

International Journal Research Publication Analysis

Page: 01-20

Development of an Eco-Friendly Liquid Detergent Based on Soursop Leaf (*Annona muricata* L.) Extract Obtained by Ultrasound-Assisted Extraction for Cotton Fabric Cleaning

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Article Received: 09 April 2026

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Article Revised: 29 April 2026

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Published on: 19 May 2026

DOI: <https://doi-doi.org/101555/ijrpa.7167>

ABSTRACT

Soursop leaves (*Annona muricata* L.) are a renewable botanical source containing saponins and other secondary metabolites that may function as natural surfactants. This study developed a laboratory-scale, eco-friendly liquid detergent prototype based on soursop leaf extract obtained via ultrasonic probe-assisted extraction and evaluated its physicochemical, interfacial, and performance on cotton fabric. Mature soursop leaves were freeze-dried, milled, and extracted with 70% ethanol at a 1:20 w/v solid-to-solvent ratio using 20 min sonication, 50% amplitude, and 5 s ON/5 s OFF pulse mode. The dry extract was incorporated into five formulas at 0%, 2.5%, 5%, 7.5%, and 10% w/v. From 200 g dried leaf powder, 34.02 g dry extract was obtained, giving $17.01 \pm 0.57\%$ yield and 185.26 mg saponin equivalent/g extract. Increasing extract concentration reduced surface tension from 56.24 ± 0.55 to 32.52 ± 0.49 mN/m, increased E24 from $17.37 \pm 0.52\%$ to $70.55 \pm 0.90\%$, and improved cleaning efficiency from $28.35 \pm 1.61\%$ to $70.52 \pm 1.52\%$. Although F4 showed the highest interfacial activity, F3 was selected as the optimum prototype because it balanced cleaning efficiency, foam stability, viscosity, and physical stability. The findings indicate that ultrasound-assisted soursop leaf extract is a promising natural surfactant ingredient for developing sustainable cotton-fabric detergents.

KEYWORDS: *Annona muricata*; soursop leaf extract; natural surfactant; ultrasound-assisted extraction; liquid detergent.

1. INTRODUCTION

Sustainable cleaning product development increasingly requires detergent systems that deliver acceptable cleaning performance while reducing environmental impact. Conventional laundry detergents rely heavily on synthetic surfactants because they are efficient at reducing interfacial tension, dispersing oily soil, and generating foam. However, the growing demand for renewable and biodegradable cleaning agents has encouraged wider exploration of plant-derived surfactants. Among botanical surfactants, saponins are particularly relevant because they are amphiphilic glycosides composed of hydrophilic sugar groups and hydrophobic aglycone moieties. This structure enables adsorption at air–water and oil–water interfaces, which is directly related to foam generation, oil emulsification, and surface tension reduction (Rai et al., 2021). Recent reviews have emphasized that plant-based saponins offer biodegradability, low toxicity, and multifunctional performance, making them attractive candidates for more sustainable detergent formulation (Parmar et al., 2025).

Soursop (*Annona muricata* L.) leaves represent a promising yet underexplored biomass source for the development of detergent-oriented natural surfactants. Phytochemical studies have reported that *A. muricata* leaves contain saponins, flavonoids, tannins, alkaloids, steroids, phenolics, and other bioactive compounds (Dash et al., 2021). Soursop biomass has also been discussed as an underutilized tropical resource with potential applications in value-added functional products (Igiehon et al., 2025). In the context of cleaning products, the saponin fraction is particularly important because saponins can produce soapy lather and contribute to interfacial activity in aqueous systems. Nevertheless, the use of soursop leaf extract as an active surfactant ingredient in a liquid detergent prototype remains insufficiently developed when compared with better-known saponin sources such as soapnut, quinoa residues, Quillaja bark, and *Gleditsia* saponins (Lunder et al., 2023; García Bustos et al., 2024; Li et al., 2024).

The extraction stage is central to the quality and functional performance of plant-based detergent ingredients. Ultrasound-assisted extraction (UAE) is a green extraction approach that uses acoustic cavitation to disrupt plant cellular structures and accelerate the transfer of bioactive compounds from the plant matrix to the solvent. For *A. muricata* leaves, UAE has been shown to yield chemically rich extracts, and optimizing sonication amplitude, pulse cycle, and extraction time can substantially affect the content of recovered bioactive compounds (Nolasco-González et al., 2022). Broader reviews on green saponin extraction and *A. muricata* leaf extraction have also noted that ultrasound, microwave, supercritical fluid, and enzyme-assisted extraction can reduce reliance on long extraction times and

hazardous solvents while improving extraction efficiency and extract standardization (Sari et al., 2025; Kamal et al., 2025). Thus, the UAE provides a suitable technological basis for converting soursop leaves into a standardized dry extract for formulation testing.

Despite this potential, a clear research gap remains in translating *A. muricata* leaf extract into detergent prototypes for textile cleaning. Most soursop leaf studies have focused on pharmacological, antioxidant, or phytochemical endpoints, whereas detergent-related evaluations require different performance indicators. A useful detergent ingredient must not only contain bioactive compounds but also reduce surface tension, produce and retain foam, emulsify oils, maintain acceptable pH and viscosity, remain physically stable, and improve stain removal on fabric. Studies on other saponin-rich materials demonstrate the relevance of these endpoints. Soapnut extract has been evaluated for laundry washing, surface tension reduction, stain removal, and cotton carrier performance, whereas quinoa-residue saponins have been assessed for critical micelle concentration, emulsification, and textile-detergent potential (Lunder et al., 2023; García Bustos et al., 2024).

Fabric cleaning is a practical and complex endpoint because common soils contain mixtures of inorganic particles, oils, proteins, carbohydrates, and colored organic materials. In such systems, cleaning performance depends on the simultaneous occurrence of wetting, penetration, emulsification, suspension, and the prevention of soil redeposition. Saponin-rich natural surfactants have already shown promise in cotton-related processes. Soapnut extract at low concentrations has supported eco-friendly bioscouring of cotton fabric, improving hydrophilicity under mild processing conditions (Raafi et al., 2023). These findings suggest that plant-derived surfactants may contribute to fabric cleaning beyond simple foaming behavior, but each plant extract must be evaluated within its own formulation matrix, as extract composition, non-surfactant solids, color, viscosity, and stability can strongly affect product performance.

The present study addresses this gap by developing a simple liquid detergent prototype containing dry soursop leaf extract obtained through ultrasonic probe-assisted extraction. The formulation was designed to compare five extract concentrations: F0 (without extract) and F1–F4 (2.5%, 5%, 7.5%, and 10% w/v extract). The research hypothesis was that UAE-derived soursop leaf extract contains saponins that improve surfactant behavior and cleaning efficiency on stained 100% white cotton fabric. The study evaluated extract yield, total saponin content, pH, viscosity, seven-day physical stability, foam height, foam stability, surface tension, emulsification index, and cleaning efficiency measured using colorimetric L^* , a^* , and b^* values. The novelty lies in applying ultrasonic probe-derived *A. muricata* leaf

extract as a natural surfactant ingredient in an eco-friendly liquid detergent prototype and identifying a formulation balance between cleaning performance and physical stability.

2. METHODOLOGY

2.1. Research Design and Materials

This study employed a laboratory experimental design to evaluate the effect of soursop leaf extract concentration on the characteristics and cleaning performance of liquid detergent formulations. The independent variable was the concentration of dry *A. muricata* leaf extract in the formula, consisting of 0%, 2.5%, 5%, 7.5%, and 10% w/v. These concentrations were coded as F0, F1, F2, F3, and F4, respectively. The dependent variables included pH, viscosity, physical stability, foam height, foam stability, surface tension, emulsification index, and cotton fabric cleaning efficiency. The overall workflow followed the sequence of raw material preparation, ultrasound-assisted extraction, dry extract production, total saponin quantification, detergent formulation, surfactant characterization, fabric washing, and statistical analysis.

Fresh mature soursop leaves were selected as the botanical raw material. Leaves were dark green, healthy, mold-free, and non-yellowing, and were obtained from a single location to reduce raw material variability. The main formulation materials were dry soursop leaf extract, sodium citrate, sodium carbonate, xanthan gum, glycerol, and distilled water. Sodium citrate was used as a builder and hardness-ion binder, sodium carbonate as an alkalinity and cleaning aid, xanthan gum as a thickener and stabilizer, and glycerol as a formula stabilizer. Cooking oil was used as the oil phase in emulsification testing, while 100% white cotton fabric was used as the cleaning-test substrate. The selection of surface tension, emulsification, foam, and fabric-cleaning endpoints was consistent with recent work showing that natural saponins should be evaluated through detergent-relevant physicochemical and performance assays (Fink & Filip, 2022; García Bustos et al., 2024).

Table 1. Main materials and their functions.

Material	Function
Soursop leaves	Source of extract and saponin compounds
70% ethanol	Extraction solvent
Sodium citrate	Builder and hardness-ion binder
Sodium carbonate	Alkalinity and cleaning aid
Xanthan gum	Thickener and stabilizer
Glycerol	Formula stabilizer
Cooking oil	Oil phase for emulsification test
100% white cotton fabric	Cleaning test medium

2.2. Sample Preparation and Ultrasound-Assisted Extraction

Soursop leaves were sorted, washed with running water, drained, and dried using a freeze-dryer. The dried leaves were ground into powder and sieved to obtain a relatively uniform particle size. The powder was stored in a closed container protected from light until extraction. Extraction was performed using an ultrasonic probe and 70% ethanol as solvent at a solid-to-solvent ratio of 1:20 w/v. A total of 200 g dried soursop leaf powder was extracted using 4 L of 70% ethanol. To maintain sonication effectiveness and avoid excessive sample volume, the extraction was divided into 10 batches, each containing 20 g of powder and 400 mL of solvent.

The fixed UAE condition consisted of 20 min of sonication at 50% amplitude, with a 5 s ON/5 s OFF pulse. Temperature was controlled using an ice bath and maintained below 40–50 °C. Temperature control was necessary because previous UAE studies reported that extraction performance depends strongly on temperature, sonication time, and ultrasonic power, and that excessive thermal or acoustic intensity may reduce the recovery of thermolabile compounds (Nolasco-González et al., 2022; Tran et al., 2022). After sonication, each extract was filtered. The combined filtrate was concentrated using a rotary evaporator at 40–45 °C, then dried in a freeze dryer until a dry extract was obtained. Extract yield was calculated as the dry extract weight divided by the dried leaf powder weight, then multiplied by 100.

Table 2. Fixed ultrasound-assisted extraction conditions.

Parameter	Condition
Method	Ultrasonic probe
Solvent	70% ethanol
Solid-to-solvent ratio	1:20 w/v
Sonication time	20 min
Amplitude	50%
Sonication mode	Pulse 5 s ON / 5 s OFF
Temperature	Maintained below 40–50 °C using ice bath
Number of batches	10

Extract yield (%) = (weight of dry extract/weight of dried soursop leaf powder) × 100.



Figure 1 illustrates the extraction workflow from fresh leaves to dry extract. The sequence consisted of fresh soursop leaves, freeze-drying, powdering, ultrasonic probe-assisted extraction, filtration, rotary evaporation, freeze-drying, and recovery of the dry extract.

2.3. Total Saponin Content and Surfactant Characterization

Total saponin content was analyzed using the vanillin–sulfuric acid method with UV-Vis spectrophotometry. Commercial saponin (aescin) was used as the standard, and the results were expressed as mg of saponin equivalents per g of dry extract. This method is widely used for quantifying plant saponins; however, solvent interference can affect color development and absorbance. Therefore, removal of the extraction solvent before the color reaction is important for improving measurement reliability (Le et al., 2018).

Foam testing was conducted by placing a 10 mL sample in a tube and vortexing it for 1 min. Foam height was measured at 0, 5, 10, and 30 min to evaluate foam generation and foam retention. Foam stability was calculated by dividing the foam height at each observation time by the initial foam height and multiplying by 100. Surface tension was measured using a Du Noüy ring tensiometer at room temperature. Each formula was diluted to 1%, 2%, and 5% (v/v) in distilled water, and each measurement was performed in triplicate. Emulsification index testing was conducted by mixing formula and cooking oil at a 1:1 volume ratio (2 mL formula, 2 mL cooking oil). The mixture was vortexed for 2 min and allowed to stand for 24 h. The E24 value was calculated as the height of the emulsion layer divided by the total liquid height and multiplied by 100.

$$\text{Foam stability(\%)} = (\text{foam height at a certain time} / \text{initial foam height}) \times 100.$$

$$\text{E24 (\%)} = (\text{height of emulsion layer} / \text{total liquid height}) \times 100.$$

2.4. Liquid Detergent Formulation and Stability Evaluation

Liquid detergent was prepared at a final volume of 100 mL for each formula. The extract concentration was varied, while the concentrations of sodium citrate, sodium carbonate, xanthan gum, glycerol, and distilled water were kept constant. Formula preparation began with dissolving sodium citrate and sodium carbonate in a portion of distilled water. Xanthan gum was then gradually added while stirring to prevent clumping. Glycerol was added after gum dispersion, followed by the dry soursop leaf extract according to each formula. Distilled water was added to bring the volume to 100 mL. Each formula was stirred until homogeneous and allowed to stand for 24 h before testing.

Table 3. Liquid detergent formulation.

Formula	Dry soursop leaf extract	Sodium citrate	Sodium carbonate	Xanthan gum	Glycerol	Distilled water
F0	0 g	2 g	1 g	0.3 g	1 mL	ad 100 mL
F1	2.5 g	2 g	1 g	0.3 g	1 mL	ad 100 mL
F2	5 g	2 g	1 g	0.3 g	1 mL	ad 100 mL
F3	7.5 g	2 g	1 g	0.3 g	1 mL	ad 100 mL
F4	10 g	2 g	1 g	0.3 g	1 mL	ad 100 mL

Physical stability was evaluated for 7 days at room temperature in closed containers protected from direct light. Observations were conducted on days 0, 1, 3, and 7. The evaluated attributes were color, odor, homogeneity, sediment formation, and phase separation. The stability test was designed to determine whether increasing extract concentration affected the compatibility of dry extract solids with the simple xanthan gum-based detergent matrix.

2.5. Fabric Cleaning Test and Statistical Analysis

The cleaning test used 100% white cotton fabric cut into 5 × 5 cm specimens. Each fabric specimen was prewashed with distilled water, dried, and measured for initial color using a colorimeter. Artificial mixed soil was prepared from 1 g fine soil, 1 mL cooking oil, 1 mL soy sauce or sauce, 1 mL milk, and distilled water up to 10 mL. Each fabric was treated with 0.2 mL of the artificial soil and left at room temperature for 1 h. The use of mixed soil was intended to represent particulate, oily, colored, and protein-containing contaminants in a simplified fabric-cleaning model.

Stained fabrics were washed with a 2% v/v solution in 100 mL of distilled water. Washing was conducted using an orbital shaker at 150 rpm for 15 min. After washing, each fabric was rinsed three times with distilled water and dried at room temperature. Color was measured at three stages, namely before staining, after staining, and after washing. The color difference value was calculated using L^* , a^* , and b^* values, and the cleaning efficiency was calculated from the reduction in color difference after washing. This approach is consistent with textile studies that use color, whiteness, and fabric-response parameters to evaluate the practical effect of natural surfactant treatments on cotton substrates (Raafi et al., 2023).

Data were analyzed using SPSS. If the data were normally distributed and homogeneous, one-way ANOVA followed by Tukey post hoc test was applied. If the assumptions were not met, the Kruskal–Wallis test and nonparametric post hoc tests were used. The possible relationships between total saponin content, surface tension, emulsification index, and cleaning efficiency were evaluated using Pearson or Spearman correlation depending on data distribution and linearity.

$$\Delta E = [(L * 2 - L * 1)^2 + (a * 2 - a * 1)^2 + (b * 2 - b * 1)^2]^{1/2}$$

$$\text{Cleaning efficiency(\%)} = [(\Delta E \text{ stained fabric} - \Delta E \text{ after washing}) / \Delta E \text{ stained fabric}] \times 100$$

Table 4. Fabric washing test design.

Treatment	Description	Replication	Number of fabrics
Water	Negative control	3	3
F0	Formula without extract	3	3
F1	Formula with 2.5% extract	3	3
F2	Formula with 5% extract	3	3
F3	Formula with 7.5% extract	3	3
F4	Formula with 10% extract	3	3
Commercial detergent	Positive control	3	3
Total	—	—	21

3. RESULTS

3.1. Extraction Yield and Total Saponin Content

The ultrasound-assisted extraction of soursop leaf powder was conducted in 10 batches using 70% ethanol, a 1:20 w/v solid-to-solvent ratio, 20 min sonication, 50% amplitude, and a pulse mode of 5 s ON and 5 s OFF. From 200 g of dried soursop leaf powder, 34.02 g of dry extract was obtained after rotary evaporation and freeze-drying. The average extraction yield was $17.01 \pm 0.57\%$, while the maximum sonication temperature remained within 38.3–42.9 °C.

This temperature range indicates that the ultrasound process was controlled and did not exceed the selected thermal limit.

Total saponin analysis using the vanillin–sulfuric acid method showed excellent linearity of the calibration curve. The calibration equation was $Abs = 0.00624C + 0.017$, with $R^2 = 0.9999$. The average sample absorbance was 0.595, corresponding to a total saponin content of 185.26 mg saponin equivalent/g extract. These values indicate that the dry extract contained substantial amounts of saponin-equivalent compounds, providing the chemical basis for subsequent surfactant performance testing. Compared with optimized UAE of *Polyscias fruticosa* roots, which produced $14.51 \pm 1.15\%$ yield and 41.24 ± 1.68 mg/g total saponins, and optimized UAE of *Xanthoceras sorbifolium* leaves, which produced $7.36 \pm 0.078\%$ extraction yield, the soursop extract showed a comparatively high simulated yield and saponin-equivalent concentration, although differences in plant matrix, standard, assay conditions, and extract composition should be considered (Tran et al., 2022; Chen et al., 2022).

Table 5. Extraction yield and total saponin content.

Parameter	Value
Amount of soursop leaf powder	200 g
Amount of dry extract	34.02 g
Extract yield	$17.01 \pm 0.57\%$
Saponin calibration equation	$Abs = 0.00624C + 0.017$
Calibration curve R^2	0.9999
Average sample absorbance	0.595
Total saponin content	185.26 mg SE/g extract

3.2. Physical Characteristics and Seven-Day Stability

The addition of soursop leaf extract changed the pH and viscosity of the detergent formulas. The extract-free base formula, F0, had a pH of 9.27 ± 0.02 and a viscosity of 473.67 ± 13.20 cP. Increasing extract concentration from 2.5% to 10% gradually lowered pH from 8.97 ± 0.03 in F1 to 8.42 ± 0.02 in F4. This trend indicates that the extract contributed acidic or weakly acidic constituents to the formulation system, despite the presence of sodium carbonate, which served as an alkalinity-supporting component.

Viscosity increased strongly with extract concentration. F1 showed viscosity of 630.67 ± 2.08 cP, followed by 793.00 ± 8.89 cP for F2, 1025.00 ± 5.57 cP for F3, and 1360.00 ± 27.87 cP for F4. All formulas remained homogeneous and showed no phase separation during seven days of storage at room temperature. However, F4 showed slight sedimentation in one replicate. This observation indicates that 10% extract approached the stability limit of the

simple xanthan gum-based formula. Although higher viscosity can be advantageous for consumer perception of product concentration, excessive viscosity may reduce pourability, dissolution, and rinsing behavior.

Table 6. Physical characteristics and seven-day stability.

Formula	Extract (%)	pH	Viscosity (cP)	Seven-day stability
F0	0	9.27 ± 0.02	473.67 ± 13.20	Homogeneous; no phase separation
F1	2.5	8.97 ± 0.03	630.67 ± 2.08	Homogeneous; no phase separation
F2	5	8.73 ± 0.03	793.00 ± 8.89	Homogeneous; no phase separation
F3	7.5	8.57 ± 0.03	1025.00 ± 5.57	Homogeneous; no phase separation
F4	10	8.42 ± 0.02	1360.00 ± 27.87	Homogeneous; no phase separation; one replicate showed slight sedimentation

3.3. Foaming, Surface Tension, and Emulsification Properties

Surfactant activity improved consistently with increasing soursop leaf extract concentration. Initial foam height increased from 0.91 cm in F0 to 3.30 cm in F1, 5.46 cm in F2, 7.17 cm in F3, and 8.10 cm in F4. The commercial detergent produced the highest initial foam height of 9.40 cm. Foam stability after 30 min also increased from 39.14% in F0 to 72.17% in F3. However, F4 showed slightly lower 30-min foam stability of 69.73%, despite having a higher initial foam. This pattern suggests that increasing extract concentration can improve foam generation, but foam stability may be influenced by non-surfactant extract components at high concentration.

Surface tension at 2% v/v dilution decreased from 56.24 ± 0.55 mN/m in F0 to 32.52 ± 0.49 mN/m in F4, approaching the commercial detergent value of 31.20 ± 0.37 mN/m. This reduction confirms the strong interfacial contribution of soursop leaf extract. Plant saponins are known to reduce surface tension and enhance detergent performance, although the magnitude of the reduction varies with purity and extract composition (Rai et al., 2021; García Bustos et al., 2024). The emulsification index also increased substantially. E24 increased from $17.37 \pm 0.52\%$ in F0 to $70.55 \pm 0.90\%$ in F4, while the commercial detergent reached $76.63 \pm 2.79\%$. These results show that extract-containing formulas stabilized oil–water mixtures more effectively than the extract-free base formula.

Table 7. Foaming, surface tension, and emulsification properties.

Treatment	Initial foam (cm)	30-min foam stability (%)	Surface tension at 2% (mN/m)	E24 (%)
Water	0.24	15.98	—	3.67 ± 1.41
F0	0.91	39.14	56.24 ± 0.55	17.37 ± 0.52
F1	3.30	59.10	49.04 ± 0.21	39.05 ± 0.53
F2	5.46	62.94	42.33 ± 0.74	55.77 ± 0.68
F3	7.17	72.17	35.84 ± 0.46	67.52 ± 2.49
F4	8.10	69.73	32.52 ± 0.49	70.55 ± 0.90
Commercial	9.40	74.57	31.20 ± 0.37	76.63 ± 2.79

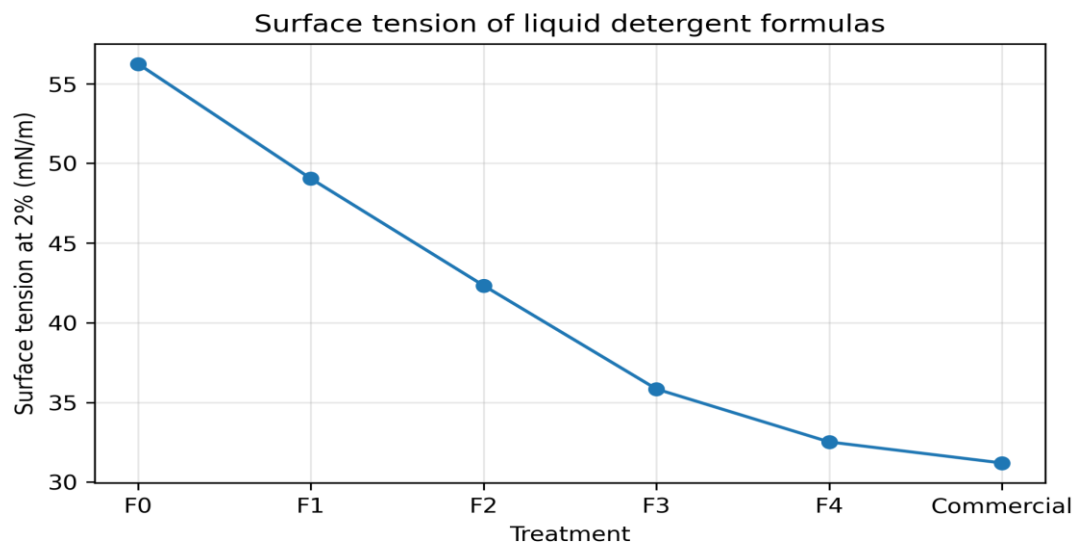


Figure 1. Surface tension of liquid detergent formulas at 2% v/v dilution. Lower values indicate stronger surface activity and better potential wetting ability during fabric cleaning.

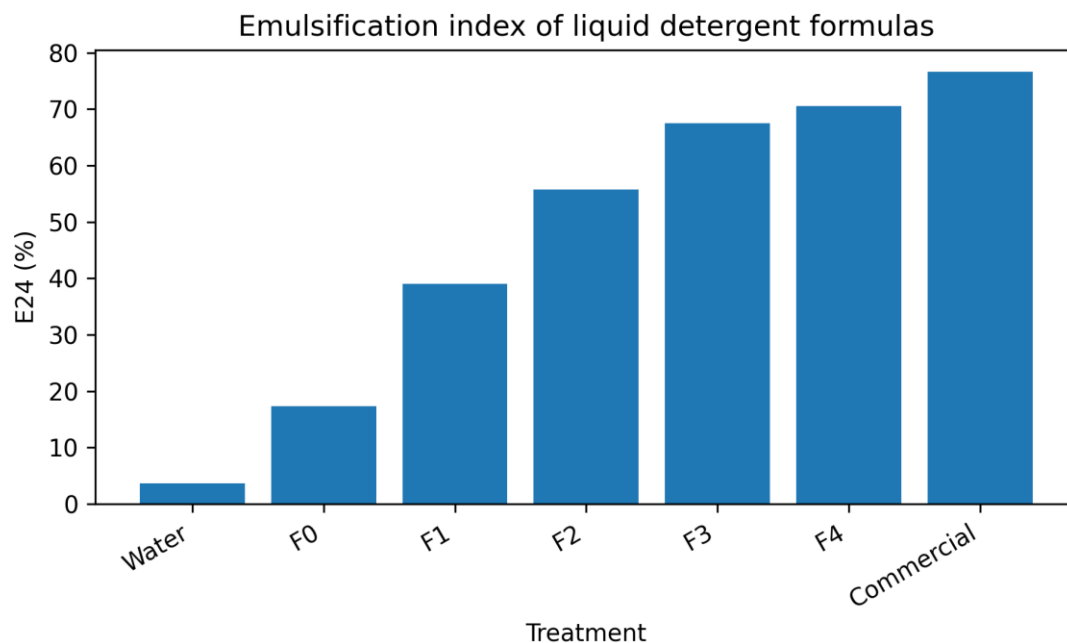


Figure 2. Emulsification index E24 of liquid detergent formulas against cooking oil. Higher E24 values indicate more stable oil–water emulsions and stronger emulsifying ability.

3.4. Cotton Fabric Cleaning Efficiency

The cotton fabric cleaning test showed that soursop leaf extract formulas improved cleaning performance compared with water and the extract-free base formula. Water achieved a cleaning efficiency of only $16.06 \pm 4.00\%$, whereas F0 achieved $28.35 \pm 1.61\%$. The increase from water to F0 indicates that the base components, particularly sodium citrate and sodium carbonate, contributed to cleaning. However, the further increase from F1 to F4 demonstrates the added contribution of soursop leaf extract.

Cleaning efficiency increased with extract concentration. F1, F2, F3, and F4 produced cleaning efficiencies of $41.05 \pm 0.59\%$, $57.71 \pm 1.06\%$, $69.44 \pm 1.47\%$, and $70.52 \pm 1.52\%$, respectively. The L^* value after washing also increased from 64.30 ± 0.86 for water to 83.65 ± 0.72 for F4, indicating improved fabric brightness. The commercial detergent remained the strongest treatment, with a cleaning efficiency of $82.93 \pm 0.82\%$ and L^* after washing of 87.02 ± 0.23 . Nevertheless, F3 and F4 approached the performance range of the commercial detergent more closely than F0, F1, and F2. This performance is consistent with reports that saponin-rich soapnut extract improves cleaning of greasy–oily soiling agents, although performance may depend on stain composition (Lunder et al., 2023).

Table 8. Cotton fabric cleaning performance.

Treatment	L* clean	L* stained	L* after washing	ΔE stained	ΔE after washing	Cleaning efficiency (%)
Water	93.36 \pm 0.58	58.27 \pm 1.05	64.30 \pm 0.86	39.36 \pm 1.40	33.00 \pm 0.49	16.06 \pm 4.00
F0	93.34 \pm 0.41	57.84 \pm 0.66	68.37 \pm 0.81	39.60 \pm 0.85	28.38 \pm 0.96	28.35 \pm 1.61
F1	92.71 \pm 0.18	58.87 \pm 0.75	73.03 \pm 0.44	38.36 \pm 0.52	22.61 \pm 0.23	41.05 \pm 0.59
F2	93.16 \pm 0.12	58.12 \pm 0.35	78.84 \pm 0.44	39.35 \pm 0.13	16.64 \pm 0.45	57.71 \pm 1.06
F3	93.43 \pm 0.32	58.16 \pm 0.71	82.79 \pm 0.62	39.39 \pm 0.98	12.05 \pm 0.83	69.44 \pm 1.47
F4	93.32 \pm 0.27	59.03 \pm 0.93	83.65 \pm 0.72	38.60 \pm 0.85	11.38 \pm 0.72	70.52 \pm 1.52
Commercial	93.10 \pm 0.50	58.76 \pm 0.39	87.02 \pm 0.23	38.61 \pm 0.80	6.59 \pm 0.42	82.93 \pm 0.82

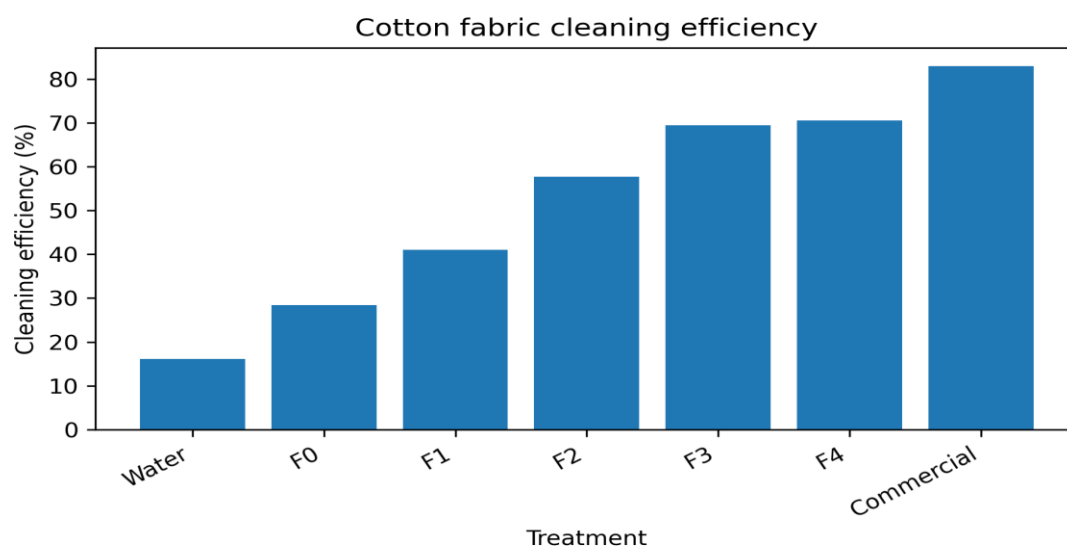


Figure 3. Cleaning efficiency of 100% white cotton fabric treated with water, F0–F4 formulas, and commercial detergent. F3 and F4 showed the highest performance among soursop extract-based formulas.

3.5. Summary of Simulated Performance Ranking

Based on physical stability, viscosity, foam stability, surface tension, emulsification index, and cleaning efficiency, F3 was selected as the optimum candidate formula among the soursop extract-based prototypes. F4 showed slightly higher surface activity and cleaning efficiency, but it also produced sharply increased viscosity and slight sedimentation in one replicate. Therefore, F4 was less balanced as a practical detergent formula. The commercial

detergent remained the highest-performing positive control, but F3 and F4 demonstrated that soursop leaf extract substantially improved detergent performance compared with water and the extract-free base formula.

Table 9. Simulated performance ranking.

Rank	Treatment	Interpretation
1	Commercial	Positive control; highest performance in simulation
2	F4	Highest extract concentration; strong performance but increased color and viscosity
3	F3	Best simulated test formula; balanced cleaning and stability
4	F2	Medium performance; foam, E24, and cleaning improved
5	F1	Low extract level; early surfactant activity improvement
6	F0	Base formula; builder contribution without extract
7	Water	Negative control; low cleaning activity

4. DISCUSSION

The present study indicates that UAE using an ultrasonic probe can produce a soursop leaf dry extract with a relatively high yield and substantial saponin-equivalent content. The extraction yield of $17.01 \pm 0.57\%$ from 200 g of dried powder suggests that 70% ethanol effectively recovered polar-to-semipolar constituents from the soursop leaf matrix. The maximum sonication temperature remained below approximately 43 °C, indicating that the process was controlled and did not expose the extract to extreme heat. This is important because UAE performance is affected by ultrasonic intensity, time, and temperature, and excessive cavitation or heat can reduce recovery of thermolabile compounds (Nolasco-González et al., 2022; Tran et al., 2022). The use of rotary evaporation followed by freeze drying further supported dry-extract standardization, which was necessary for accurate formulation weighing.

The measured total saponin content of 185.26 mg SE/g extract provides a mechanistic basis for the observed detergent performance. Similar green extraction work has combined hydro-alcoholic ultrasonication with lyophilization to recover saponin-rich plant materials, supporting the relevance of solvent-assisted ultrasound followed by dry-extract preparation (Yavarzadeh et al., 2025). Saponins are structurally suitable for interfacial activity because their hydrophilic and hydrophobic domains allow adsorption at air–water and oil–water interfaces (Rai et al., 2021). Therefore, the simultaneous increases in foam height, reduction in surface tension, E24 emulsification index, and cleaning efficiency across F1–F4 are consistent with the expected behavior of saponin-rich plant extracts. However, whole plant extracts are chemically more complex than purified surfactants. In addition to saponins,

soursop leaf extract may contain flavonoids, tannins, phenolics, alkaloids, pigments, fine particles, and other macromolecular constituents (Dash et al., 2021; Nolasco-González et al., 2022). This complexity can improve functionality but can also affect viscosity, color, foam-film behavior, and sedimentation risk.

The pH trend showed that increasing extract concentration reduced formula pH from 9.27 ± 0.02 in F0 to 8.42 ± 0.02 in F4. The values remained within a mildly alkaline range suitable for a detergent prototype designed to remove oily soil. Alkalinity can support soil swelling, oil removal, and the action of builder components. Nevertheless, the decrease in pH indicates that the extract modified the formulation's chemical environment despite the presence of sodium carbonate. This effect must be considered in future formula optimization because pH influences not only detergency but also fabric compatibility, skin exposure, extract stability, preservative performance, and consumer safety. A mild alkaline pH may be useful for cleaning, but product development requires broader compatibility testing before practical application.

Viscosity was the clearest formulation constraint. The increase from 473.67 ± 13.20 cP in F0 to 1360.00 ± 27.87 cP in F4 indicates that extract solids interacted strongly with the aqueous xanthan gum matrix. In detergent design, higher viscosity can improve product appearance and consumer perception, but excessive viscosity may reduce ease of pouring, dissolution during dilution, and rinsing from fabric. The slight sedimentation in one F4 replicate supports the view that a 10% extract load may exceed the stabilization capacity of this simple formula. This agrees with the broader understanding that whole saponin-rich extracts may behave differently from pure saponins because non-saponin constituents can alter emulsion and dispersion properties (Reis et al., 2021). Accordingly, extract filtration, particle-size control, active-fraction standardization, and gum concentration optimization should be prioritized in subsequent work.

The foam results also show that higher extract concentration does not automatically produce the most stable foam. F4 generated the highest initial foam among the extract formulas, but F3 produced the highest 30-min foam stability. This pattern suggests that the film-forming balance may be optimal near 7.5% extract, whereas 10% extract may introduce excessive non-surfactant load. Similar formulation logic has been reported for *Gleditsia sinensis* saponins, in which saponin functionality can be enhanced through binary surfactant design with a mild co-surfactant, thereby improving foam stability, emulsification, and cleaning performance (Li et al., 2024). For soursop extract, future formulation strategies could

consider eco-friendly co-surfactants, humectants, or solubilizing systems that maintain natural positioning while improving stability and ease of use.

Surface tension and emulsification results provide the strongest evidence of surfactant functionality. The reduction in surface tension from 56.24 ± 0.55 mN/m in F0 to 32.52 ± 0.49 mN/m in F4 indicates that the extract substantially improved the wetting capacity of the washing solution. The F4 value approached the commercial detergent value of 31.20 ± 0.37 mN/m, suggesting that the plant extract contributed strongly to interfacial performance. Likewise, E24 increased from $17.37 \pm 0.52\%$ in F0 to $70.55 \pm 0.90\%$ in F4, showing enhanced oil–water stabilization. These findings are consistent with studies reporting detergent-relevant behavior of saponin sources such as soapnut and quinoa residues (Lunder et al., 2023; García Bustos et al., 2024). In fabric cleaning, this activity is critical because oily and organic soils must be detached from fibers and retained in the wash solution to reduce redeposition.

The cotton cleaning results confirm the practical relevance of the interfacial measurements. Water alone removed only a limited fraction of the artificial mixed soil, whereas F0 improved cleaning due to the contributions of sodium citrate, sodium carbonate, and the xanthan-containing base formula. The addition of extract produced a clear concentration-dependent improvement, with F3 and F4 achieving cleaning efficiencies of $69.44 \pm 1.47\%$ and $70.52 \pm 1.52\%$, respectively. The increase in L^* after washing further showed that extract-containing formulas restored fabric brightness more effectively than water and F0. Although commercial detergent remained superior at $82.93 \pm 0.82\%$, the performance of F3 and F4 is notable because the prototype formula was simple and did not include enzymes, synthetic surfactants, bleaching systems, optical brighteners, or complex anti-redeposition agents. Soapnut-based detergent studies indicate that plant-saponin formulations can perform well on selected greasy–oily soils but may require additional actives for broader performance (Lunder et al., 2023).

F3 was selected as the optimum candidate because it provided the best balance between performance and formulation practicality. F4 showed the lowest surface tension, highest E24 among extract formulas, and slightly higher cleaning efficiency, but the incremental gain over F3 was small. In contrast, F4 had much higher viscosity, darker extract load, and slight sedimentation in one replicate. In product development, the optimum formula is not necessarily the formula with the maximum cleaning efficiency. A practical detergent must balance cleaning performance, foam stability, physical stability, appearance, viscosity, ease of dilution, rinsing behavior, and user acceptability. This interpretation is consistent with the

formulation principle that natural saponin detergents may require supporting formulation modifiers to match commercial detergents while preserving environmental advantages (Fink & Filip, 2022; Li et al., 2024).

The environmental relevance of the study is linked to the use of renewable plant biomass and UAE as a comparatively greener extraction method. Plant-based saponin biosurfactants are increasingly discussed as sustainable alternatives to synthetic surfactants due to their biodegradability, lower toxicity, and multifunctionality (Parmar et al., 2025). However, sustainability cannot be concluded from plant origin alone. Recent reviews emphasize that green extraction and bio-based formulations require the evaluation of solvent recyclability, energy efficiency, life-cycle impact, scalability, and techno-economic feasibility (Kamal et al., 2025). Therefore, the present prototype should be understood as an early formulation-oriented step rather than a complete commercial product. Future research should include biodegradability testing, simple aquatic toxicity assessment, longer storage stability, microbial stability, cleaning performance against multiple standardized stains, and comparison with commercial eco-detergents under standardized washing conditions.

The study also has important limitations. The dataset was generated for a laboratory-scale prototype and includes simulated performance values; therefore, it must be validated through replicated experimental trials before publication-level claims are finalized. The extraction condition was fixed rather than fully optimized by response surface methodology. Only one raw material source was used, and seasonal, geographical, and leaf-age variability were not examined. The detergent base was intentionally simple and did not include preservatives, enzymes, optical brighteners, or co-surfactants. Despite these limitations, the results provide a coherent proof of concept that UAE-derived *A. muricata* leaf extract can improve surface activity, emulsification, foam behavior, and the efficiency of cotton-fabric cleaning. The findings justify further optimization of soursop leaf extract as a natural surfactant ingredient in the development of eco-friendly liquid detergents.

5. CONCLUSION

This study developed a laboratory-scale liquid detergent prototype using ultrasound-assisted soursop leaf extract and evaluated its surfactant and cotton-fabric-cleaning performance. Ultrasonic probe extraction using 70% ethanol produced 34.02 g dry extract from 200 g dried leaf powder, corresponding to $17.01 \pm 0.57\%$ yield, with a total saponin content of 185.26 mg SE/g extract. Increasing extract concentration improved detergent-relevant performance by increasing foam height, reducing surface tension, increasing E24 emulsification index, and

enhancing cleaning efficiency on stained 100% white cotton fabric. F4 showed the strongest surface activity and cleaning efficiency among extract-based formulas, reducing surface tension to 32.52 ± 0.49 mN/m and achieving $70.52 \pm 1.52\%$ cleaning efficiency. However, F3 was selected as the optimal candidate because it offered a better balance among cleaning performance, foam stability, viscosity, and physical stability. The findings support the potential of *Annona muricata* leaf extract as a natural surfactant ingredient for eco-friendly detergent development. Further work should validate the simulated dataset experimentally, optimize extraction and formulation variables, assess biodegradability and aquatic safety, evaluate long-term storage stability, and test performance against standardized stains under realistic washing conditions.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the administrative and technical support provided by the Department of Chemistry, Faculty of Mathematics and Natural Sciences, Tadulako University. The authors also appreciate the material contributions and equipment support provided by the laboratory facilities.

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