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Phenolic-Rich *Annona muricata* L. Leaf Extract Provides Broad-Spectrum Photoprotection: Linking SPF Enhancement with UVB/UVA Transmission Reduction

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Abstract. The search for safer, more environmentally friendly ultraviolet (UV) filters has led to the exploration of bioactive plant compounds as alternatives to synthetic UV filters. This study evaluates the phytochemical composition and photoprotective potential of ethanol extracts from *Annona muricata* L. leaves as candidates for a natural photoprotective ingredient. The ethanol extract of soursop leaves contains polyphenolic secondary metabolites with a total phenolic content of 67.30 ± 1.27 mg GAE/g extract and a total flavonoid content of 63.62 ± 0.67 mg QE/g extract. These phenolic and flavonoid compounds contribute to photoprotective activity. The SPF value increased significantly ($p<0.05$) with rising extract concentrations, reaching a maximum of 32.84 ± 0.75 at 1,000 µg/mL, indicating a strong dose–response relationship between extract concentration and protection against UVB radiation ($r \approx 0.99$). To achieve SPF 15, the soursop leaf ethanol extract required a concentration of 451.72 ± 1.09 µg/mL, while concentrations of 950.06 ± 1.42 µg/mL and 1,614.51 ± 1.37 µg/mL were needed for SPF 30 and SPF 50, respectively. The extract effectively blocks UVB radiation (measured by erythema percentage) and UVA radiation (measured by pigmentation percentage) at a concentration of 800 µg/mL. Overall, the ethanol extract of *A. muricata* L. leaves shows promise as a candidate for further evaluation as a natural photoprotective ingredient. These findings suggest that this extract could be developed as an active ingredient for multifunctional natural photoprotective formulations.

Keywords: *Annona muricata* leaf extract; Natural photoprotection; Sun protection factor (SPF); UVB/UVA, Phenolic, Transmission.

I. INTRODUCTION

Exposure to ultraviolet (UV) radiation from the sun is a primary environmental factor contributing to skin damage [1]. UV radiation consists of two main components that reach the Earth's surface: UVA (320–400 nm) and UVB (280–320 nm). UVB primarily causes erythema, sunburn, and direct DNA damage, while UVA contributes to premature skin aging (photoaging), hyperpigmentation, and the formation of reactive oxygen species (ROS), which trigger oxidative stress in skin cells [2], [3]. Increased exposure to UV radiation is also linked to a higher risk of skin cancer, extracellular matrix damage, and alterations in cellular function due to prolonged oxidative stress [4]. Therefore, using photoprotective agents, such as sunscreen, is a crucial strategy for safeguarding the skin against the harmful effects of UV radiation.

Commercial sunscreens typically contain synthetic UV filters, such as benzophenone-3 (oxybenzone), which absorb UV radiation and convert it into heat. This compound is highly effective even at low concentrations,

making it widely used in cosmetic and skincare formulations [5]. However, various studies report that oxybenzone can be absorbed through the skin and detected in biological fluids, including urine, blood plasma, breast milk, and human reproductive fluids [6], [7]. Additionally, long-term exposure to this compound has been linked to potential endocrine disruption, developmental toxicity, and ecological impacts as a persistent pollutant in aquatic environments [8], [9]. These concerns have led to increased attention on developing safer, more environmentally friendly sunscreens based on natural ingredients.

From an environmental sciences perspective, the growing reliance on synthetic UV filters represents a significant and underappreciated source of chemical pollution. Compounds such as oxybenzone and octinoxate are continuously released into aquatic environments through recreational water activities and wastewater effluents, where they have been detected in rivers, coastal waters, and marine sediments worldwide. Their persistence, lipophilicity, and endocrine-disrupting potential classify them as emerging contaminants of concern, capable of accumulating in aquatic food webs and disrupting coral reef ecosystems [10]–[13]. The development of photoprotective agents derived from plant secondary metabolites, therefore, carries a dual environmental rationale: reducing both the demand for synthetic UV filters and the associated anthropogenic pollutant load in natural ecosystems. In this context, tropical biodiversity represents an underexplored reservoir of photoprotective compounds. Tropical regions, particularly those of Southeast Asia, harbor the world's highest concentrations of vascular plant species, many of which have evolved rich polyphenolic profiles in response to intense equatorial UV radiation and diverse biotic pressures. Systematic bioprospecting of these plants for photoprotective applications constitutes a scientifically sound and ecologically relevant strategy, aligned with the principles of sustainable use of biodiversity and environmentally responsible innovation.

In recent years, plant secondary metabolites, particularly phenolics and flavonoids, have garnered significant attention as potential natural photoprotective agents. These compounds feature conjugated aromatic structures that absorb UV radiation, acting as natural UV filters [14]. Furthermore, polyphenols serve as potent antioxidants, neutralizing reactive oxygen species (ROS) generated by UV exposure and preventing oxidative damage to biomolecules such as lipids, proteins, and DNA [15], [16]. The presence of chromophore groups in phenolic and flavonoid structures allows for electron delocalization, effectively absorbing UV radiation—a mechanism that functionally resembles melanin's role as the skin's natural defense against solar radiation [17].

One tropical plant with potential as a source of photoprotective compounds is soursop (*Annona muricata* L.), a member of the Annonaceae family that has long been utilized in traditional medicine. The leaves of this plant contain various bioactive secondary metabolites, including phenolics, flavonoids, acetogenins, and alkaloids, which exhibit antioxidant, anti-inflammatory, and other biological activities [18]. Previous studies have reported that soursop leaf extract has a relatively high content of phenolics and flavonoids; however, the values may vary depending on the extraction method, the solvent used, and environmental factors such as light intensity, temperature, and soil nutrients that influence the biosynthesis of secondary metabolites in plants [19], [20]. Phenolic compounds and flavonoids in plants are known to absorb UV radiation, particularly in the UVB and some UVA wavelength ranges. Flavonoids, such as flavones and flavonols, exhibit absorption peaks in the 240–380 nm range, allowing them to function as natural UV absorbers [21]. This capability positions polyphenol-rich plant extracts as promising candidates for the development of natural-based sunscreens. Additionally, several studies indicate that tropical medicinal plants with high phenolic content often demonstrate photoprotective activity that correlates with their antioxidant capacity [22].

Although the photoprotective potential of soursop leaf extract has been investigated in prior work [23]–[25]. These studies have primarily assessed SPF in the context of formulated products or evaluated either SPF or UV transmission independently. The present study addresses this gap by providing an integrated evaluation of phytochemical content (TPC and TFC), SPF values, and dual UV-transmission parameters (%Te and %Tp) as a function of extract concentration, thereby enabling quantitative dose-response characterization and the determination of target concentrations required for SPF 15, 30, and 50. This approach offers a more comprehensive and reproducible baseline for assessing the photoprotective potential of this extract as a candidate natural UV filter. Therefore, this study aims to assess the phenolic and flavonoid content of soursop leaf ethanol extract and analyze its photoprotective activity by measuring SPF, erythema transmission (%Te), and pigmentation transmission (%Tp). Additionally, the extract's performance was compared with oxybenzone, a positive control, to evaluate its potential as a natural photoprotective ingredient in safer, more sustainable sunscreen formulations.

II. METHODS

Materials

Soursop (*Annona muricata* L.) leaf samples were collected from Pasir Gintung Village, Tanjung Karang Pusat Subdistrict, Bandar Lampung City, Lampung Province, Indonesia, at the coordinates 5°24′11″ S and 105°15′21″ E. The soursop leaves used were fresh and dark green. The plant material was authenticated by a qualified botanist, and a voucher specimen was deposited in the Herbarium Lampungense, Universitas Lampung (Voucher No. HL-2025-AM-238).

Preparation of Ethanol Extract

The extraction method refers to the research by Muaja et al. [26] with some modification. Two kilograms of soursop leaves are washed thoroughly with water, then air-dried until completely dry. Cut the dried leaves into smaller pieces, then blend them into a smooth paste. Macerate the soursop leaf mixture by soaking 300 grams in 1.5 liters of ethanol for 3 days, stirring occasionally. After maceration, filter the mixture to separate the liquid from the residue. The residue was re-macerated, and the macerate was placed in a light-protected container and concentrated using a rotary evaporator at 40°C until a thick extract was obtained.

Measurement of Total Phenolic Content

A 1 mg/mL ethanol extract of soursop leaves was diluted 5-fold by mixing 1 mL of the extract with 4 mL of ethanol. Subsequently, 1 mL of the diluted sample was combined with 4 mL of $NaCO_3$, followed by the addition of 400 µL of Folin-Ciocalteu reagent and 4.6 mL of distilled water [27]. The sample was then incubated in the dark for 2 hours. After incubation, the solution absorbance was measured at 750 nm using a Thermo Scientific Spectrophotometer (Genesys 150 UV-Vis, US). The total phenolic content was calculated from a gallic acid standard curve and expressed as mg GAE/g of sample.

Measurement of Total Flavonoid Content

A 250 µL sample of soursop leaf ethanol extract at 1 mg/mL was mixed with 75 µL of $NaNO_2$, followed by 75 µL of 10% $AlCl_3$. Next, 500 µL of 1 M NaOH and 1.6 mL of distilled water were added [27]. The absorbance of the resulting solution was measured at 415 nm using a UV-Vis spectrophotometer (Thermospectronic Spectrophotometer (Genesys 150 UV-Vis, US). Total flavonoids were expressed as quercetin equivalents based on a standard curve, reported as mg QE/g of sample, with quercetin concentration correlated with the measured absorbance.

2.2.4. Measurement of Sun Protection Factor Values. The photoprotective effect of soursop leaf ethanol extract against UVB radiation was assessed using the sun protection factor (SPF) method with modifications [28]. The extract was suspended in 10% DMSO at various concentrations (100–1,000 µg/mL). The 10% DMSO is used as both the solvent and the control. The UV absorption capacity of the soursop leaf ethanol extract was measured at wavelengths of 290–320 nm in 5-nm intervals using a UV-vis spectrophotometer (Thermospectronic Spectrophotometer (Genesys 150 UV-Vis, US)). Oxybenzone at various concentrations served as a positive control. SPF values were calculated using the Mansur equation [29]:

$$SPF = CF\ x \sum_{290}^{320} EE(\lambda) x I(\lambda) x Abs(\lambda)$$

Where CF is the correction factor (=10), EE is the erythemal effect of radiation at wavelength (λ), "I" represents the solar irradiance spectrum, and "Abs" denotes absorbance. The product "EE(λ) × I(λ) is a constant, as shown in Table 1 [30], and is categorized according to Table 2 [21].

A linear calibration curve was constructed by plotting the SPF values (y) against the concentration of A. muricata leaf ethanol extract (x, µg/mL), resulting in the regression equation ($y = 0.0301x + 1.4031$, $R^2 = 0.986$), where y represents the calculated SPF value and x represents the extract concentration (µg/mL). The regression model showed a strong linear relationship between concentration and SPF ($R^2 = 0.986$). This equation was used to estimate the extract concentration required to achieve target SPF values commonly used for commercial sunscreen classification (SPF 15, 30, and 50). The required concentration was calculated by rearranging the equation as:

$$x = \frac{(SPF\ target - 1.0431)}{0.0301}$$

Table 1.
Normalized product functions used in the calculation of the sun protection factor (SPF)

Wavelength (λ nm)	EE x I (Normalized)
290	0,0150
295	0,0817
300	0,2874
305	0,3278
310	0,1864
315	0,0839
320	0,0180

Table 2.
Protection categories based on SPF values

SPF value	Protection level
2-15	*Low*
15-30	*Medium*
30-50	*High*
>50	*Very high (for extreme condition)*

Measurement of the percentage transmission of erythema and pigmentation.

The percentage transmission of erythema (%Te) and pigmentation (%Tp) was determined by measuring the absorbance of soursop leaf ethanol extracts at concentrations ranging from 100 to 1,000 µg/mL. The 10% DMSO is used as both the solvent and the control. Measurements were taken at wavelengths associated with erythema, specifically within the range of 292.5–372.5 nm (UVB), at 5-nm intervals [31]. For %Tp measurements, the pigmentation spectrum was measured from 322.5 to 372.5 nm (UVA), also at 5-nm intervals. Absorbance values were then converted to transmittance (T) using the equation A = −Log T. The %Te and %Tp values were calculated using the following formula:

$$\%Te = \frac{Ee}{\sum Flux\ of\ erythema} = \frac{\sum T\ x\ Fe}{\sum Fe}$$

$$\%Tp = \frac{Ep}{\sum Flux\ of\ pigmentation} = \frac{\sum T\ x\ Fp}{\sum Fp}$$

Ee stands for erythema effectiveness, while Ep stands for pigmentation effectiveness. The erythema flux (Fe) values are measured at 290–320 nm, and the pigmentation flux (Fp) values at 320–375 nm, as shown in Table 3. The protection categories based on the %Te and %Tp values are detailed in Table 4 [32].

Table 3.
Erythema and pigmentation flux values for sunscreens

Wavelength (λ nm)	Flux erythema (Fe)	Flux of pigmentation (Fp)
290-295	0.1105	-
295-300	0.6720	-
300-305	1.0000	-
305-310	0.2008	-
310-315	0.1364	-
315-320	0.1125	-
320-325	-	0.1079
325-330	-	0.1020
330-335	-	0.0936
335-340	-	0.0798
340-345	-	0.0669
345-350	-	0.0570
350-355	-	0.0488
355-360	-	0.0456
360-365	-	0.0356
365-370	-	0.0310
370-375	-	0.0260

Table 4.
Categories of sunscreen activity based on the percentage of erythema and pigmentation

Category	Transmitted UV light range (%)	
	% erythema	% pigmentation
Sunblock	<1	3-40
Extra protection	1-6	42-86
Suntan	6-12	45-86
Tanning	10-18	45-86

Data Analysis

The data presented represent the mean and standard deviation from three experiments. All measurements were performed in triplicate using the prepared extract, which was reacted independently. Statistical differences were evaluated using one-way ANOVA followed by Fisher's Least Significant Difference (LSD) multiple-comparison test in OriginLab Pro Learning Edition 2026 (Northampton, USA).

III. RESULTS AND DISCUSSION

Yields, Phytochemical Composition of Annona muricata L. Leaf Extract

The extraction process yielded a thick, dark brown extract with an extraction yield of 15.90% (w/w) (Table 5), calculated as the mass of dry extract obtained relative to the mass of dry plant material used. The ethanol extract of *Annona muricata* L. leaves showed promising levels of phenolic and flavonoid compounds (Table 5). The total phenolic content (TPC) was measured at 67.30 ± 1.27 mg GAE/g extract, while the total flavonoid content (TFC) reached 63.62 ± 0.67 mg QE/g extract. The phenolic content of soursop leaf extracts has been widely reported, with values including 119.38 mg GAE/g for ethanol extract [20], 14.1 mg GAE/g ethanol extract [33], 61.5 mg GAE/100 g for the methanol extract [34], and 23.70 mg GAE/g for the methanol extract [24]. Total flavonoid contents in soursop leaf extracts have also been reported with varying values, including 505.20 mg QE/100 g for ethanol extract [35], 91.21 mg QE/g for ethanol extract [20], 8.32 mg QE/g for ethanol extract [36], 20.20 mg QE/g for methanol extract [24], and 50.3 mg QE/100 g for the methanol extract [34]. These variations in

concentration are influenced by environmental factors such as light exposure, temperature, and soil nutrients, which can affect the biosynthesis of phenolics and flavonoids in plants [19].

These relatively high concentrations of phenolics and flavonoids indicate that the ethanol extract of soursop leaves is rich in bioactive secondary metabolites with photoprotective activity. Flavonoids, particularly flavones and flavanols, are known to absorb UVB radiation [21]. The role of flavonoids in UV protection is closely linked to the total phenolic content in the extract. Phenolic compounds and flavonoids function as effective UV-absorbing molecules due to their cyclic rings and conjugated aromatic structures, which enable electron delocalization (acting as UV filter) and strong absorption in the UV spectrum at wavelengths of 240–280 nm and 300–550 nm (318 nm, 324 nm, and 356 nm) [14]. Additionally, these compounds can neutralize reactive oxygen species (ROS) generated by UV exposure, thereby preventing oxidative damage to the skin [15], [16]. Phenolic and flavonoid compounds also contain chromophore groups [25]. The function of these chromophore groups in polyphenolic compounds as UV filters is similar to that of melanin in human skin, which serves as the primary defense mechanism against UV radiation [17]. Mechanistically, a higher concentration of the extract correlates with an increased total polyphenol content in the system, thereby enhancing its capacity for UV absorption (physicochemical effect) and ROS scavenging (biochemical effect).

A key limitation of this study is the absence of chromatographic identification of specific phenolic constituents. While TPC and TFC provide useful bulk estimates of polyphenol content, they do not allow attribution of UV-absorbing activity to specific compounds. The roles of acetogenins, alkaloids, and other non-phenolic metabolites present in *A. muricata* [34] cannot be excluded based on the current data. Future studies should employ HPLC-DAD, LC-MS/MS, or UHPLC-QTOF profiling to identify and quantify the dominant photoactive constituents and to establish structure-activity relationships.

Table 5.
Yield, total phenolic, and flavonoid content in soursop leaf ethanol extract.

Parameters	Results
Yield (%)	15.90
Total phenolic content (mg GAE/ g extract)	67.30±1.27
Total flavonoid content (mg QE/g extract)	63.62±0.67

*The data shown represents the mean and standard deviation from three replicates.

Evaluation of Sun Protection Factor (SPF) Values

The SPF value of the soursop leaf ethanol extract increased significantly ($p<0.001$) with higher concentrations (Table 6). The SPF value indicates the photoprotective activity of the soursop leaf ethanol extract in absorbing, reflecting, or scattering UVB rays [21]. At a concentration of 100 µg/mL, the extract exhibited an SPF value of 6.04 ± 0.35, which progressively increased to 32.84 ± 0.75 at 1,000 µg/mL. This trend confirms a strong dose–response relationship between extract concentration and protection against UVB radiation.

Table 6.
Sun Protection Factor (SPF) values of soursop leaf ethanol extract.

Concentration (µg/mL)	SPF value
100	6.04±0.35
200	6.76±0.44
400	12.26±0.50
800	24.31±0.39
1000	32.84±0.75

*The data shown represent the mean and standard deviation from three replicates.

According to the internationally recognized SPF classification by the U.S. Food and Drug Administration (FDA), the ethanol extract of soursop leaves provides high protection at a concentration of 1,000 µg/mL. In this study, the photoprotective activity of the soursop leaf ethanol extract exceeded that reported by [23] , which had an SPF value of only 0.2302 at a 0.5% extract concentration. Additionally, it was comparable to the SPF value of soursop leaf methanol extract, which was 35.03 at 1,000 µg/mL [24]. These findings align with previous studies indicating that members of the Annonaceae family contain active compounds with strong antioxidant and UV-absorbing properties, making them promising candidates for development as natural photoprotective agents [18]. A natural photoprotective formulation derived from soursop leaf ethanol extract has been developed into a body butter, with a 1% concentration yielding an SPF of 7.07 [25]. These results are consistent with a recent study that reported significant variations in total flavonoid and phenolic content, which influence the antioxidant and photoprotective properties of tropical medicinal plants [22].

The SPF value of the soursop leaf ethanol extract in this study was influenced by the presence of phenolic compounds, which are known for their strong light-absorbing properties [34]. This makes the extract used in this study a potential component in formulations designed to combat UV-ray-induced damage. A Pearson correlation analysis between the concentration of soursop leaf ethanol

extract and the SPF value revealed a very strong positive relationship (r ≈ 0.99), indicating a nearly perfect linear relationship between increased concentration and enhanced UVB protection (Figure 1). The correlation between extract concentration and SPF was r = 0.990, with the regression equation: SPF = 0.0301 × [Concentration] + 1.406 (R^2 = 0.986, F(1,3) = 212.82, p < 0.001). This high correlation further supports the hypothesis that the active components in the extract directly contribute to the increase in SPF. In summary, a higher concentration of phenolic compounds and flavonoids significantly enhances the UV absorption capacity.

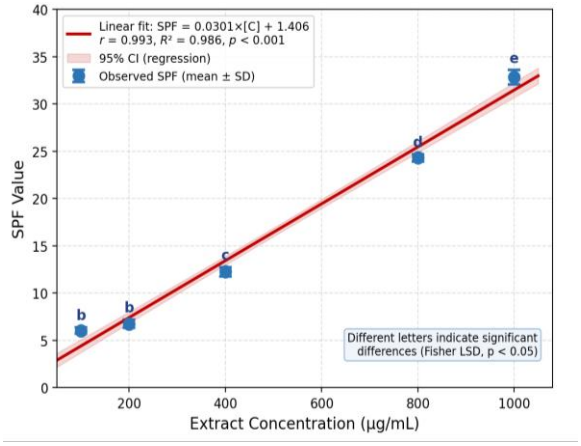

Figure 1. Pearson Correlation and Linear Regression: Extract Concentration vs SPF Value

In comparison, oxybenzone, a positive control for chemical sunscreens (Table 7), demonstrated a higher SPF at a much lower concentration. Specifically, oxybenzone achieved an SPF of 22.19 at a concentration of just 50 µg/mL, while the soursop leaf ethanol extract needed 800 µg/mL to reach an SPF of 24.31. This discrepancy can be attributed to the fact that oxybenzone is a synthetic UV filter specifically designed to effectively absorb UV radiation [37]. In contrast, plant extracts contain natural compounds with broader UV-filtering properties but at lower concentrations. However, natural extracts have an advantage over commercial sunscreens, as they do not contain active compounds (UV filters) that can be released into the environment [38]. These compounds can act as persistent pollutants, accumulating in the fatty tissues and bodily fluids of living organisms [34]. Health risks associated with UV filters are concerning, as these substances can enter the body through skin absorption and the consumption of contaminated food and water. UV filters can be detected in the bloodstream and are present in bodily fluids such as urine, semen, and breast milk [6], [7]. Further research into the presence of toxic byproducts in these extracts resulting from ultraviolet radiation would be valuable.

Table 7.
Sun Protection Factor (SPF) values of oxybenzone as a positive control for UV-protective agents.

Concentration (µg/mL)	SPF value
10	7.99±0.01
20	10.77±0.01
30	14.10±0.02
40	16.92±0.02
50	22.19±0.02

*The data shown represent the mean and standard deviation from three replicates.

Concentrations required to achieve target SPF values.

Table 8 presents the estimated concentrations needed to achieve SPF values of 15, 30, and 50. The soursop leaf ethanol extract requires 451.72 ± 1.09 µg/mL for SPF 15, 950.06 ± 1.42 µg/mL for SPF 30, and 1,614.51 ± 1.37 µg/mL for SPF 50. In contrast, oxybenzone achieves the same SPF levels at significantly lower concentrations of 32.65, 78.52, and 134.34 µg/mL, respectively. Although the potency of the soursop leaf ethanol extract is lower than that of the synthetic control, its ability to reach SPF 30 and SPF 50 indicates promising potential as a natural photoprotective agent.

Table 8.
The SPF values (15, 30, and 50) achieved by soursop leaf ethanol extracts are as follows:

Sample	SPF value at a concentration of (µg/mL)		
	15	30	50
Soursop leaf ethanol extract	451.72 ±1.09	950.06±1.42	1614.51±1.37
Oxybenzone*	32.65±0.05	78.52±0.08	134.34±0.12

*as a positive control for chemical sunscreen ingredients. The data shown represent the mean and standard deviation from three replicates

The lower the concentration of a compound needed to protect against UVA and UVB rays, the more effective that compound is. Natural ingredients generally have fewer side effects than chemical ingredients such as oxybenzone.

Oxybenzone is approved by the U.S. FDA and EU Commission at concentrations up to 6% and 10%, respectively, and is considered safe under normal use conditions at permitted concentrations [39]. The toxicological concerns pertain primarily to high-dose or prolonged experimental exposures, and their relevance to typical consumer use remains under regulatory review. Several side effects of this compound have been identified, including Hirschsprung's disease (HSCR) and intestinal abnormalities in infants, which result from the failure of enteric nerve cell migration during the 5–12-week embryogenesis period [8]. Additionally, exposure to oxybenzone can cause endocrine disruption, hinder fetal growth, and induce neuronal apoptosis, thereby inhibiting autophagy [9]. Oxybenzone levels ranging from 1.06–4.08 ppm have been detected in the umbilical cord, fetal blood, and maternal blood of women exposed to 48 ppm of oxybenzone during pregnancy. This indicates that, with each exposure, the body absorbs approximately 3.84 ppm over a four-hour period, which then accumulates [5].

A similar response was observed in *Schizosaccharomyces pombe* model cells, where an oxybenzone concentration of 50 µg/mL was found to be toxic, leading to yeast cell death [39]. These findings support the potential use of soursop leaf ethanol extract as an alternative to oxybenzone in sunscreen formulations. It is important to note that the safety profile of the soursop leaf ethanol extract itself has not been evaluated in this study. No cytotoxicity, skin irritation, phototoxicity, or sensitization data are available, and such characterization is essential before any claims of safety advantage over established UV filters can be made.

Erythema and Pigmentation Transmission.

The erythema transmission percentage (%Te) and pigmentation transmission percentage (%Tp) further confirm the protective capacity of soursop leaf ethanol extract (Table 9). At low concentrations (100–200 µg/mL), soursop leaf ethanol extract provides limited protection against UVB radiation but demonstrates moderate to strong UVA-blocking activity. At a concentration of 400 µg/mL, %Te decreased significantly ($p<0.001$, F: 16197.87) (Figure 2) to 5.57%, indicating ultra-protection against UVB. At concentrations of 800 and 1000 µg/mL, the %Te value dropped below 1%, suggesting that the soursop leaf ethanol extract functions as a sunblock for both UVB and UVA [32]. It's demonstrated UV absorption capacity spanning the UVB range and extending into part of the UVA region, as indicated by erythema (%Te) and pigmentation (%Tp) transmission measurements [2]. The erythema transmission (<1%) and pigmentation transmission (0–40%) values indicate the effectiveness of soursop and ethanol extracts as sunscreens in preventing redness and dark spots after UV radiation exposure [39].

Table 9.
% Transmission of erythema and pigmentation caused by soursop leaf ethanol extract

Concentration (µg/mL)	%Te	%Tp	Category
100	24.19±0.15	40.80±0.12	No protection of UVB and ultraviolet protection of UVA
200	19.76±0.17	39.60±0.15	No protection from UVB and Sunblock of UVA
400	5.57±0.11	15.30±0.10	Ultra protection of UVB and Sunblock UVA
800	0.35±0.21	2.30±0.19	Sunblock of UVB and UVA
1000	0.07±0.10	0.78±0.11	Sunblock of UVB and UVA

*The data shown represent the mean and standard deviation from three replicates.

Table 10.
% Transmission of erythema and pigmentation caused by oxybenzone

Concentration (µg/mL)	% Te	% Tp	Category
10	14.47±0.10	45.08±0.04	Tanning of UV B and Extra Protection of UV A
20	7.51±0.06	34.48±0.14	Suntan of UV B and Sunblock of UV A
30	3.45±0.01	25.81±0.10	Ultra Protection of UV B and Sunblock of UV A
40	1.77±0.02	18.35±0.07	Ultra Protection of UV B and Sunblock of UV A
50	0.63±0.17	10.76±0.14	Sunblock of UV A and UV B

*The data shown represent the mean and standard deviation from three replicates.

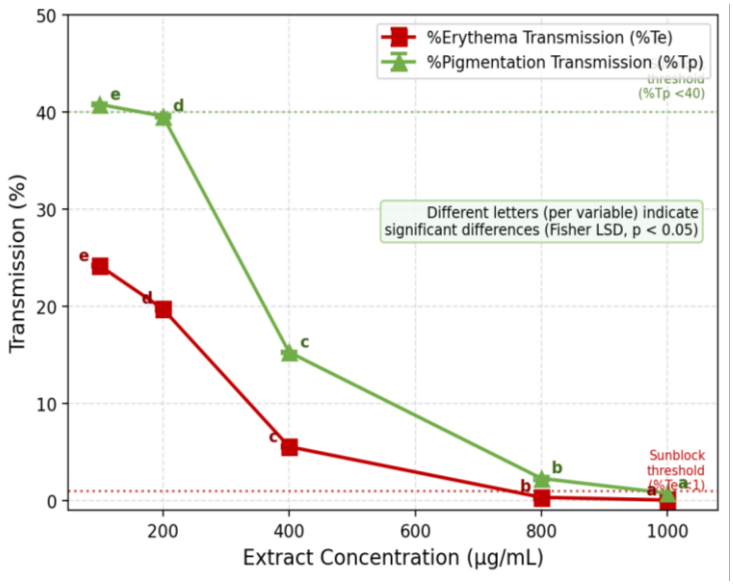

Figure 2. UV Transmission Reduction Vs Extract Concentration: Erythema (%Te) and Pigmentation (%Tp).

The %Te and %Tp values must be as low as possible for a product to be classified as a sunscreen. UVB rays cause sunburn, and prolonged exposure can even lead to skin cancer. Skin erythema is primarily caused by UVB, despite a greater amount of UVA reaching the Earth's surface [3]. A reduction in erythema (UVB-induced damage) and pigmentation (skin darkening and aging caused by UVA) indicates the presence of a dual protective mechanism, which is expected to safeguard skin cells from damage that leads to erythema and hyperpigmentation. Antioxidant properties further help reduce oxidative stress caused by UVA, which contributes to irregular pigmentation patterns [4]. These properties are derived from the presence of phenolic compounds and flavonoids in the extract. Compared to oxybenzone (Table 10), the synthetic control showed greater potential at low concentrations. However, at higher extract concentrations, the transmission percentage approaches that of oxybenzone, suggesting the potential to develop high-concentration botanical formulations.

Although soursop leaf ethanol extract requires a higher concentration than oxybenzone to achieve an equivalent SPF, its broad-spectrum activity and high phenolic content highlight its potential as a natural photoprotective ingredient for further evaluation in sunscreen formulations. A significant limitation of the current study is the absence of safety characterization. No cytotoxicity (e.g., HaCaT or fibroblast cell assays), skin irritation, phototoxicity, genotoxicity, or sensitization data were generated. Many plant extracts contain compounds capable of causing adverse skin reactions, including photosensitization [40]. Therefore, any conclusions regarding the suitability of this extract for cosmetic application must await comprehensive safety evaluation in accordance with internationally recognized guidelines (e.g., OECD or ISO 10993 series). Future research should focus on formulation, stability, in vivo SPF validation, cytotoxicity evaluation, and photostability testing.

Beyond its pharmaceutical implications, the present findings are relevant to environmental sciences and the sustainable use of tropical biodiversity. *Annona muricata* L. is a representative of tropical biodiversity, indigenous to and now widely cultivated across the equatorial belt of Southeast Asia, Latin America, and Africa—regions that collectively harbor over 50% of global vascular plant diversity and experience the highest solar UV irradiance on Earth. The demonstrated UV-absorbing capacity of its leaf polyphenols illustrates the broader principle that tropical plants, shaped by intense solar radiation and rich evolutionary pressures, constitute a largely untapped reservoir of natural photoprotective compounds. Systematic bioprospecting of such species, guided by phytochemical screening frameworks similar to that employed here, represents a scientifically rigorous and ecologically aligned strategy for discovering green alternatives to synthetic UV filters. From an environmental pollution standpoint, the substitution or partial replacement of synthetic UV filters such as oxybenzone with plant-derived photoprotective agents would directly contribute to reducing the input of persistent organic pollutants into aquatic ecosystems, where synthetic UV filters accumulate in sediments, enter food webs, and disrupt endocrine function in non-target organisms, including coral, fish, and marine invertebrates [10]–[13]. The use of a renewable, locally sourced tropical plant such as *A. muricata* as a photoprotective ingredient furthermore aligns with the circular bioeconomy model—utilizing leaf biomass that is otherwise discarded during fruit harvesting

[33] and contributes to reducing reliance on persistent synthetic UV filter pollutants in favor of biodegradable, nature-derived alternatives. Taken together, these considerations position the study of tropical plant-derived UV filters not merely as a cosmetic science endeavor but as an integral component of the broader agenda for environmental health, biodiversity conservation, and sustainable innovation.

IV. CONCLUSION

The ethanol extract of soursop leaves (*A. muricata* L.) contains significant levels of phenolic and flavonoid compounds and demonstrates strong, concentration-dependent photoprotective activity. At higher concentrations, this extract offers a very high SPF value and demonstrates UV absorption capacity spanning the UVB range and extending into part of the UVA region, as indicated by erythema (%Te) and pigmentation (%Tp) transmission measurements, highlighting its potential as a candidate for further evaluation as a natural photoprotective ingredient. It must be noted that the present findings are derived from in vitro spectrophotometric assays and do not constitute evidence of clinical sunscreen efficacy. Regulatory classification as a broad-spectrum sunscreen requires additional parameters, including the critical wavelength (λc), UVA-PF determination, photostability assessment, water-resistance testing, and in vivo validation. These remain important directions for future research.

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CONFLICT OF INTEREST

The authors declare no conflict of interest

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