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From Pod to Product: A Comparative Evaluation of a Biosurfactant-Based Liquid Detergent Formulated from Cola Hispida Agro-Waste

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Abstract- The transition from laboratory biosurfactant production to functional consumer products remains a critical hurdle for sustainable biotechnology. This study completes a circular bioeconomy model by formulating and evaluating a liquid detergent using glycolipid biosurfactants produced from the fermentation of Cola hispida pod agro-waste. Biosurfactants from individual cultures of a Bacillus sp. and a Pseudomonas sp., and from their synergistic consortium, were integrated as the primary active ingredient into a green detergent base. Performance was assessed through foaming ability and stability. The consortium-derived biosurfactant detergent demonstrated superior foaming performance, producing high, persistent foam (rated +++), outperforming detergents from individual cultures (rated ++). A comparative analysis with existing literature on biosurfactant-based cleaners positions our formulation's performance within the context of established systems, while highlighting its unique origin from underutilized agro-waste. This work successfully closes the valorization chain, providing a tangible proof-of-concept for converting agricultural residue into a market-relevant cleaning product. It underscores a viable model for reducing reliance on petrochemical surfactants while addressing waste management challenges through circular production.

Index Terms - Biosurfactant Application, Green Detergent Formulation, Foaming Capacity, Circular Bioeconomy, Agro-Waste Valorization, Cola Hispida, Comparative Performance.

I. INTRODUCTION

The global surfactant market, foundational to the multi-billion dollar cleaning products industry, remains predominantly dependent on synthetic, petroleum-derived compounds. This reliance imposes significant environmental burdens, including the persistence of poorly biodegradable metabolites in aquatic systems, toxicity to flora and fauna, and the unsustainable consumption of fossil resources [1], [2]. Consequently, a pressing industrial and regulatory demand exists for sustainable, "green" alternatives that maintain performance while minimizing ecological footprint [3]. Microbial biosurfactants have emerged as promising candidates, celebrated for their high biodegradability, low toxicity, and effective surface-active properties across diverse conditions [4], [5]. However, for these biological molecules to achieve substantial market penetration, two major barriers must be overcome: production must be economically viable, and their successful integration into stable, efficacious end-user products must be unequivocally demonstrated [6].

Our prior research has systematically addressed the first challenge. We identified Cola hispida pod, a plentiful and nutrient-rich agro-waste in West Africa, as a low-cost fermentation substrate [7]. We isolated and utilized native biosurfactant-producing bacteria from hydrocarbon-polluted environments [8], optimized their cultivation to yield a high-performance surfactant [9], and characterized the primary product as a glycolipid [10]. This establishes a robust and sustainable production platform. The logical and necessary culmination of this work is to confront the application challenge by developing a prototype consumer product, thereby validating the entire circular model.

In liquid detergents designed for manual dishwashing and household cleaning, foaming characteristics are functionally and perceptually important. While excessive foam is undesirable in machine washing, in manual applications, foam serves as a key visual and tactile indicator of cleaning efficacy for consumers and can enhance soil removal by improving surface contact and soil suspension [11], [12]. Glycolipid biosurfactants, such as rhamnolipids and sophorolipids, are recognized for their favorable foaming properties and compatibility with various detergent ingredients [13], [14].

Therefore, this study aimed to bridge the gap between laboratory-scale production and practical utility by formulating a prototype liquid detergent using the Cola hispida-derived glycolipid biosurfactant as a central functional component. We specifically compared detergents formulated with biosurfactants from individual microbes versus their consortium, hypothesizing that the consortium's biosurfactant—with its previously demonstrated superior surface activity—would yield a detergent with enhanced foaming performance. Furthermore, we contextualize our findings through a comparative analysis with existing literature, evaluating our waste-derived formulation against the performance benchmarks of other biosurfactant systems. This effort represents the closure of a circular economic loop, offering a concrete example of how agricultural waste can be transformed into a value-added, biodegradable consumer product and presenting a practical framework for sustainable industrial biotechnology.

II. MATERIALS AND METHODS

A. Source and Preparation of Biosurfactant

The glycolipid biosurfactants employed as the active base for detergent formulation were produced and recovered as detailed in our preceding studies [9], [10]. Briefly, a defined mixed culture of Bacillus sp. and Pseudomonas sp., along with the individual pure cultures, were cultivated separately via submerged fermentation. The medium consisted of a Basal Mineral Salt Medium supplemented with 14% (w/v) powdered Cola hispida pod as the sole nutrient source. Fermentation proceeded for 7 days at 30°C under agitated conditions. Subsequently, the broths were centrifuged to remove cellular biomass. The cell-free supernatants were acidified to pH 2.0 using 6 N HCl to precipitate the biosurfactants. The resulting precipitates were collected, dissolved in a chloroform-methanol mixture (2:1 v/v), and the solvent was evaporated under a gentle stream of nitrogen gas to yield dried, crude biosurfactant powders. These powders were stored in a desiccator and served as the primary surfactant for three distinct detergent batches.

B. Formulation of Liquid Detergent

The liquid detergent was formulated using a base recipe adapted from green chemistry principles for cleaning products [15], wherein the biosurfactant directly substituted a portion of conventional synthetic surfactants. The stepwise procedure was as follows:

1. Preparation of Alkali Solutions: Caustic soda ($NaOH$) and soda ash (Na_2CO_3) were separately dissolved in 250 mL of distilled water each and allowed to hydrate for 24 hours.

2. Mixing of Primary Components: One liter of distilled water was placed in a stainless-steel mixing vessel. Ethylenediaminetetraacetic acid (EDTA, 0.5% w/v) was added first as a water-softening agent. Under constant mechanical stirring, the following components were incorporated sequentially:
   - Linear Alkylbenzene Sulphonic Acid (LABSA, 10% v/v) – an anionic surfactant for grease cutting.
   - Sodium Laureth Sulfate (Texapon/SLES, 5% v/v) – a high-foaming anionic surfactant.
   - The extracted Cola hispida biosurfactant (5% w/v) – the principal green surfactant component.
   - Hydroxyethyl cellulose (Nitrosol, 1% w/v, pre-dispersed in water) – a thickener and stabilizer.

3. Addition of Builders and Alkalis: With stirring maintained, the pre-hydrated soda ash solution was introduced slowly, followed by the caustic soda solution. Sodium tripolyphosphate (STPP, 2% w/v, pre-dissolved) was then added as a builder to enhance cleaning efficiency.

4. Finalization: A minimal quantity of formalin (0.1% v/v) was added as a preservative.

5. Maturation: The mixture was stirred vigorously for an additional 30 minutes and then allowed to stand (mature) for 24 hours at ambient temperature (~25°C). This maturation period permitted complete hydration and stabilization, yielding a uniform, viscous liquid.

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Three separate batches were produced, corresponding to the biosurfactants derived from Bacillus sp. (SB-Det), Pseudomonas sp. (SP-Det), and the Mixed culture consortium (SD-Det).

C. Performance Evaluation: Foaming Ability and Stability Test

The foaming capacity and foam stability of the formulated detergents were assessed using a modified cylinder shake test, based on standard principles [16]. A 1% (v/v) solution of each detergent was prepared using distilled water. Ten milliliters of this solution was transferred to a clean, stoppered 25 mL graduated glass cylinder. The cylinder was sealed, inverted forcefully, and shaken vigorously for 30 seconds. Immediately after shaking (time = 0 min), the total height of the contents and the height of the liquid layer beneath the foam were recorded to calculate the initial foam volume. The cylinder was then left undisturbed, and the remaining foam height was recorded at 1, 3, 5, and 15-minute intervals. All tests were performed in triplicate. Based on the observed initial foam volume and its retention over the 15-minute period, foaming performance was qualitatively rated as: + (low/poor), ++ (moderate/good), or +++ (high/excellent).

D. Physical and Stability Assessment

The freshly prepared and matured detergent batches were visually inspected for color, clarity, homogeneity, and consistency. They were stored in transparent high-density polyethylene (HDPE) bottles at room temperature (25 ± 3°C) and monitored weekly for one month for any indications of physical instability, such as phase separation, sedimentation, or visible microbial growth.

III. RESULTS AND DISCUSSION

A. Successful Formulation and Basic Physical Properties

All three types of biosurfactants were successfully incorporated into stable liquid detergent matrices. The formulated products were homogeneous, viscous liquids exhibiting a consistent light amber to pale brown hue, attributable to natural pigments present in the Cola hispida pod substrate. No instances of precipitation, gelation, or phase separation were observed following the mixing or the 24-hour maturation period. This represents a critical practical outcome: the glycolipid biosurfactants produced via this method demonstrate compatibility with common anionic co-surfactants (LABSA, SLES), builders (STPP), alkalis, and polymeric thickeners. Such compatibility is not assured, as certain biosurfactants can exhibit unfavorable interactions with ionic components, leading to precipitation or a reduction in activity [17]. The successful formulation indicates that these bio-surfactants can be integrated into established detergent manufacturing processes with minimal procedural adjustment.

B. Foaming Performance: Demonstrating Consortium Advantage in a Product

The foaming test revealed clear, application-relevant differences between the formulations, as summarized in Table I. The detergent formulated with the mixed culture-derived biosurfactant (SD-Det) consistently generated the highest initial foam volume and, more significantly, exhibited the greatest foam stability. The foam column remained largely intact for over five minutes, draining and collapsing at a slower rate, warranting a qualitative rating of "+++" (excellent). Conversely, detergents SB-Det and SP-Det, while producing good initial foam, demonstrated faster collapse, with foam volume diminishing more rapidly over the 15-minute observation window, earning a rating of "++" (good).

Table I: Comparative Foaming Performance of Biosurfactant-Based Liquid Detergents

Detergent Formulation	Foam Rating	(Qualitative) Key Observations (0-15 min)
SB-Det (Bacillus)	++	Good initial foam, moderate stability, gradual collapse.
SP-Det (Pseudomonas)	++	Good initial foam, moderate stability, gradual collapse.
SD-Det (Diculture)	+++	High initial foam, excellent stability, slow collapse.

This superior performance is a direct, practical consequence of the enhanced physicochemical properties previously documented for the consortium biosurfactant [9]. Its lower critical micelle concentration (CMC) and higher emulsification index facilitate the formation of more elastic and mechanically robust foam lamellae. These films are more resistant to the primary mechanisms of foam collapse: drainage, coalescence, and Ostwald ripening [18]. Consequently, SD-Det not only

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produces more foam but also sustains it longer—a desirable attribute from a consumer perspective. This finding robustly underscores the practical benefit of employing the microbial consortium; the metabolic synergy observed during production translates into a tangible, superior advantage in the final consumer product.

C. Comparative Performance Benchmarking Against Literature

To contextualize the performance of our Cola hispida-based detergent within the broader field of biosurfactant application, a comparative analysis was conducted against selected studies from the literature. This comparison, detailed in Table II, evaluates key parameters such as biosurfactant source, substrate, performance focus, and formulation context.

Table II: Comparative Analysis of Biosurfactant-Based Cleaning Formulations from Literature

Study Reference	Biosurfactant Source	Substrate Production Context	Key Performance Metrics Reported	Formulation Context & Key Findings
This Study (SD-Det)	Bacillus-Pseudomonas consortium	Cola hispida pod agro-waste	Excellent foaming (+++), good compatibility in full detergent matrix.	Complete liquid detergent with builders/thickeners. Key strength: Direct agro-waste valorization in a consumer-grade product.
Mnif & Ghribi, 2015 [5]	Bacillus subtilis	SPB1 Industrial by-products (e.g., tuna fish waste)	High emulsification index (E24=75%), stability at extreme pH/temp.	Surfactin in model systems for bioremediation/oil recovery. Highlights stability but not in consumer detergent format.
Daverey & Pakshirajan, 2010 [19]	Candida bombicola	Glucose & oleic acid Sophorolipid production yield; surface tension reduction to 33 mN/m.	Sophorolipids characterized for general surfactant properties.	Focus on production from costly first-generation substrates.
Azeez & Abegunde, 2016 [15]	Plant-based (soapnut)	Sapindus mukorossi fruits Good cleaning of stained fabrics, moderate foam.	Eco-friendly liquid detergent prototype.	Shows viability of plant-derived surfactants but uses edible plant resource.

The comparison reveals several insightful perspectives. Firstly, our study aligns with the trajectory of research seeking sustainable surfactant feedstocks, moving from refined substrates like glucose and oleic acid [19] to industrial or agricultural wastes [5, 15]. Secondly, while many studies report excellent surface-active properties (e.g., low surface tension, high E24) in purified or model systems [5, 19], our work demonstrates functionality within a complex, multi-ingredient consumer product. This step from "surfactant property" to "product performance" is critical for commercial translation but is less frequently documented. Thirdly, the performance of our SD-Det, qualitatively rated as excellent, appears competitive with other bio-based cleaners reported in the literature, such as those derived from soapnut [15]. The distinct advantage of our model lies in its integrated circularity utilizing a regionally abundant, non-food agro-waste from inception, thereby addressing waste management and resource sustainability concurrently.

D. Practical Considerations, Stability, and the Circular Model

This application study successfully demonstrates the closure of a sustainable, circular production loop. The model initiates with Cola hispida pod, an agricultural residue with disposal challenges, and through microbial fermentation converts it into a valuable glycolipid biosurfactant. This biochemical is subsequently incorporated into a functional liquid detergent, presenting a biodegradable alternative to conventional, petrochemical-based products.

A notable practical observation during extended storage was the emergence of visible microbial growth (fungal mold) in some bottles after approximately four weeks. This is likely attributable to the organic, nutrient-rich composition of the biosurfactant itself, coupled with the water-based, minimally preserved formulation. This highlights a crucial area for future product development: the identification and integration of effective, broad-spectrum, and environmentally benign preservative systems suitable for biosurfactant-rich formulations [20]. Potential solutions may include the use of approved natural preservatives, optimization of pH, or enhanced packaging technologies to limit microbial ingress.

The foaming performance, stability in formulation, and comparative positioning collectively validate the consortium approach. The synergy between Bacillus and Pseudomonas species, which enhanced biosurfactant yield and quality during fermentation [9], now proves to confer a tangible functional benefit in the end product. This underscores the value of optimizing not just the surfactant molecule, but the entire production consortium for application-specific outcomes.

IV. CONCLUSION

This study delivers a practical and comparative proof-of-concept, culminating a multi-stage research endeavor with a tangible application output. We have successfully formulated a functional liquid detergent utilizing a sustainably produced glycolipid biosurfactant derived from the fermentation of Cola hispida pod agro-waste. The detergent incorporating the consortium-derived biosurfactant exhibited superior foaming capacity and stability, outperforming variants formulated with individual culture biosurfactants, thereby validating the functional synergy of the microbial consortium in a real-world product context.

Positioned against the landscape of existing biosurfactant application research, this work demonstrates that performance metrics competitive with other bio-based systems can be achieved using a crude, waste-derived surfactant integrated into a complete detergent matrix. Beyond mere performance validation, this work embodies a practical circular bioeconomy. It delineates a viable pathway for transforming low-value agricultural waste into a value-added, biodegradable consumer product, directly confronting dual challenges of waste management and sustainable chemistry. Future work should prioritize: i) optimizing preservative systems to ensure adequate shelf-life, ii) conducting comprehensive cleaning efficacy tests against standardized soils, iii) performing formal toxicological and biodegradability assays to substantiate environmental safety claims, and iv) undertaking techno-economic analysis to evaluate commercial scalability. This research establishes a robust foundation for the development of commercially feasible, eco-friendly detergent products sourced from renewable, waste-based materials.

V. ACKNOWLEDGMENT

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AUTHOR CONTRIBUTIONS

K.C. Ali: Conceptualization, Investigation, Methodology, Writing – original draft. A.E. Onovo: Formal analysis, Validation. A.O. Olusegun: Data curation, Visualization. C.C. Uzoefuna: Resources, Writing – review & editing. T.J. Oluwadepo: Project administration, Supervision, Writing – review & editing. E.C. Aham: Investigation, Methodology. H.A. Adewuyi: Supervision, Validation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ETHICAL APPROVAL

The present research work does not contain any studies performed on animals/humans subjects by any of the authors.

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