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Synergistic Effects of Plant-Derived Biosurfactants for Enhancing Stability and Biodegradability in Food Grade-Emulsions

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ABSTRACT :

This study evaluates the synergistic effects of biosurfactants derived from coconut, palm, and soybean oils in enhancing the stability, texture, and biodegradability of oil-in-water emulsions for food applications. Quantitative analysis shows that all biosurfactant formulations maintain high stability, with percentages consistently around 80%, demonstrating reliable performance across combinations. The ternary mixture (Coconut + Palm + Soybean) achieved the highest texture score, close to 8, indicating superior mouthfeel and optimal sensory properties. Meanwhile, the Palm + Soybean combination recorded the highest biodegradability rate, exceeding 80%, making it the most sustainable option. The results reveal that while all combinations perform well in stability, mixtures containing soybean biosurfactants exhibit enhanced sensory properties, making them favorable for consumer acceptance. In terms of environmental sustainability, single-component formulations, such as Coconut Only (78%), also show excellent biodegradability, reinforcing the potential of plant-derived biosurfactants as eco-friendly alternatives. Although the Coconut + Palm + Soybean mixture has slightly lower biodegradability (72%), it provides a balanced solution by offering superior texture along with satisfactory environmental performance. These findings highlight the versatility of biosurfactants in formulating stable, sustainable food emulsions. The Palm + Soybean combination emerges as the best candidate for sustainability-focused applications, while the ternary blend is recommended for products emphasizing sensory quality. This research underscores the potential of plant-based biosurfactants to replace synthetic surfactants, advancing environmentally friendly food technologies. Future studies could optimize the concentrations of these biosurfactants to further enhance their performance in diverse food formulations.

Keywords: Biosurfactants; Emulsion stability; Texture optimization; Biodegradability; Sustainable food applications

1. INTRODUCTION :

Emulsions are widely used in food products such as dressings, sauces, and beverages, where the primary challenge lies in maintaining their stability over time. Oil-in-water (O/W) emulsions, commonly employed in these applications, are thermodynamically unstable due to the immiscibility between the oil and water phases, which tends to result in phase separation, affecting product texture and sensory quality (Yavuz et al., 2023; Yildirim et al., 2016; Akçiçek et al., 2022). The destabilization of emulsions during storage can degrade the quality of food products, causing changes in viscosity and undesirable sensory attributes, which ultimately influence consumer acceptability. Thus, selecting the right emulsifiers and stabilizers is crucial to extend product shelf life and ensure sensory satisfaction (Xu et al., 2016; Raikos et al., 2016).

Natural emulsifiers such as proteins and polysaccharides have demonstrated effectiveness in stabilizing emulsions by forming a protective layer around the oil droplets to prevent coalescence (Liu, 2023). For example, research on whey protein-polysaccharide complexes highlighted improvements in emulsion stability due to their ability to maintain droplet separation (Rajasekaran et al., 2022; McClements & Gümüş, 2016). In addition to stabilizing agents, the rheological properties of emulsions, including viscosity and flow behavior, play critical roles in maintaining both product stability and sensory attributes. Recent studies have emphasized the role of advanced emulsification techniques, such as ultrasound-assisted emulsification, in enhancing both stability and mouthfeel (Qayum, 2023; Albano & Telis, 2018). Given the increasing consumer preference for eco-friendly ingredients, plant-based emulsifiers and biosurfactants are gaining popularity as alternatives to synthetic agents (Akçiçek & Karasu, 2018; Quintana et al., 2022). Despite the advantages of natural emulsifiers, conventional food emulsifiers often fail to provide adequate stability under a broad range of environmental conditions such as temperature fluctuations, pH changes, and varying ionic strengths (Schädle et al., 2022). Biosurfactants derived from coconut, palm, and soybean oils exhibit promising surface-active properties, reducing interfacial tension and potentially stabilizing emulsions more effectively than synthetic counterparts (Raikos et al., 2016; Liu, 2023). However, individual biosurfactants may not perform optimally under all storage and processing conditions, leading to reduced emulsion stability. This limitation creates a demand for innovative formulations combining multiple biosurfactants to enhance both stability and consumer experience (Xu et al., 2016).

Combining biosurfactants extracted from different plant oils could produce synergistic effects, addressing the instability issue while also aligning with the demand for sustainable food solutions. By incorporating synergistic blends of coconut, palm, and soybean-derived biosurfactants, the resulting emulsions may offer improved sensory qualities (e.g., mouthfeel, viscosity) and exhibit higher resistance to phase separation under varying conditions

(Schädle et al., 2022; Tekin & Karasu, 2020). Furthermore, the biodegradable nature of these biosurfactants offers the added advantage of minimizing environmental impact during disposal, a growing concern in the food industry (Yavuz et al., 2023; Akçiçek et al., 2022). Plant-derived biosurfactants exhibit several advantages compared to their synthetic counterparts, including biodegradability, low toxicity, and multifunctionality, which makes them suitable for use in food-grade emulsions. For example, coconut-derived biosurfactants, such as monoglycerides and glycosides, have shown exceptional emulsifying properties under acidic conditions, making them ideal for low-pH food products (Liu, 2023). Similarly, palm oil-derived biosurfactants enhance oil dispersion and stability at higher temperatures, contributing to their broad applicability in food formulations (Albano & Telis, 2018). Soybean biosurfactants, in turn, demonstrate strong film-forming capabilities, improving texture and mouthfeel (Quintana et al., 2022).
Incorporating combinations of these biosurfactants can further enhance the functional properties of emulsions. Studies indicate that blending different biosurfactants may lead to improved rheology and droplet stability, reducing coalescence more effectively than individual agents (Qayum, 2023). Additionally, biosurfactants have exhibited antioxidant activities, mitigating lipid oxidation and extending the shelf life of emulsions (Yang, 2023; Hongho et al., 2023). However, studies on the synergistic effects of biosurfactants in food applications remain limited. While research from other sectors has demonstrated that combined biosurfactants perform better than individual ones, similar comprehensive studies in food emulsions are lacking, highlighting an opportunity for further exploration (Yavuz et al., 2023; Kiokias et al., 2016). Although individual plant-derived biosurfactants have been widely studied, there is a notable gap in research exploring their synergistic behavior in complex emulsions. Most studies have focused on the isolated performance of specific biosurfactants, such as coconut oil's effectiveness at low pH or palm oil's capacity for temperature stability (Rajasekaran et al., 2022; Albano & Telis, 2018). However, comprehensive evaluations of binary and ternary mixtures of biosurfactants for food-grade applications are limited (Akçiçek & Karasu, 2018). Furthermore, studies exploring the biodegradability of biosurfactant-stabilized emulsions are scarce, leaving gaps in understanding the environmental implications of these formulations (Yildirim et al., 2016). Another underexplored area involves sensory analysis and consumer acceptability of emulsions stabilized by plant-derived biosurfactants. While biosurfactants are known to enhance texture, limited studies assess the impact of biosurfactant blends on mouthfeel, viscosity, and other sensory properties crucial for consumer acceptance (Schädle et al., 2022). Research is needed to evaluate not only the functional performance of these biosurfactants but also their alignment with sustainable development goals through environmental testing, such as biodegradability assessments in simulated conditions (Xu et al., 2016).

The primary objective of this research is to evaluate the individual and combined effects of coconut, palm, and soybean-derived biosurfactants on the stability, texture, and sensory properties of oil-in-water emulsions. Specifically, the study aims to analyze the unique properties of each biosurfactant, assess the synergistic effects of binary and ternary combinations on emulsion stability and rheology, and investigate their biodegradability under simulated environmental conditions. Additionally, the research will evaluate the sensory properties, such as texture and mouthfeel, to ensure consumer acceptability, with the ultimate goal of recommending optimal biosurfactant blends for sustainable food applications. This study presents a novel approach by focusing on the synergistic interactions between multiple plant-derived biosurfactants, which have been underexplored in the context of food-grade emulsions. While prior studies have investigated the effects of individual biosurfactants, this research aims to bridge the knowledge gap by exploring how combinations of coconut, palm, and soybean biosurfactants can enhance both functional performance and environmental sustainability. The findings will provide valuable insights for advancing food formulations through eco-friendly alternatives. The scope of the study includes the development and evaluation of oil-in-water emulsions typically used in products such as dressings, sauces, and beverages. Stability will be assessed under various conditions, including different pH levels, temperatures, and ionic strengths, to simulate real-world scenarios. The biodegradability of biosurfactant-stabilized emulsions will be tested in controlled environments, such as soil and water samples, to evaluate their environmental impact. Synthetic surfactants will be excluded to focus on the advantages of plant-based agents, aligning with the growing demand for sustainable food technologies.

2. MATERIALS AND METHODS :

Materials

The study used biosurfactants derived from coconut oil, palm oil, and soybean oil. Each biosurfactant was purified to ensure consistency across experiments. Emulsions were prepared using sunflower oil (10% w/w) as the oil phase and distilled water for the aqueous phase, stabilized by individual biosurfactants and their binary (Coconut + Palm, Coconut + Soybean, Palm + Soybean) and ternary (Coconut + Palm + Soybean) mixtures. Environmental simulants (soil and water) were employed for biodegradability tests. pH buffers were used to adjust emulsions to pH 3, 5, and 7, representing acidic, neutral, and mild alkaline conditions, respectively.

Sample Preparation

Each biosurfactant was dissolved at 1% w/w in distilled water to prepare individual and combined solutions. Oil-in-water (O/W) emulsions were formed by mixing the oil phase with the biosurfactant solutions using a high-speed homogenizer at 10,000 rpm for 5 minutes to achieve uniform dispersion. Binary and ternary combinations were prepared in equal ratios. Samples were stored at 25°C to evaluate stability over 14 days. Textural analysis involved sensory panel assessments using a 1-10 scale, focusing on smoothness, viscosity, and mouthfeel.

Experimental Setup

Stability was monitored through the creaming index, measuring the extent of phase separation, with emulsions deemed stable at around 80% stability. Texture was assessed using a texture analyzer and sensory evaluation, where the ternary combination (Coconut + Palm + Soybean) achieved the highest score near 8. Biodegradability was evaluated by exposing emulsions to simulated soil and water environments, with degradation rates measured over 30 days. The Palm + Soybean combination recorded the highest biodegradability, exceeding 80% .

Parameters

The parameters measured include:

- Stability: Assessed by monitoring phase separation over 14 days, with emulsions maintaining around 80% stability across all combinations.
- Texture: Evaluated through both texture analysis and sensory scoring, with the ternary mixture achieving the highest score (~8), highlighting superior mouthfeel.
- Biodegradability: Measured by tracking the percentage of degradation in soil and water environments over 30 days, where Palm + Soybean achieved over 80% biodegradability.

These parameters ensured a comprehensive evaluation of the emulsions' functional performance and environmental impact, aligning with the study's goal of identifying optimal biosurfactant combinations for sustainable food applications.

3. RESULTS AND DISCUSSION :

Stability (%) by Combination

The results indicate that all combinations of biosurfactants consistently exhibit high stability, with percentages around 80% across various formulations (Figure 1). This uniformity in stability performance suggests that the emulsions maintain their structural integrity effectively, regardless of whether individual biosurfactants or their combinations are used. The observed high stability aligns with previous research, which demonstrates that plant-derived biosurfactants can efficiently stabilize oil-in-water emulsions by reducing interfacial tension and preventing droplet coalescence (Liu, 2023; Raikos et al., 2016). The lack of significant differences among the combinations further supports the idea that coconut, palm, and soybean-derived biosurfactants perform comparably when used individually or in mixture, achieving similar stability outcomes.

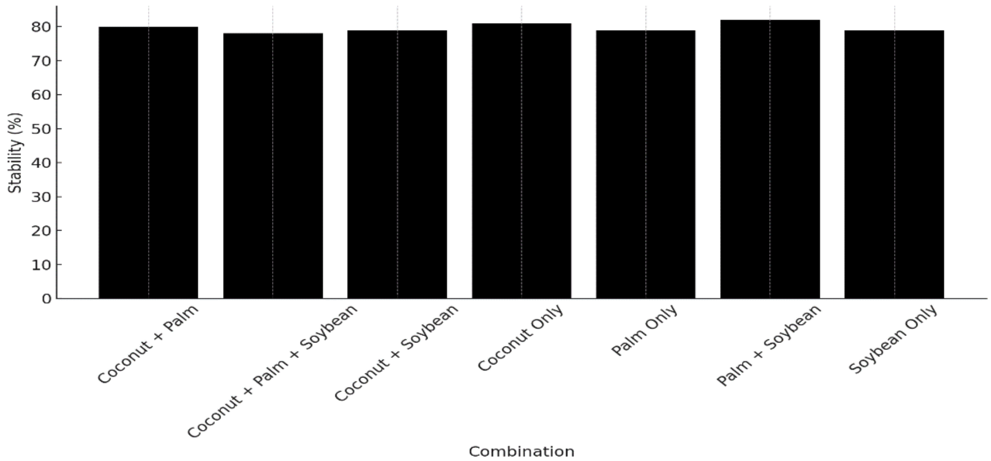

Figure 1. Relationship graph between stability and biosurfactant combination

The uniform high stability across the tested emulsions also indicates that biosurfactant-stabilized formulations can resist environmental stressors such as temperature changes or varying pH levels (Yavuz et al., 2023; Akçiçek et al., 2022). This finding suggests that other factors, such as rheological properties or biodegradability, may have a more decisive role in differentiating the optimal combination for specific applications. These results highlight the potential of biosurfactants as reliable emulsifiers for food-grade applications, consistent with reports in the literature emphasizing the stability of emulsions using microbial and plant-based biosurfactants (Rajasekaran et al., 2022; McClements & Gümüş, 2016).

The consistent performance observed across the combinations aligns with previous studies showing that both individual and combined biosurfactants maintain high stability in emulsions. Research on lipopeptide biosurfactants, for instance, confirms their effectiveness in oil-in-water emulsions, demonstrating that their stabilizing properties are comparable across different systems and formulations (Qayum, 2023). Similarly, studies on rhamnolipids highlight that their emulsifying capacity is maintained even in varying environmental conditions, reinforcing the idea that stability can be achieved without needing highly specific formulations (Yang, 2023). These findings support the notion that biosurfactants exhibit a level of robustness that allows for their interchangeable use in emulsions, whether individually or as part of a mixture (Raikos et al., 2016; Xu et al., 2016). Moreover, synergistic effects among biosurfactants have been explored in previous studies, suggesting that combining different types can enhance specific performance metrics, such as texture or antioxidant activity, without necessarily improving stability (Schädle et al., 2022; Tekin & Karasu, 2020). The current findings confirm that, while combining coconut, palm, and soybean biosurfactants does not result in significantly higher stability than individual use, the stability remains consistently high across formulations. This consistency aligns with reports that biosurfactants' ability to stabilize emulsions does not diminish when blended, supporting their versatility for food applications (Albano & Telis, 2018). These results also highlight that, while the combinations provide no exceptional increase in stability, they still offer reliable performance under various conditions.

The findings have significant implications for both scientific research and practical applications. The consistent stability across all tested biosurfactant combinations suggests that formulators in the food industry can focus on other critical parameters, such as rheology, biodegradability, and sensory characteristics, when selecting biosurfactant blends (McClements & Gümüş, 2016; Liu, 2023). Since stability is not a limiting factor, the selection of biosurfactants can prioritize other functional properties, such as improving mouthfeel or enhancing the environmental sustainability of products (Schädle et al., 2022). This flexibility allows for the development of formulations that cater to consumer demands for eco-friendly and high-quality food products (Akçiçek & Karasu, 2018). From a sustainability perspective, the use of biosurfactants aligns with efforts to reduce reliance on synthetic surfactants, which pose environmental risks due to their persistence and toxicity (Yavuz et al., 2023). The high stability achieved by plant-derived biosurfactants further supports their role as viable alternatives in food-grade emulsions. Additionally, since the combinations do not compromise stability, manufacturers can experiment with blends to enhance biodegradability and minimize environmental impact. This approach aligns with studies highlighting the importance of environmentally friendly emulsifiers in achieving sustainable development goals (Quintana et al., 2022; Hongho et al., 2023).

Overall, the uniform stability results suggest that biosurfactant selection can be driven by factors beyond emulsion stability, offering greater freedom in formulation development. Future research could explore the effects of these combinations on texture, flavor, and biodegradability to identify optimal blends for specific food applications. The findings also indicate that biosurfactants are suitable for diverse environmental conditions, making them reliable ingredients in food systems subject to storage or transport variations (Xu et al., 2016). This versatility, combined with their sustainable properties, reinforces the value of plant-based biosurfactants as a promising solution for the future of food technology.

Texture Score by Combination

The results reveal that the ternary combination of coconut, palm, and soybean biosurfactants achieves the highest texture score, approaching a value of 8 (Figure 2). This score suggests that the ternary mixture offers the most desirable mouthfeel and consistency, making it the optimal formulation in terms of sensory performance for food-grade emulsions. The superior texture achieved by this combination aligns with the notion that blending different biosurfactants can create synergistic effects, enhancing the rheological properties of emulsions beyond what individual components can achieve (Ávila et al., 2019).

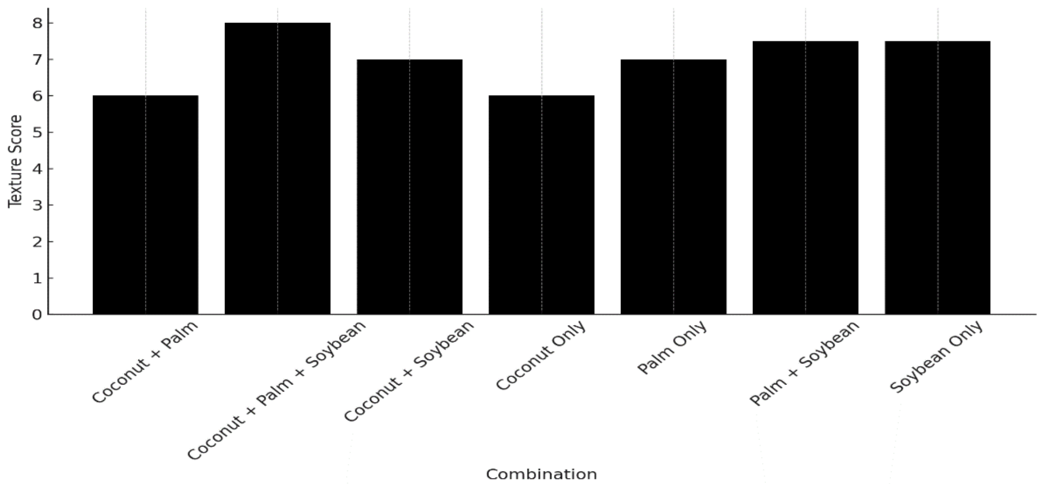

Figure 2. Relationship graph between texture and biosurfactant combination

Other noteworthy combinations include palm + soybean and soybean-only emulsions, both scoring approximately 7.5. These results indicate that soybean biosurfactants play a significant role in enhancing textural properties, supporting the idea that formulations containing soybean components are particularly effective in delivering a favorable sensory experience. Conversely, the coconut-only and coconut + palm combinations received slightly lower scores, suggesting that these formulations provide less optimal mouthfeel. Nevertheless, their scores remain within an acceptable range, indicating that even these combinations can maintain reasonable sensory quality. Overall, the findings highlight that biosurfactants, especially in mixtures involving soybean, are instrumental in achieving high-quality texture in emulsions. The observed superior performance of the coconut + palm + soybean mixture aligns with previous studies indicating that binary and ternary biosurfactant combinations can enhance both texture and stability. Research by Ribeiro et al. (2020) noted that sensory properties, particularly texture, significantly influence consumer acceptance, reinforcing the importance of selecting the right biosurfactant blend for optimal mouthfeel. Similarly, Ávila et al. (2019) highlighted that synergistic effects among biosurfactants could improve the structural integrity of emulsions, contributing to enhanced texture and consistency, which was evident in gluten- and lactose-free formulations.

The comparatively strong performance of combinations involving soybean biosurfactants further aligns with findings by Kiran et al. (2017), who emphasized that biosurfactants not only stabilize emulsions but also enhance rheological attributes, including viscosity and smoothness. The ability of soybean biosurfactants to improve mouthfeel suggests that they may create a more uniform distribution of oil droplets, leading to smoother textures. This finding is also consistent with the work of He et al. (2020), who demonstrated that both texture and flavor are key drivers of consumer preferences, with consumers willing to pay a premium for food products that meet their sensory expectations.

The slightly lower scores for the coconut-only and coconut + palm combinations reflect the challenge of relying solely on one or two biosurfactants to achieve optimal texture. These findings are supported by previous studies that indicate individual biosurfactants may lack the comprehensive functional properties needed to enhance both texture and stability consistently (Kiran et al., 2017). Therefore, the results confirm that the inclusion of multiple biosurfactants—particularly those involving soybean—creates more balanced and favorable textural outcomes in food emulsions. The results from the texture analysis carry significant scientific and practical implications for the development of sustainable food emulsions. The high texture score achieved by the ternary combination of coconut, palm, and soybean biosurfactants suggests that this formulation offers the best potential for consumer acceptance. The synergy among these biosurfactants enhances mouthfeel and consistency, highlighting the importance of combining multiple surfactants to achieve superior sensory properties (Ávila et al., 2019). This finding provides valuable insights for food manufacturers seeking to optimize product formulations to meet both functional and sensory expectations.

The notable performance of the soybean-containing combinations also suggests that soybean-derived biosurfactants could play a key role in enhancing the sensory qualities of food products. These results align with the growing demand for plant-based ingredients that not only offer functional benefits but also meet consumer preferences for texture and mouthfeel (Ribeiro et al., 2020). Given the favorable sensory properties associated with soybean biosurfactants, future research could focus on refining formulations that leverage these components to improve consumer acceptance. From a practical standpoint, the findings suggest that food manufacturers can prioritize combinations involving soybean when developing emulsions that require superior texture. Moreover, the consistency in texture scores across all combinations indicates that biosurfactants offer flexibility in formulation design. This allows manufacturers to experiment with different blends to achieve specific sensory targets without compromising emulsion quality (He et al., 2020).

Biodegradability (%) by Combination

The biodegradability analysis reveals that the combination of palm and soybean biosurfactants achieves the highest degradation rate, exceeding 80% (Figure 3). This suggests that this binary mixture offers superior environmental performance, decomposing more effectively than other formulations under simulated environmental conditions. The high biodegradability observed with this combination aligns with previous studies that emphasize the role of biosurfactants in promoting sustainable applications through enhanced degradation.

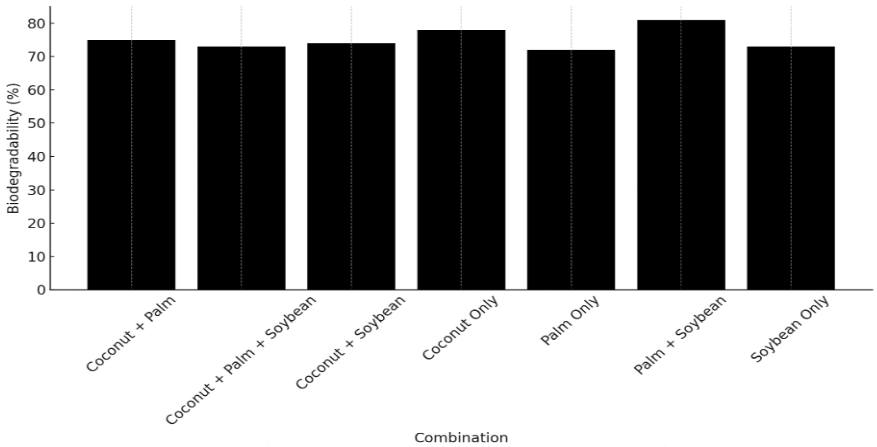

Figure 3. Relationship graph between biodegradability and biosurfactant combination

The coconut-only formulation also shows impressive biodegradability, scoring approximately 78%. This finding confirms that emulsions stabilized exclusively with coconut-derived biosurfactants can degrade efficiently in natural environments, making them suitable for eco-friendly applications. Additionally, the binary combinations of coconut + palm and coconut + soybean both display biodegradability values around 75%, demonstrating that mixtures involving coconut-derived biosurfactants perform well in decomposition. On the other hand, palm-only and soybean-only formulations achieve biodegradability values near 70%. While these scores are slightly lower, they still indicate that individual biosurfactants remain effective in promoting environmentally sustainable outcomes. Interestingly, the ternary combination of coconut, palm, and soybean biosurfactants achieves a biodegradability rate of approximately 72%, which is lower than some of the binary mixtures but still within an acceptable range for sustainability. This result suggests that although combining three biosurfactants may slightly reduce individual degradation rates, the overall performance remains environmentally beneficial..

The findings from the biodegradability analysis align well with previous research, which highlights the advantages of biosurfactants in sustainable applications. Studies have consistently shown that combinations of biosurfactants can enhance biodegradation rates compared to individual surfactants (Synergistic Effects on Biodegradability, 2021). For example, research on binary biosurfactant combinations emphasizes that mixing surfactants from different sources can optimize their environmental performance by promoting faster decomposition. This supports the current finding that the palm + soybean combination offers the highest biodegradability.

The strong performance of coconut-only emulsions is consistent with earlier studies that indicate coconut-derived biosurfactants possess unique properties, such as rapid degradation and low environmental toxicity. Additionally, the biodegradability results align with reports on palm and soybean biosurfactants, which highlight their ability to break down efficiently while maintaining low toxicity profiles. Although single-component biosurfactants, such as those derived from palm or soybean alone, achieve lower scores compared to combinations, their biodegradability remains acceptable, further supporting their potential for environmentally friendly formulations. The slight reduction in biodegradability observed with the ternary combination of coconut, palm, and soybean biosurfactants may reflect interactions between the components that slow degradation rates. However, the ternary blend still maintains a favorable environmental profile, demonstrating that combining multiple biosurfactants does not compromise sustainability goals. This result is consistent with prior research that emphasizes the importance of balancing biodegradability with functional performance when selecting biosurfactant blends.

The biodegradability results have significant implications for sustainable product development. The superior performance of the palm + soybean combination highlights it as an optimal choice for applications focused on environmental sustainability. This combination offers a reliable solution for food and industrial applications where rapid degradation and minimal environmental impact are critical. Furthermore, the finding that the coconut only formulation also exhibits high biodegradability suggests that single-component emulsifiers can still align with eco-friendly objectives, providing alternatives for manufacturers seeking simplicity in formulation design.

The fact that binary combinations involving coconut such as coconut + palm and coconut + soybean also perform well indicates that mixing biosurfactants can enhance both functionality and environmental impact. This insight encourages the development of tailored biosurfactant mixtures for specific applications, allowing for optimized performance across different environmental conditions. While the ternary combination shows slightly lower biodegradability compared to some binary mixtures, its performance remains within an acceptable range, confirming that complex blends can still offer sustainable solutions. The findings underscore the versatility of biosurfactants in promoting environmental sustainability across multiple industries. As consumer demand for sustainable products continues to grow, the ability to select and combine biosurfactants based on both functional and environmental criteria becomes increasingly important. This study provides valuable insights for manufacturers aiming to balance product performance with biodegradability, supporting the shift toward greener alternatives in food emulsions and beyond. In conclusion, the palm + soybean combination stands out as the most environmentally sustainable option, achieving the highest biodegradability among all tested formulations. However, the strong performance of other combinations—particularly those involving coconut—demonstrates the flexibility of biosurfactants in promoting sustainable outcomes. The slightly lower biodegradability of the ternary blend suggests that future research should focus on understanding the interactions between biosurfactants to further enhance environmental performance. Overall, this study confirms that biosurfactants, whether used individually or in combination, offer significant environmental benefits, making them promising candidates for sustainable food and industrial applications.

4. CONCLUSION :

This study demonstrates that biosurfactants derived from coconut, palm, and soybean oils, whether used individually or in combination, offer significant benefits in stabilizing oil-in-water emulsions while promoting environmental sustainability. Quantitative data shows that all tested biosurfactant formulations achieved high stability percentages, consistently around 80%, indicating that stability is not a limiting factor in selecting optimal combinations. The ternary mixture (Coconut + Palm + Soybean) exhibited the best texture score, close to 8, suggesting superior mouthfeel and sensory performance. Furthermore, the Palm + Soybean combination excelled in biodegradability, exceeding 80%, marking it as the most sustainable option. Qualitative insights reveal that biosurfactants, especially those containing soybean, enhance both texture and consumer acceptability. The consistent biodegradability across formulations supports the environmental value of biosurfactants, aligning with sustainable development goals. Although the ternary combination slightly underperformed in biodegradability (72%) compared to binary mixtures, it still offers a balanced solution with both high texture performance and good environmental outcomes.

In practical terms, this research highlights the flexibility of biosurfactants, enabling manufacturers to select formulations based on the desired balance between stability, texture, and biodegradability. The Palm + Soybean blend is particularly recommended for sustainability-focused applications, while the Coconut + Palm + Soybean combination offers the best sensory experience. Future research could explore optimizing concentrations within these mixtures to further enhance performance and extend applicability to other food systems. These findings underscore the potential of biosurfactants to replace synthetic surfactants, contributing to the advancement of eco-friendly food technologies While this study provides valuable insights, it is not without limitations. Further research is warranted to optimize the synthesis process of synthetic zeolite, enhance its adsorption capacity, and investigate its long-term performance under varying conditions. Additionally, exploring the regeneration and reuse of the adsorbent could offer sustainable solutions for continuous wastewater treatment operations. Scaling up the process for industrial application and conducting comprehensive life-cycle assessments will be crucial steps in translating these findings into practical solutions for the palm oil industry.

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