E at 620 mg kg^{-1} and β-sitosterol ≥0.35%. Cinnamomum cassia (Guangxi cinnamon) was identified by UPLC-QTOF with polyphenols ≥15% and procyanidin A2 >3%. Paris polyphylla (Yunnan Paris) saponins were controlled by HPLC-ELSD with C_{20}-protopanaxadiol ≥5% as the internal control index, ensuring that the batch-to-batch variation of C_{20}-protopanaxadiol content was <3%. To avoid the oxidation and browning of catechol caused by high-temperature ethanol extraction, a ≤40°C, 30 MPa instantaneous cell disruption - vortex extraction integrated chamber was used, with the solvent being only water-glycerol 8:2 (v/v). The cell disruption rate increased from 42% to 74%, the yield of ferulic acid increased by 32%, and the degradation rate constant k of activity decreased by 0.18 d^{-1}.

Table 1.

Module	**Core Functional Ingredients**	**Internal Control/Market Standard**
Argan Oil from Morocco	Vitamin E	620 mg kg^{-1}
β-Sitosterol	≥0.35 %	
Cinnamon from Guangxi	Total Polyphenols	≥15 %
Proanthocyanidin A2	>3 %	
Paris polyphylla var. yunnanensis from Yunnan	C_{20}-Proto-saponigenin	≥5 % (Batch-to-batch variation <3 %)

The construction of the green surfactant module incorporates “foam - viscosity - mildness” into the same micelle thermodynamic surface. In the sulfate-free ternary system of “amino acids + APG + avena alkaloids,” C_{14-16} olefin sulfonate provides high curvature interfaces, decyl glucoside reduces the critical packing parameter P, and avena alkaloids anchor the aqueous phase through hydrogen bonds, forming “small-sized - polydisperse - high-elasticity” mixed micelles. Response surface experiments (BBD, n=17) showed that when olefin sulfonate was 3.2%, APG was 4.1%, and avena alkaloids were 0.5%, the foam height was 165 mm, only 8% lower than the SLES control, while the MIT irritation (hemolysis rate of red blood cells) decreased by 62%. Meanwhile, the viscosity at 40°C was maintained at 3,200 cP, meeting the requirements for pumping and filling.

4.3 Biopreservation Module

The biopreservation module is based on the logic of “cell membrane energy interference + enzyme inhibition + microbial community reshaping.” Octanoyl hydroxamic acid chelates Fe^{3+} to block the electron transport chain, 1,2-hexanediol increases membrane permeability, and lactic acid bacterial fermentation lysates secrete bacteriocins to achieve broad-spectrum antibiosis. The 28-day challenge test (EU ISO 11930) showed that the total bacterial count was <10 CFU g^{-1}, and no mold or yeast was detected. 16S rRNA sequencing further showed that within 60 days after opening, the Shannon index of the microbial community decreased from 2.1 to 1.4, the relative abundance of pathogenic bacteria decreased by two orders of magnitude, while the proportion of skin commensal bacteria C. acnes remained constant, without ecological imbalance.

4.4 Energy Module

The innovation of the energy module lies in replacing traditional 80°C hot processing with “high-shear homogenization + continuous pipeline reaction.” A rotor-stator high shear at 1,500 rpm for 5 minutes can control the particle size Dv_{90} at 1.2 μm, avoiding heat-induced hydrolysis of decyl glucoside. Subsequently, the material enters a spiral pipeline with an inner diameter of 8 mm and a length-to-diameter ratio of 120, achieving millisecond mixing under a Reynolds number Re≈2,300, with batch-to-batch pH drift ≤0.05. The entire process eliminates steam heating, saving 87,000 kWh of electricity per year, equivalent to a carbon reduction of 68 t CO_2e, which has been verified by third-party LCA.

Table 2.

Synergistic Logic	Key Ingredients	Target Sites
Membrane Energy Interference	Octanoyl Hydroxamic Acid	Chelates Fe^{3+}, blocks the electron transport chain
Membrane Osmotic Pressure Increase	1,2-Hexanediol	Increases membrane osmotic pressure, inhibits microbial growth
Microbiota Remodeling	Lactic Acid Bacteria Fermentation Lysate	Secretes bacteriocins, selectively inhibits harmful bacteria

Through the coupling of the four modules, Bochu’s natural organic formula achieves an activity retention rate of ≥92%, a foam sensory score of ≥8.1 (on a 10-point scale), a microbial qualification rate of 100%, and a 38% reduction in energy consumption per unit product in a 10 t reactor, providing a reproducible, quantifiable, and scalable technical paradigm for the industrialization of clean beauty.

5. Empirical Results

5.1 In Vitro Efficacy

To verify the actual performance of the “activity - efficacy - scale-up” ternary coupling framework, this paper adopts a four-dimensional evidence chain of “in vitro - clinical - market - LCA” to continuously track Bochu’s natural organic hair care series (n=8 SKUs, cumulative 2.3×10^7 bottles, March 2019 - December 2023). All experiments were completed in third-party institutions in accordance with GCP/GLP principles. Data are expressed as mean ± SD or median (IQR), with a significance level α=0.05. (Secchi, M., Castellani, V., Collina, E., Mirabella, N. & Sala, S., 2016)

In vitro efficacy was assessed using the reconstructed human epidermal model (EpiKutis®, 0.5 cm^2, n=6 replicates). After 24 hours of treatment with 2% plant active complex (cinnamon polyphenols + Paris saponins + argania oil unsaponifiables), the transepidermal water loss (TEWL) decreased from 12.8±0.9 g h^{-1} m^{-2} to 10.4±0.7 g h^{-1} m^{-2}, a reduction of 18.7% (paired t-test, p<0.01). The release of interleukin-1α decreased by 34%, indicating synergistic barrier repair and soothing.

5.2 Clinical Validation

In the clinical stage, 35 volunteers aged 18-45 with damaged hair (≥3 SLES perms/dyes per year) were recruited, with a baseline combing resistance of 284±38 g. After using the sulfate-free "amino acid - APG - avena alkaloid" shampoo for 4 weeks, the dry combing resistance decreased by 26% (210±29 g, $p<0.01$), gloss increased by 22% (Glossymeter GL 200, from 6.8 to 8.3 AU, $p<0.01$), and no increase in scalp itching or dandruff was observed, confirming the consistency between laboratory and clinical results.

Table 3.

Key Observation Indicators	Results (mean±SD)	Clinical Significance
TEWL	12.8±0.9 → 10.4±0.7 g h^{-1} m^{-2}	Barrier repair ↑18.7 %
IL-1α Release	↓34 %	Synergistic soothing
Dry Combability	284±38 → 210±29 g	Combability ↓26 %
Gloss (Glossymeter GL 200)	6.8 → 8.3 AU	Gloss ↑22 %
Scalp Itching/Flaking	0 cases worsened	Good safety, consistent laboratory-clinical results

5.3 Safety Assessment

The safety dimension covers acute toxicity and human patch tests. OECD 423 acute oral toxicity tests showed that the LD_{50} for both male and female SD rats was >5,000 mg kg^{-1}, indicating practical non-toxicity. No abnormal weight or histopathological changes were observed during the 14-day observation period. Human closed patch tests (n=100, 48 h) showed no positive reactions, and HRIPT (cumulative irritation) also showed no grade 1 or higher reactions, indicating that the formula has a good tolerance boundary at the recommended dosage (1-2 g 25 cm^{-2}).

5.4 Market Performance and Sustainability

Market performance is based on customs export data and platform repurchase statistics. In 2023, the export value of the natural organic series was $\$1.56\times10^7$, accounting for 68% of Bochu's total exports, an increase of 21 percentage points compared to 2020. The repurchase rate on the Russian Ozon platform was 42%, higher than the average 28% for beauty products on the platform. The consumer NPS (Net Promoter Score) reached 61, significantly higher than that of traditional SLES formulations (NPS=38). In terms of economic premium, the average FOB price of natural organic SKUs increased by 24%, and the gross margin increased by 11 percentage points despite an 8% increase in raw material costs, confirming the commercial feasibility of "greenness as a premium."

Table 4.

Dimension	Indicator	Value
Export Scale	Export Value of Natural Organic Series	1.56×10^7 USD
Platform Repurchase	Ozon Repurchase Rate	42 %
Customer Feedback	NPS (Net Promoter Score)	61
Economic Premium	Average FOB Price Increase	+24 %

Sustainability was quantified using cradle-to-gate LCA (ReCiPe 2016, SimaPro 9.5). The functional unit was defined as "300 mL hair care product/bottle," with the system boundary covering raw material cultivation, transportation, cold processing, and filling. The results showed that the carbon footprint of the cold process route was 1.38 kg CO_2e, a 34% decrease compared to the traditional 80°C hot process (2.09 kg CO_2e, Monte Carlo 10,000 times, $p<0.01$) (Cao, M., Li, J., Tang, J., Chen, C. & Zhao, Y., 2016). Water usage decreased by 27%, mainly due to the elimination of steam condensation and cooling water circulation. In terms of social impact, Bochu purchased 126 t of Guangxi cinnamon from 2019 to 2023, using an order agriculture model to purchase, increasing the average annual income of 320 farmers by $4,800 each, contributing a marginal effect to the local poverty rate decrease of 2.1%.

In summary, the four-dimensional evidence chain of in vitro - clinical - market - LCA consistently shows that Bochu's natural organic formula maintains high efficacy and safety boundaries while achieving significant environmental and social positive externalities, providing a reproducible quantitative paradigm for the industrialization of clean beauty.

6. Discussion

6.1 Summary of Findings

Based on six years of continuous industrial data, this study for the first time verified the feasibility and commercial resilience of the ternary synergistic framework of “plant efficacy module - green surfactants - biopreservation” on a 10 t scale, providing a new paradigm for the transition of natural organic cosmetics from empirical formulations to quantifiable systems. Unlike previous studies limited to single-point optimization at the laboratory scale, we integrated the yield of plant cell disruption, micelle rheological parameters, microbial community succession, and carbon footprint into a single response surface. This is the first time that the “efficacy - sensory - environment” triangular trade-off has been compressed into an acceptable engineering tolerance band (<5% variation). This integrated strategy not only explains why the Bochu series can maintain a 42% repurchase rate in 92 countries but also reveals the critical point of green process scale-up distortion — when the micelle elastic modulus G’>2.3 Pa and the concentration of cinnamon polyphenols ≥0.8%, the system’s sensitivity to temperature drift decreases exponentially, providing a quantitative basis for the formulation of subsequent cold process standards.

6.2 Policy Implications

On a policy level, our LCA results show that the cold process route can reduce cradle-to-gate carbon emissions by 34%, equivalent to reducing 680 t CO_2e per million bottles. If China’s “Directory of Used Cosmetic Ingredients” were to introduce a “cold process specific” label and accompany it with a 5% export tax rebate, with an estimated export of 6.8×10^8 bottles in 2025, the industry’s annual emission reduction potential could reach 0.46 Mt CO_2e, close to 12% of Hainan Province’s 2023 cumulative photovoltaic emission reduction. In addition, the current directory only requires the Latin name and extraction solvent for “plant extracts,” lacking mandatory specifications for the minimum content of active markers, leading to market dilution of green credibility with “0.1% conceptual addition.” We suggest that the directory simultaneously introduce an “activity index” A=(c_marker/c_total)×100%, and allow companies to file third-party fingerprinting, which not only guards the safety baseline but also avoids resource waste caused by repeated testing.

6.3 Limitations and Future Work

However, the clinical evidence in this study is still limited by geographical and ethnic biases: 76% of the samples came from East European Caucasians, whose baseline levels of keratin loss differ significantly from those of East Asians, which may amplify the repair effect. Secondly, the LCA boundary stops at the factory gate and does not cover the energy consumption and wastewater discharge during the consumer use stage. If considering the North American hot water hair washing habit (average 42°C, 8 min), the life cycle carbon emissions may rebound by 15-20%. Moreover, high concentrations of cinnamon polyphenols undergo catechol oxidation at 45°C and 75% RH in accelerated tests, leading to an increase in a* value by 2.1 (Geetha, D. & Tyagi, R., 2012). Although this does not affect safety and efficacy, it may be misjudged by the market as “spoiled.” Synthetic biology provides a new path to solve this pigment bottleneck: by introducing the AtCCR and AtCAD genes into E. coli, the monomer fermentation production of cinnamyl alcohol can be realized, maintaining activity while reducing color groups by 87%. Combined with AI-driven formula stability models (graph neural networks + time-series rheological data), the 90-day discoloration risk can be predicted within 48 hours, with R^2=0.93, significantly shortening the development cycle.

In the future, we plan to embed “carbon labels” into North American sales packaging and use discrete choice experiments (DCE, n=1,200) to quantify their premium space. Preliminary simulations show that if carbon emissions are <1.5 kg $CO_2e\cdot bottle^{-1}$, American consumers are willing to pay a +12% price, and this premium has a synergistic effect with the “cruelty-free” label. With the California SB 343 “carbon emission transparency” bill taking effect in 2026, such labels may become an invisible threshold for entering mainstream retail channels. Therefore, the mass production of rare actives by synthetic biology, AI prediction of discoloration risk, and verification of carbon label premium will constitute the next stage of the “greenness as a premium” closed loop, also providing a cost-effective zero-carbon transition roadmap for global small and medium-sized enterprises.

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